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# FACIES CHARACTERISTICS AND PATTERNS IN MID-ESTUARY INTERTIDAL FLAT DEPOSITS, WILLAPA BAY, WASHINGTON

by

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## ABSTRACT

The purpose of this study is to characterize the deposits of mid-estuary intertidal flats in Willapa Bay, Washington, based on texture, composition, and sedimentary structures (both physical and biogenic).

The average textural characteristics of mid-estuary intertidal 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 sediments fining upslope and up-estuary reflecting a response to decreasing hydraulic energy and increasing distance from the main sand source (the tidal inlet).

Compositionally, mid-estuary intertidal flat sediments are mainly (greater than 90%) light minerals, mostly quartz with small amounts of lithic fragments, pumice, vegetation, and biogenic shell fragments. Heavy minerals make up about 4% of the sediment. The most common heavy minerals are clinopyroxene, orthopyroxene, hornblende, epidote, and opaque. Clay minerals comprise less than 5% of the sediment. The principal clay minerals are montmorillonite, illite, and chlorite; two clay mineral suites are present: (1) muddy flat suite with 44% montmorillonite, and (2) sandy flat suite with 88% montmorillonite. Fossils make up less than one percent of the sediment. The most common microfossils are forams separated into two assemblages - one modern shallow-water and the second a relic deep-water assemblage. Macrofossils consist of shells of the modern tidal flat mollusc assemblage.

Where sand occurs, bedforms ranging from large sandwaves to small

scale ripples exist. Due to low sedimentation rates on the flats, the sediment experiences extensive biogenic reworking except where local conditions preclude faunal activity. Overall, therefore, bioturbate textured sediments are characteristic of mid-estuary intertidal deposits. The most common preservable trace in sandy sediments are the large subvertical, branching burrows of the ghost shrimp Callianassa. Large Upogebia borings are common in exposed, consolidated Pleistocene mud deposits which floor some parts of the intertidal flats.

Mid-estuary intertidal flats are similar in texture to outer flats (intertidal flats near the bay inlet); structurally, however, mid-estuary intertidal flats are similar to inner flats (intertidal flats near the river). Compositionally, mid-estuary intertidal flats are transitional between outer and inner flats reflecting a mixture of components derived from main sand sources at the bay mouth and mud supplied by the rivers.

## INTRODUCTION

Many studies have been conducted to geologically characterize modern estuarine processes and deposits (e.g., Davis, 1978). One important application of such studies has been in their use by geologists in recognising estuarine deposits in the rock record (e.g., Clifton and Phillips, 1980). Such application is difficult, however, because estuaries are complex, containing many "subenvironments", each with a different set of characteristics (e.g., tidal deltas, tidal channels, point bars, barrier spits). Todate, not all subenvironments have attracted equal study. Those deposits with distinct and unique characteristics have received the most attention. For example, (1) relatively high energy subenvironments near tidal inlets have been investigated (e.g., Kumar and Sarders, 1974) due principally to the diversity of physical processes and products, while (2) studies of relatively low energy subenvironments such as salt marshes (e.g., Frey and Basan, 1978) are recognised principally by their biological signature. Mid-estuary intertidal flat sediments have received little, if any, detailed study. The purpose of this paper is to characterize the deposits of mid-estuary intertidal flats in Willapa Bay, Washington, based on texture, composition, and sedimentary structures (physical and biogenic).

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 Survery (Menlo Park, California) have contributed to the understanding of depositional processes operative in Willapa Bay (e.g., Clifton and others, 1976, 1979; Anima, 1979; Hill and Chin, 1979; Luepke and Clifton, 1979; Phillips, 1979; Rapp, 1979; Clifton and Phillips, 1980).

Terminology: Willapa Bay is a coastal plains estuary (Andrews, 1965). An estuary is a marginal, semi-enclosed marine water body in which fluvial discharge measurably dilutes the salinity (Fairbridge, 1968). In this report, general geographic subdivisions of Willapa Bay are outer, mid-, or inner estuary. Outer estuary refers to the area near the bay mouth while areas nearest the rivers are termed inner estuary. Between the two is the mid-estuary. A tidal flat is a horizontal, barren or marshy land that is alternately covered and uncovered by the rise and fall of the tide (American Geological Institute, 1974). Relative to tidal flats within the bay, "upper" refers to an area of a flat nearest of the shoreline; the "lower" flat is adjacent to the main tidal channels. Between the upper and lower flat is the mid-flat. 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 souce (i.e., rivers and creeks).

## ENVIRONMENTAL SETTING

Willapa Bay is located in the southwestern Washington coast approximately 47 km north of the Columbia River mouth (Fig. 1). The bay forms a total water area (at high tide) of about 348 $km^2$: deep tidal channels below 6 m water depth represents 51 $km^2$, subtidal flats to 6 m below mean low water represents 127 $km^2$, and 170 $km^2$ represent tidal flats (Clifton and Phillips, 1980). Several relatively small rivers, draining about 2400 $km^2$ of land (Garrett and others, 1962), empty into Willapa Bay.

Separating the bay from the Pacific Ocean is North Beach Peninsula, a barrier spit measuring approximately 30 km long, 2.5 km average width, and standing 7.5 meters above sea level. This spit (1) consists of a series of parallel beach-dune ridges separated by linear lakes, (2) is formed of sediment from the Columbia River carried north by littoral transport, (3) is covered with vegetation except for the beach areas and northernmost tip, and (4) represents a sand deposit as much a few hundred meters thick (Ballard, 1964; Andrews, 1965). Well-exposed cliffs of Pleistocene estuarine deposits flank most of the north and east sides of the bay; Tertiary (Eocene to Miocene) bedrock outcrops locally in the southern bay area (Andrews, 1965; Clifton and Phillips, 1980).

The bay inlet is about 8 km across and generally obstructed by a complex of large sandshoals and tidal channels. Over the past hundred years, the bay inlet has migrated nearly 3 km northward (Clifton, 1979). Willapa Bay has two main channels (Fig. 2). The south channel (Nahcotta) is about 29 km long, extends the length of the bay, and is bounded by broad sandy subtidal shoals and intertidal flats (Clifton and Phillips, 1980). The other 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; width ranges approximately from 90 to 2200 meters.

Extensive tidal flats represent more than half the bay area, extending up to a kilometer offshore locally. Two main environments compose the tidal flats (Clifton and Phillips, 1980): (1) intertidal flats which are inundated by astronomical tides, and (2) supratidal flats which are inundated by a combination of astronomical and meteorlogical tides. Locally, salt marsh environments occur between intertidal and supratidal flats. Runoff channels cross the tidal flats.

Characteristic of mixed tides on the Pacific coast, tides in the bay show diurnal inequality. The diurnal variance is 2.5 m at the bay inlet and 3.1 at Nahcotta (Andrews, 1965) which classifies Willapa Bay as a mesotidal estuary (Clifton and Phillips, 1980). At the bay inlet, tidal currents average 1.3 m/s on maximum flood and range from 2.1 to 3.1 m/s maximum ebb (U. S. Coast and Geodetic Survey, 1962; Clifton and Phillips, 1980).

Except at the bay entrance, oceanic waves have little effect on the bay sediment. At the bay inlet the sandy shoals are intensively reworked by oceanic waves. Local winds are the most significant agent generating waves in the inner bay.

Sediments in Willapa Bay (Fig. 3) are predominantly mud (mainly silt and clay) and fine sand (Clifton and Phillips, 1980). The majority of mud in the bay is introduced by river discharge while the Pacific

Ocean supplies most of the sand (Andrews, 1965).

There have been no detailed studies of the flora and fauna in Willapa Bay. The few reports concerning organisms address problems related to the minor oyster industry operating in the bay (e. g., Sayce, 1976).

The specific study area for this report is located on the intertidal flats between approximately Goose Point and Pickernell 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. Limited salt marsh and supratidal flat environments occur near the Palix River and Pickernell Creek. Indurated terrace deposits occur along the entire shoreline adjacent to the flats.

Detailed descriptions of Willapa Bay are given in Garrett and others (1962), Andrews, (1965), Clifton and Phillips,(1978, 1980), and Anima (1979).

## METHODS

Samples for analyses of texture, composition, and sedimentary structures were taken at 36 sample locations (Fig. 4). For textural and compositional analyses, samples were taken using 3.5 X 15.5 cm butyrate tubes. Prelabelled tubes (4 at each station) were (1) pushed into the sediment as far as possible, (2) excavated, and (3) capped immediately. All samples were immediately refrigerated to retard bacterial growth; refrigeration continued until the samples were opened for analysis.

### Texture

All sediment size analyses were conducted in 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 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. Hydrophotometer 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 coverts sediment data to graphical and moment statistics, ratios, cumulative and straight percent, histograms, and cumulative curves.

## Composition

### Heavy and Light Minerals

Heavy and light mineral samples were obtained by splitting off a representative sample, in the 2-4 Ø size range, of the sand fraction sample (-1 to +4 Ø) obtained during textural analysis. This subsample was separated into heavy and light fractions using tetrabromoethane (specific gravity: 2.92-2.94). Heavy and light mineral fractions were weighed and slide mounted for petrographic analysis. For heavies, a 300-600 point count was used due to the large amount of opaque minerals, whereas a 100 point count was used for the lights.

### Clay Minerals

Clay mineral samples were obtained from original, unanalysed surface samples (one of the four tube samples). A small representative sample was taken and run through an ultrasonic disperser. Sediment in suspension was then poured off and centrifuged to separate out the less than 63 um fraction for clay mineralogy analysis. The less than 63 um fraction was mounted on glass slides and analysed on a Picker X-ray diffraction unit. Each sample was X-rayed after air drying, overnight glycolation (ethylene glycol), and 1-hour heating at 550°C.

### Carbon and Nitrogen

Surface sample splits were freeze dried then powdered with mortar and pestle. Powdered samples were analysed on a Leco WR12 Carbon Determinator for total carbon content. Part of the freeze dried samples were sent to Rinehart Laboratories (Arvada, Colorado) for standard analysis for organic carbon, total nitrogen, and organic nitrogen.

Paleontology

For micropaleontology analysis, a subsample of the sand fraction from each station was split off during textural analysis. This subsample was run through a "foram float" procedure using carbon-tetrachloride (Paula Quinterno, U. S. Geological Survey, Menlo Park, California; personal communication). The light fraction and heavy fraction were both checked for forams.

Macropaleo identifications were made using biological samples obtained by washing box core sediments through a 0.5 mm mesh sieve. Macrofossils were collected from the sieves and identified.

## Sedimentary Structures

Relatively undisturbed box cores (10 X 14 X 20 cm) were collected from each station on the tidal flat. In the laboratory, the cores were opened, discribed, and x-ray radiographs were made using a portable industrial x-ray unit equipped with a beryllium window hotshot head and type-M industrial x-ray film. Epoxy peels were made for the analysis of physical and biogenic sedimentary structures.

A modification of burrow-casting techniques (Mayou, Howard, and Smith, 1969), and trenching were used to determine large burrow morphologies. Burrow casts were made using epoxy and fiberglass resins.

Type and number of various burrow openings at the sediment surface were counted within a meter square area at each station.

## TEXTURE

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 Variability

#### Gravel

The areal distribution of gravel-size detritus (greater than 2.00 mm) is shown in figure 5, 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-size 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 source of the clasts.

#### Sand

The areal distribution of sand-size (0.63-2.00 mm) detritus in the sediments is shown in figure 6 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 range from 33.0 to 99.3 percent. Most stations (53%) had greater than 90 percent sand content while only two stations (6%) had less than 70 percent sand.

The sand distribution map (Fig. 6) shows two trends in distribution: (a) 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. Upslope decreases in sand reflect a decrease in tidal energy away from the channels. 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). The relativelly high sand concentration between Goose Point and Sandy Point extends across the entire flat. Factors promoting the winnowing out of the finer sediment fractions in this part of the study area are (1) higher wave and current energy, and (2) longer duration of tidal flow because the area is a slight topographic low which tends to focus tidal currents.

<u>Silt</u>

The areal variability in the amount of silt-size (3.9 - 63 μm) detritus is shown in figure 7. 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 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 between Goose Point and Sandy Point. Near the Palix River and Pickernell Creek , relatively high percentages of silt extend across the entire width of the tide flat. Silt content is greatest near the silt source (rivers and creeks) and on the upper flat where tidal energy is lower.

Clay

The areal distribution of clay size (less than 3.9 μm) detritus is shown by figure 8. 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 probably the source of the clay; therefore, with increasing distance from the source the clay content decreases. Wave winnowing in higher energy areas near the channel margins and between Goose Point and Sandy Point remove clay from the sediments.

## Component-Ratio Variability

Tide flat sediment variability can also be defined in terms of component-ratio variablility. 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 (mainly silt + clay fractions) comprise the two basic textural components in the study area, and their interrelationships are shown in figure 9. Sand/mud ratios vary from 0.5 to 141.2 (Table 2). 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 in the relatively high energy environment between Goose Point and Sandy Point where the sand content is greater that 95% (fig. 6) due to winnowing out of the fine material.

### Silt/Clay Ratios

The silt/clay ratios are shown in figure 10. 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. Relatively high ratios (greater than 2.8) extend across the flats near areas adjacent to rivers. The only area approaching equal proportions of silt and clay (ratios less than 1.8) is between Goose Point and Sandy Point in the area of a very high sand content (greater than 95 percent; Fig. 6) 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 wave surge on the upper flat.

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.

## 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 11. 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. 12).

A general synthesis of all the textural variability previously described is shown by the sediment distribution map (Fig. 12) 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 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 prevent significant amounts of mud deposition.

## Granulometric Analysis

The sediments were also evaluated texturally in terms of their statistical grain-size parameters. The 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 figure 13. 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 lower flats.

Overall, the map of mean grain size distribution shows a grain-size pattern similar to some of the other patterns, 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 decreased 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 areas of coarser material extending onto the mid to upper flat result for different reasons. Area one, the flat between Goose Point and Sandy Point, is closer to (1) major sand sources (e.g., Ellen Sands) and (2) higher tidal energy. The second area of coarser sediment 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 higher on the flat.

Standard Deviations

The standard deviation was used as a measure of sediment sorting and is shown by figure 14, 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 were classified as well sorted (0-0.1 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 (Figs. 13-14): 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 figure 15, and tabulated in Table 3. Values at individual sample stations range from +1.00 to -0.17. Approximately 3 percent of the samples were coarse-skewed (-0.1 to -0.3), 14 percent near symmetrical (-0.1 to +0.1), 14 percent fine-skewed (+0.1 to +0.3), and 69 percent 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 neary symmetrical sediments had relatively coarse mean grain sizes (Table 3).

The general distribution trend is an increase in strongly fine-skewed sediments up-estuary and, perhaps, upslope. The pattern exhibits a good correlation with mean grain size (Fig. 13). The trend appears to reflect transport of finer material toward the beach or erosion of fine material from cliffs. Duane (1964) related skewness to environmental energy in Pamlico Sound sediments. He found that truncation of the fine fraction occurred in sediments deposited in relatively high energy areas where intensive winnowing 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 distribution, 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 16. 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 single log-normal population. The kurtosis distribution pattern in the study area indicates that the relatively mesokurtic sediments near the Palix River and Pickernell Creek result from the mixing of a sand population transported in tidal channels from the Bay mouth with a finer mud population transported by the rivers. 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 this question, 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 my study area (Fig. 17). 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. 18). Three aspects of this pattern are noteworthy: (1) relatively 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, 2.5$\phi$ mean grain size; Table 5).

The pattern of sediment distribution of 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.

## COMPOSITION

Compositional characteristics and variability in the study area are discussed in terms of clay mineralogy, heavy minerals, light minerals, paleontology, and organic geochemistry.

### Mineralogy

#### Clay Minerals

Distribution: The areal distribution of clay-size detritus is shown by figure 8. Percentage (by weight) of clay in bottom sediments at individual stations range from 0.3% to 7.1%. As noted earlier, clay content increases upslope and up-estuary with higher concentrations (greater than 3 percent) 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.

Composition: The results of clay mineral analysis of selected samples is presented in Table 6. The principal clay minerals are montmorillonite, illite, and chlorite. Areal distribution of montmorillonite is shown in figure 19. Two clay mineral suites are present, one found on muddy flats adjacent to rivers and one associated with the sand flats between Goose Point and Ramsey Point. The clay mineral suite in sediments on flats next to the Palix River and Pickernell Creek is characterized by the following average composition: 44% montmorillonite, 37% illite, and 19% chlorite. In contrast, the clay mineral suite of the sandy flats away from the rivers is characterized by very high amounts of montmorillonite; average compositin is 88% montmorillonite, 6.5% illite, and 5.5% chlorite.

Source: The two clay mineral suites probably represent two different sources. The low montmorillonite suite characteristic of flats adjacent to the Palix River and Pickernell Creek are probably supplied by these rivers. The high montmorillonite suite characteristic of the sandy flats is probably supplied by erosion of the terrace deposits adjacent to the upper flat. The Bay Center Mud (Clifton and Phillips, 1978) is an example of a relatively thick (5 m) mud unit in the terrace deposits.

<u>Heavy Minerals</u>

Distribution: The percentages of heavy minerals in each sample are tabulated in Table 7 and the areal distribution shown in figure 20. Heavy mineral content of the bottom samples range from 1% to 12%;

average heavy mineral content was 3.3%. Most samples (75%) had less than 4% heavy minerals and only one station (S810-1) had more than 10%.

The distribution of heavy minerals shows a trend upslope and up-estuary. In the northern part of the study area (Goose Point to Sandy Point), samples containing greater than 4% heavy minerals are only located on the upper tidal flat near the vertical cliffs. To the south, relatively high percentages of heavy minerals (greater than 4%) occur across the entire intertidal flat from the beach to MLLW line. Samples taken near the Palix River and Pickernell Creek, however, had 3% or less heavy minerals. The concentrations of heavies in the north probably indicates concentration due to wave reworking of sediments eroded from the nearby cliffs. In Andrews (1965) study of the channel sediments in Willapa Bay, he found an increase in abundance of heavy minerals in Nahcotta Channel and contributed this to sediment supplied by the Naselle River. The abundance of heavies across the flats south of Sandy Point could be explained, therefore, as (1) being closer to the source area (i.e., Naselle River), and (2) are distributed across the entire flat due to tidal action.

Composition: Mineralogical analysis of all samples show that opaque minerals compose 6 to 40% of the heavy fraction in the 2-4 Ø size range; average value 23% (Table 8). Although identification of opaque minerals was not done in this study, Andrews (1965) reports the opaque minerals in the bay are mostly magnetite with minor amounts of ilmenite and rutile.

Analysis of the non-opaque heavy minerals in four randomly selected samples found an average composition to be 25.2% clinopyroxene, 24.6%

orthopyroxene, 23.1% hornblende, 19.8% epidote, 3.5% garnet, 1.6% lamprobolite, and 2.2% other minerals such as sphene, rutile, aegerine-augite, kyanite, staurolite, apatite, zircon, chloritoid, and topaz (Table 9). These non-opaque mineral species and their relative abundance are very similar to those reported by Anima (1979) for several samples collected near the large intertidal channel between Goose Point and Sandy Point. No significant trends in non-opaque mineral variations either upslope or up-estuary are evident.

Source: The mineral suite in the tidal flat represents a mix of sediments from different sources including (1) rivers, (2) ocean and ocean beaches, and (3) reworked local deposits. Andrews (1965) notes that Eocene basalts (chiefly tholeiitic pillow lavas) in the bay drainage system are a possible source of such minerals as clinopyroxene, amphiboles, and magnetite. The Columbia River is the dominant source for material carried by littoral drift into Willapa Bay (Ballard, 1964). Augite, ilmenite, magnetite, and rutile are examples of detrital minerals derived from basic igneous rocks such as the tholeiitic Columbia River basalts and the andesite strato-volcanoes of the Cascade Range (Waters, 1962) in the drainage basin of the Columbia River. Metamorphic rocks of the Idaho batholith, also in the Columbia River drainage basin, may be the source of high-grade metamorphic minerals like garnet, kyanite, and sillimanite (Andrews, 1965). Locally reworked Tertiary and Quaternary deposits probably supply some of the heavies but a proportionately greater amount of the light mineral fraction.

<u>Light Mineral Fraction</u>

Distribution: Tidal flat samples consist of 88-99% material with a specific gravity less than 2.92 (= light mineral fraction). Most samples (89%) have a light fraction equal to or greater than 95% of the total composition (Table 7). The average light fraction content is 96.4%.

Trends in the variation in abundance of lights is the inverse of the trends already discussed for the heavy minerals; i.e., increasing abundance of heavies to the south and near the beach results in a proportionate decrease in the light fraction in those areas. Significance of such trends has already been discussed.

Composition: Analysis of the light fraction was conducted for all bottom samples. The average composition was 89% quartz, 5% lithic fragments, 4% opaque minerals, and 2% other material including pumice, wood chips, pieces of vegetation (mainly eel grass *Zostera*), and biogenic shell fragments (foram tests, echinoderm spines, ostracod shells, bryozoan fragments) (Table 10). No significant compositional trends upslope or up-estuary within the study area were noted.

Source: Tertiary and Quaternary terrace deposits supply much of the lighter sand size material to the flats. These terrace deposits characterized by high (10 m) cliffs occur along the entire length of the study area. The deposits are eroded by wind, rain, slumping, and wave action. Siliceous sand beds are common in the terrace deposits. As discussed earlier, other significant sources of the light fraction include material supplied by rivers and littoral drift through the Bay entrance.

## Paleontology

### Microfossils

Microfossils make up significantly less than one percent of the bottom sediments. The majority of microfossils are forams with diatoms and ostracods being relatively rare. Only the forams were identified for this study; results are tabulated in Table 11.

Analysis of forams in selected samples show two foram assemblages exist on the flat. These assemblages can be differentiated by taxonomic analysis, age, and environmental analysis. The first assemblage consists of the modern fauna *Trochammina inflata*, *Trochammina pacifica* var. *simplex*, *Ammobaculites* (or *Ammoscalaria*) sp., and *Miliammia fusca*. These species were most common and abundant in samples near the Palix River and Pickernell Creek. This assemblage represents a mixture of marine and brackish water species and is a good indicator of shallow-water marine environments near a source of less saline water such as a river (Parker and Athearn, 1959; Millman, 1963; Andrews, 1965).

The second foram assemblage on the flat is most common in the predominantly sandy areas between Goose Point and Sandy Point. Common species include *Bathysiphon* sp., *Martinotiella* sp., *Rhabdammina* sp., and *Cyclammina trullissata*. All these species are reworked from rocks as old as perhaps Eocene to Cretaceous (Robert Arnal, U.S. Geological Survey, Menlo Park, California; personal communication) and indicate outer shelf to bathyal depths. Many of these species are represented by individuals that are fragmented, iron-stained, or had a crystalline test.

## Macrofossils

The only preservable macrofossils collected in the samples were the molluscs *Ostrea lurida*, *Cryptomya californica*, *Mya arenaria*, *Macoma* sp. and *Tapes japonica*. All these species are currently living on the tidal flats with the possible exception of the oyster *Ostrea lurida* which lives in adjacent environments. Some of the molluscs (e.g., *Ostrea lurida*) are present as fossils in terrace deposits adjacent to the upper flats and are eroded out of the cliffs on occasion. Much of the vegetation that is present in the sediment is transported out or quickly decomposes. However, large trees or branches occasionally topple onto the flat as the cliffs erode and could get incorporated into the tidal flat deposits. Large logs are preserved in the terrace deposits, however, they are mainly in channel deposits (Clifton and Phillips, 1980).

# Organic Geochemistry

## Carbon

The concentration (ppm) of total carbon, organic carbon, and carbonate carbon for each sample is given in Table 12, the areal distribution of organic carbon is shown in figure 21. Organic carbon concentrations ranged from 1.15% (11450 ppm) to 0.008% (800 ppm), the average was 0.3% (3122 ppm).

The greatest concentration of organic carbon is on the flats adjacent to the Palix River and Pickernell Creek with organic carbon concentrations generally greater than 2500 ppm (Fig. 21). Relatively low concentrations (less that 1500 ppm) of organic carbon are generally restricted to the upper flat between Goose Point and Ramsey Point; low concentrations extend offshore across the flat only off Sandy Point. Generally, organic carbon concentrations increase up-estuary; no upslope trends are obvious.

The organic carbon content of the tidal flat sediment increases slightly as mean grain size diminishes (Fig. 22). In most of the very sandy areas (between Goose Point and Ramsey Point) where sand comprises 95% of the sediment, small amounts of organic carbon (generally less than 0.15% are typical. Muddy sediments near the rivers usually contain 0.25% to 1.15% organic carbon.

The inverse relationship between total organic carbon and mean grain size has been documented by many studies over many years (e.g., Trask, 1932). However, the variation in organic carbon concentration within sands is not well known although a number of recent investigations have addressed this topic (e.g., Pinet and Frey, 1977). The amount of organic carbon (less than 0.2%) in the sandy tidal flat deposits is more typical of shelf sands such as those off Georgia (Pinet and Frey, 1977) and Washington-Oregon (Gross and others, 1972) than in estuaries. For example, Andrews (1965) reports organic carbon content as high as 2.5% in muddy inner tidal flats in Willapa Bay (Fig. 22).

The distribution pattern of organic carbon within the study area reflects the relation of organic carbon to hydraulics. The Palix River probably supplies relatively large amounts of organic carbon to the adjacent flats. The lowest concentrations of organic carbon occurs in the sandiest part of the tidal flat (between Goose Point and Sandy Point), an area with the highest current energy generated by tidal hydraulics. Even though substantial organic material is produced locally on the sandy flats (e.g., macrobenthic infauna and marine grasses), tidal currents and sediment reworking by waves apparently flush most of the organic material off this section of the tide flat. Permeability is also greater in sandy sediments allowing for more complete oxidation of organic matter.

## Nitrogen

Total nitrogen and organic nitrogen content for each sample is tabulated in Table 12 and the distribution of organic nitrogen is shown in figure 23. Concentrations of organic nitrogen range from 6 ppm to 1563 ppm with an average value of 280 ppm. Most of the nitrogen is organic (Table 12).

Like organic carbon, the highest concentrations of nitrogen are on flats near the Palix River and Pickernell Creek. The lowest concentrations are in sediments between Goose Point and Sandy Point. Organic nitrogen increases up-estuary; no upslope trends exist.

As the sediment becomes muddier, the nitrogen content increases (Fig. 24). This relationship is similar to that observed for grain size versus organic carbon (Fig. 22). A correlation exists between organic carbon and organic nitrogen; as organic carbon increases so does organic nitrogen (Fig. 25). However, concentration of organic carbon is several times greater than organic nitrogen on the average. The distribution, concentrations, relation to organic carbon and grain size are similar to the results of Andrews (1965) for other tidal flats in Willapa Bay.

C/N Ratios

C/N ratios for each station are given in Table 12; distribution of ratios in the study area is shown in figure 26. There aren't any clear trends either upslope or up-estuary in the distribution of C/N ratios.

Weight ratio of organic carbon to organic nitrogen (C/N ratio) is used frequently to characterize and identify different types of organic matter. For example, higher plant forms charcteristic of terrestrial or certain nearshore environments contain less than 20% protein (the main nitrogen compounds of living organisms) and therefore show high C/N ratios (e.g., Zostera - ratio equals 14-21; Muller, 1977). Lower plants which are the main producers of organic matter in the sea are relatively rich in protein and thus show lower C/N ratios (e.g., blue green algae - ratio equals 6.5; Vinogradov, 1953). Overall, therefore, influx of terrestrial plant debris into an estuary increases the C/N ratio in estuarine over shelf sediments (Andrews, 1965). Scholl (1963) calculated that C/N values range from 18 to 35 for coastal swamps and 8 to 12 for most marine shelf sediments. Andrews (1965) noted two types of organic matter in Willapa Bay, (1) average C/N ratios of 13.8 associated with fine grained tidal flats in the inner estuary, and (2) organic matter with an average C/N ratio of 6.1 associated with coarser channel sediments.

C/N ratios on the sandy intertidal flats in the study area are in the range of Scholl's (1963) values for shelf deposits. The ratios are intermediate relative to Andrew's (1965) data (i.e., values lie between those for marine influenced tidal channels and freshwater influenced inner estuary deposits). High C/N ratios on the flat are associated with samples taken near a freshwater source (e.g., S710-2, C/N = 28) or high on the flat in areas with relatively high grass density (e.g., S717-1, C/N = 69). Overall, the C/N ratios in the study area indicate a transitional environment between open marine and inner estuarine environments.

## SEDIMENTARY STRUCTURES

### Physical Sedimentary Structures

#### Sand Flats

The sandy portion of the flat is generally covered by bedforms including sandwaves and dunes, low-amplitude bedforms of unknown origin, runoff channels, and symmetrical or asymmetrical ripples.

Sandwaves and dunes (Fig. 27A): These large primary structures are sinuous, ebb-oriented, and up to 50 cm high. The internal structure of the sandwaves consists of medium-scale cross-stratification in the upper 30 cm over a bioturbated base (Figs. 27B and 28). Sandwaves and dunes are generally limited in distribution to the lower tidal flat. Height of these bedforms decreases to ripples upslope and up-estuary.

Low-amplitude bedforms (Fig. 29A): These bedforms, described in the study area by Clifton and Phillips (1980), consist of a complex linear pattern of ridges and troughs intersecting at high angles. The ridges are straight and have an amplitude of about 20 cm with wavelengths greater than 20 m. Internal structures of the low-amplitude ridges consist of ripple laminations largely destroyed by bioturbation below about 15-20 cm (Figs. 29A and 28). These bedforms are distributed across almost the entire sand flat with bedform height decreasing to zero toward the upper flat. Although the origin of these low-amplitude bedforms is uncertain, Clifton and Phillips (1980) speculate they may be the result of winter and summer waves and tidal runoff.

Runoff channels (Fig. 30): Length of these channels varies from a few meters to several hundred meters while the depth varies from a few centimeters to a meter or more. The channels are generally straight to sinuous with accretionary and cut banks. In the larger channels, large-scale features (e.g., megaripples) exist at the channel mouth with small-scale ripples common higher on the flat. Internal structures associated with runoff channels include trough crossbedding, ripple bedding, and plain bedding (along the thalweg). Lag deposits composed of wood, mud balls, and shell material are common in channel bottoms. A detailed study of a large intertidal runoff channel in the study area is reported by Anima (1979).

Ripples (Fig. 31): (A) Current ripples (Fig. 31A) - these ripples are asymmetrical, 1-2 cm high, and have wavelengths to 10 cm. Migration of asymmetrical ripples produce ripple laminated sand beds 5-20 cm thick. Current ripples are particularly common in topographic lows from Goose Point to Ramsey Point. (B) Irregular "linguoid" ripples (Fig. 31B) and long-crested symmetrical ripples (Fig. 31C) - these ripples are 1-5 cm high with wave lengths of 5-10 cm. Although these ripples are wave generated, sporadic movement can produce shoreward-directed ripple laminations and occasional flaser bedding (Clifton and Phillips, 1980). Owing to wave refraction these ripples generally parallel topographic contours.

## Mud Flats

Two types of mud flats occur in the study area; (1) exposures of Pleistocene indurated mud ("bedrock"), and (2) unconsolidated deposits of modern mud.

"Bedrock" (Fig. 32): Flats of this nature are characterized by irregular scour surfaces with large boring openings. These are surfaces of a Pleistocene mud (occasional local sand) unit exposed by the rise of sea level and subsequent erosion and retreat of adjacent terrace deposits. The "bedrock" is occasionally covered by a thin veneer of modern sediments. This type of mud flat occurs off Goose Point to Pickernell Creek from base of terrace to a varying distance offshore up to 300 m.

Modern soft mud flats (Fig. 33A): Surface structures on these flats include various biogenic sedimentary structures such as tracks, trails, burrow openings, and faecal pellets/strings; these biogenic structures are produced by such organisms as polychaetes, molluscs, crustaceans, birds, and mammals. Surface physical sedimentary structures are generally lacking on soft mud flats. Compared to sandy flats, vegetation is denser and more diverse climaxing in occasional supratidal meadows. Internally, the sediments of the soft muddy flats have a bioturbate texture (Fig. 33B) with two exceptions. These exceptions, described in detail by Clifton and Phillips (1980), are (A) blue-green algae mounds formed during the summer create anoxic conditions in sediments beneath the mounds resulting in thin (less than 1-2 mm) laminations of sand and mud (Fig. 34A), and (B) deposition in supratidal grass meadows during floods or storms producing laterally persistent, mud and fine sand laminations (2-10 mm thick) with abundant rhyzomes and roots (Fig. 34B). Supratidal deposits occur along flats adjacent to the Palix River, from Ramsey Point to Pickernell Creek, and locally in protected areas on the upper flats near the base of the terrace. Supratidal deposits are relatively rare within the study area, becoming more abundant up-estuary.

## Biogenic Sedimentary Structure

Biogenic sedimentary structures are "structures produced in the sediments by the activity of organisms upon or within an unconsolidated particulate substrate" (Frey, 1975). These structures vary in type, size, and orientation. While larger biogenic structures are indicated by textural differences or changes in sediment color, most small traces show only on X-ray radiographs.

Traces are classified as burrow, tube, locomotion trace, boring, or root cast. Definition of these terms follow Hertweck (1972). Burrows are open biogenic structures made in unconsolidated sediments by dwelling of locomotion of organisms; the main feature of burrows is that their walls are not cemented structures capable of supporting themselves when removed from the sediment. Tubes, which maintain their physical integrity when removed from the sediment, are animal dwelling structures constructed by direct secretion or agglutination. Subsurface biogenic structures resulting from organisms pushing through sediment without leaving cavities are termed locomotion traces. Distinct from burrows are borings. Boring by organisms is the process of excavation of hard material such as skeletal material, rocks, or hardgrounds. Root casts are branching sedimentary structures produced through the filling of voids left by plant roots.

Trace A (Fig. 35A)

Burrow: 6-10 mm diameter; 2-3 mm thick walls of sand with some mud; orientation horizontal to vertical; developed to at least 20 cm sediment depth.

Distribution: common in sandy sediments between Goose Point and Ramsey Point.

Organism: unidentified polychaete.

Trace B (Fig. 35B)

Burrow: 4 mm diameter, length to 15 cm; irregular, winding; orientation mainly vertical; smooth mucus-impregnated walls.

Distribution: rare, occurs in muddy sand near rivers; mid- to lower flat.

Organism: unidentified polychaete.

Trace C (Fig. 35C)

Burrow: 1-2 mm diameter; upper section straight, lower section is horizontal to subvertical spiral; smooth mucus-impregnated walls.

Distribution: occurs in upper 6 cm of sediment; very common throughout study area.

Organism: *Notomastus* sp.; Polychaeta.

Trace D (Fig. 35D)

Burrow: 0.5-2 mm diameter, round to occasional oval cross-section; oblique oriention; winding to sinuous; thin, smooth, mucus-impregnated walls.

Distribution: developed to sediment depth of 20 cm; very common throughout study area.

Organism: unknown.

Trace E (Fig. 35E)

Burrow: 0.5-1.5 mm diameter; branched; mainly vertical orientation; mucus-impregnated walls.

Distribution: upper 15 cm of sediment; found throughout study area but more common in sandier sediments between Goose Point and Sandy Point.

Organism: *Capitomastus* sp.; Polychaeta.

Trace F (Fig. 35F)

Burrow: 1 mm diameter; U-shaped; smooth, mucus-impregnated walls; two burrow openings at sediment-water interface.

Distribution: extends up to 5 cm deep into sediment; restricted to outer parts of muddy flats adjacent to Palix River.

Organism: gammarid amphipods.

Trace G (Fig. 36A)

Burrow: 1-2 cm diameter; thick smooth walls; branched; smooth round "turn-a-rounds" at junction of branches (Fig. 36B); inclined to vertical; inhalent (expressed at the sediment-water interface as a depression) and exhalent (expressed as a mound up to several cm high) openings.

Distribution: extends to a meter or more deep into the sediment column; very common throughout study area except where sediment cover is thin (less than 20-30 cm) on upper flats; density as indicated by counting surface openings to burrows indicate greater densities on mid-to lower sandy flats (Fig. 37).

Organism: Callianassa californiensis; Crustacea, Arthropoda.

Trace H (Fig. 38A)

Boring (Burrow?): cylindrical, 3-4 cm diameter; pits and scratch marks in unlined walls; branched with tiered system of shafts and tunnels; spherical turn-a-rounds at junctin of branches; extends to at least one meter below bedrock surface.

Distribution: trace produced in consolidated Pleistocene mud beds flooring the intertidal flat below the high tide line; common off Goose Point on the upper flat; identical trace observed in terrace deposits in the Bay Center Mud (Fig. 38B).

Organism: Upogebia pugettensis; Crustacea, Arthropoda.

Trace I (Fig. 39).

Trail: intrastratal; cylindrical, 3-5 mm diameter; sinuous; subhorizontal orientation; unbranched; trace filled with slightly lighter material than host sand due to heavy minerals being concentrated at margins. (This trace was not found in the short cores taken in this study. The above description is after Clifton and Thompson, 1978, who found these traces in longer cores, some taken in the study area.)

Distribution: modern traces produced to average depths of 80 cm below sediment-water interface (Clifton and Thompson, 1978); probably common in mid- to lower sand flats, particularly between Goose Point and Sandy Point.

Organism: Ophelia limacina Rathke; Polychaeta. (Note: Excellent description of this trace, its trace maker, and the probable ancient analog given in Clifton and Thompson, 1978).

Trace J(Fig. 40A)

Root cast: proliferating caudex or stout, short rhizome covered with persistent leaf bases; roots up to 5 cm long by 2 mm wide; upward curvature.

Distribution: found primarily in upper intertidal to supratidal zones (but may occur on uppermost middle intertidal flats); substrate variable - generally found in mud.

Organism: Triglochin maritima.

Trace K (Fig. 40B)

Root cast: rootstock (rhizome) slender to thick, creeping; length variable, width 2-5 mm, internodes 10-35 mm long with numerous roots and a leaf at each node.

Distribution: found throughout intertidal zone but predominates in middle to lower intertidal and subtidal areas; substrate variable - generally sandy mud to muddy sand; higher density near Pickernell Creek and Palix River.

Organism: Zostera marina.

Trace L (Fig. 41)

Burrow: 4-8 mm diameter; U-shaped; smooth, mucus-impregnated thin walls; two burrow openings at sediment-water interface (inhalent depression and exhalent with faecal strings around aperture).

Distribution: extends up to 15 cm deep into sediment; restricted to sand flats between Goose Point and Ramsey Point.

Organism: Saccoglossus sp.; Polychaeta.

Preservational Considerations

The above description of burrows is related to structures recently (relative to the time of sampling) inhabited by organisms. With the major exception of Callianassa burrows, preservation of burrows is difficult due to energy conditions of the intertidal environment and the nature of this particular type of biogenic structure. Substrate scour due to normal wave activity and flood tides destroys many of the shallow burrows. Due to relatively thin, weak wall construction, many burrows simply collapse and disappear after the occupant dies. Those which survive burial then must survive the intense bioturbtion of the deeper dwelling organisms such as Callianassa. The overall diversity of preserved burrows, therefore, is greatly reduced. This preservational problem has been noted for other environments as well; e.g., nearshore environment (Hertweck, 1972; Hill and Hunter, 1976).

There is also a notable lack of intrastratal trails in the intertidal deposits even though organisms known to produce such traces exist (e.g., bivalves and amphipods). The uniform texture and composition of much of the study area is part of the explanation. Also, locomotion traces produced by bivalves are usually in response to extreme erosional or depositional events during which time the organisms try to maintain their "normal" position relative to the sediment-water interface. Events of this magnitude were apparently absent in the study area at least during the period represented by the cores. Ophelia's efficiency in sediment sorting at depth produces the only trails with high preservational potential.

Borings of Upogebia in the indurated Pleistocene mud beds have an excellent chance of preservation due to (1) being produced in a consolidated material, (2) a tendency to fill with coarser material than the host sediment, and (3) their large size and configuration.

Physical vs Biological Processes

In the modern tidal flat sediments, patterns in degree of bioturbation exist (Fig. 28). Bioturbation generally increases downslope, up-estuary, and down core.

Decreased bioturbation upslope is a weak trend, not obvious in many cases. Compared to the lower flats, the portions of the tide flat near the beaches are affected by wind induced waves and currents, and organisms are subject to greater environmental stresses (e.g., prolonged exposure to air). Under these conditions, physical processes are perhaps slightly more dominant than biological processes in the upper few centimeters of the sediment column.

Bioturbation increases from Goose Point north toward the Palix River and south toward Pickernell Creek, i.e., up-estuary. The general decrease in tidal energy, finer sediment, and increased plant density associated with inner tidal flats help to account for sediments being extensively reworked, even in the upper few centimeters of the sediment column.

Physical structures exist in the upper part of the sandier sediment between Goose Point and Sandy Point. Bioturbation gradually increases from the sediment surface to a depth of approximately 15-20 cm where the sediment is, with a few exceptions, highly bioturbated. Most biogenic structures do not exceed this depth. The major exceptions to this generality are *Ophelia* intrastratal trails and *Callianassa* burrows. *Callianassa* are long lived, occur in high densities, and continually rework relatively large volumes of sediment (Hill and Hunter, 1976). Burrowing activities of _Ophelia_ and _Callianassa_ probably account for the bioturbated nature of the tidal flat sediments.

Overall, biological processes exceed physical processes in reworking tidal flat sediments in the study area. When sediments have been totally reworked by biological activity, with little or no physical sedimentary structures remaining, it is described as a bioturbate texture (Frey, 1975).

## CONCLUSIONS

### Texture

Texturally, the mid-estuary tidal flat is composed predominantly of sand; quantitatively, the dominant component is fine sand (2-3 $\phi$). The sources 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 amounts of fine material moving to other environments. Gravel detritus is quantitatively minor, and is concentrated along the base of the 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 (1) marine sands supplied from offshore (distributed by tidal channels) and/or sands eroded from terrace deposits and (2) finer material transported in suspension by the rivers. 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 intertidal flats with steep slopes have coarser material proportionately higher on the flat than relatively wide flats.

Composition

Compositionally, the intertidal flat within the study area is predominantly quartz sand (approximately 90%); subordinate fractions include other light minerals, heavy minerals, clay minerals, biogenic carbonate detritus, and organic material. Significant components other than quartz in the light fraction include lithic fragments, pumice, wood chips, and pieces of vegetation. Predominant heavy minerals are clinopyroxene, orthopyroxene, hornblende, epidote, garnet, and opaque minerals (mostly magnetite). The major clay mineral is montmorillonite with subordinate amounts of illite and chlorite. Fossils represent less than one percent of the sediment; two foram suites (one modern and one relic) dominate the microfossil component with relatively few diatoms and ostracods. The great majority of macrofossils are indigenous modern molluscs. The sediment consists of approximately 1.5% organic carbon and significantly less nitrogen.

Variability in composition is greatest near the Palix River and Pickernell Creek. Near these areas, mud content increases, marine vegetation is more diverse and abundant, density and diversity of forams increase, and opaque minerals are more common. Overall, the diversity and variability of sediment components near the rivers largely reflects the composite composition of material supplied from offshore and the terrace deposits mixed with finer material supplied by the rivers. In comparison, the dominantly sandy flats between Goose Point and Ramsey Point are less diverse and compositionally dominated by quartz sand. The relatively minor clay fraction is mainly montmorillonite. The foram assemblage is predominantly relic reworked deep-water species. Organic material represents less than one percent of the sediment.

Sediment components exhibit general distributional trends. In an up-estuary direction, sediments become muddier (with proportionally decreasing amounts of montmorillonite), contain more heavy minerals (especially opaque minerals), have more modern brackish-water forams, and contain significantly more organic matter. Distribution of sediment components reflect increasing contribution of freshwater sources to intertidal flats near the Palix River and Pickernell Creek. Upslope trends are weak or nonexistent for most components.

## Sedimentary Structures

The final sedimentological record of intertidal deposits within the study area would be a bioturbate textured sand. This record is the result of relatively low sedimentation rates coupled with high rates of biogenic reworking on the intertidal flats. Relatively thin mud deposits near the Palix River and Pickernell Creek would probably not be preserved due to erosion associated with rising sea level. The exposure of consolidated Pleistocene mud beds flooring areas of the modern flat is marked by the presence of large tiered boring systems.

In the upper 20 cm of the sediment column, bioturbation increases downslope and up-estuary. However, with increasing sediment depth, bioturbation increases due primarily to the deep burrowing of *Callianassa* and *Ophelia*. Therefore, below the upper 20-30 cm the sediment is usually totally bioturbated except for areas where conditions inhibit infaunal activity such as beneath algal mounds or in supratidal meadows.

Biogenic structures with the greatest potential for preservation in sandy sediments include *Callianassa* burrows and *Ophelia* intrastratal trails. As mud content increases, deeper penetrating roots and rhizomes (e.g., *Triglochin*) become more common. *Upogebia* boring systems are characteristic of older consolidated mud beds exposed to intertidal conditions.

## Summary

(1) The objective of this study is to characterize mid-estuary intertidal deposits in Willapa Bay, Washington, based on texture, composition, and sedimentary structures (physical and biogenic).

(2) Texturally, the mid-estuary intertidal flat is composed of poorly sorted, fine-grained sand with strongly-fine skewed leptokurtic distribution. Mid-estuary intertidal flats are more similar in texture to outer flats (intertidal flats near the bay inlet) than inner flats (intertidal flats near rivers).

(3) The composition of the sediment in the study area is predominantly quartz sand (about 90%). Significant subordinate fractions include: (a) other light minerals (mainly lithic fragments, pumice, and pieces of vegetation), (b) heavy minerals (predominantly

orthopyroxene, hornblende, and epidote), (c) clay minerals (mainly montmorillonite), (d) biogenic carbonate detritus (mainly molluscs and forams), and (e) organic carbon. Mid-estuary intertidal flats are transitional in composition between outer flats and inner flats.

(4) Relative to sedimentary structures mid-estuary intertidal deposits generally exhibit a bioturbate texture. Biogenic sedimentary structures with the greatest potential for preservation are intrastratal trails of the polychaete Ophelia and structures produced by the crustacean Callianassa (burrows) and Upogebia (borings). Structurally, mid-estuary intertidal flats are more similar to inner flats than outer flats.

(5) Within the study area, textural and compositional variability is greatest and structural variability is lowest near the Palix River and Pickernell Creek.

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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 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 | 1.71 | 0.47 |
| 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 | Mid-estuary[1] | Outer estuary[2] |
|---|---|---|
| % Sand | 94 | 94 |
| % Silt | 4 | 5 |
| % Clay | 2 | 1 |
| Mean Grain Size (Ø) | 2.52 | 2.59 |

[1] data from this study
[2] data from Andrews (1965)

Table 6. Clay mineralogy of surficial intertidal sediments.

| Station No. | % Montmorillonite | % Illite | % Chlorite | Location |
|---|---|---|---|---|
| S710-2 | 48 | 34 | 17 | Palix River |
| S720-3 | 74 | 13 | 13 | Johnson's Beach |
| S718-3 | 90 | 5 | 5 | Sandy Point |
| S801-2 | 95 | 3 | 2 | Copper Point |
| S808-2 | 93 | 5 | 2 | Ramsey Point |
| S805-2 | 40 | 39 | 21 | Pickernell Creek |

Table 7. Heavy-light mineral percentages of surficial sediments.

| Sample No. | % Heavies | % Lights |
|---|---|---|
| S706-1 | 3 | 97 |
| S706-2 | 3 | 97 |
| S710-1 | 1 | 99 |
| S710-2 | 1 | 99 |
| S711-1 | 4 | 96 |
| S711-2 | 1 | 99 |
| S711-3 | 2 | 98 |
| S712-1 | 3 | 97 |
| S712-2 | 2 | 98 |
| S714-1 | 7 | 93 |
| S717-1 | 2 | 98 |
| S718-2 | 2 | 98 |
| S718-3 | 3 | 97 |
| S718-4 | 3 | 97 |
| S719-5 | 3 | 97 |
| S719-6 | 1 | 99 |
| S720-3 | 2 | 98 |
| S720-4 | 2 | 98 |
| S721-4 | 2 | 98 |
| S723-1 | 2 | 98 |
| S723-2 | 2 | 98 |
| S723-3 | 2 | 98 |
| S801-1 | 3 | 97 |
| S801-2 | 5 | 95 |
| S801-3 | 4 | 96 |
| S804-1 | 9 | 91 |
| S804-2 | 2 | 98 |
| S804-3 | 5 | 95 |
| S805-2 | 3 | 97 |
| S805-3 | 1 | 99 |
| S806-1 | 2 | 98 |
| S808-2 | 4 | 96 |
| S809-1 | 4 | 96 |
| S810-1 | 12 | 88 |
| S810-2 | 3 | 97 |
| S810-3 | 2 | 98 |

Table 8. Percentages of opaque and non-opaque minerals of the heavy mineral fraction.

| Sample No. | % Non-opaque | % Opaque |
|---|---|---|
| S706-1 | 87 | 13 |
| S706-2 | 80 | 20 |
| S710-1 | 94 | 6 |
| S710-2 | 91 | 9 |
| S711-1 | 65 | 35 |
| S711-2 | 84 | 16 |
| S711-3 | 76 | 24 |
| S712-1 | 83 | 17 |
| S712-2 | 85 | 15 |
| S714-1 | 79 | 21 |
| S717-1 | 77 | 23 |
| S718-2 | 82 | 18 |
| S718-3 | 78 | 22 |
| S718-4 | 73 | 27 |
| S719-5 | 72 | 28 |
| S719-6 | 78 | 22 |
| S720-3 | 83 | 17 |
| S720-4 | 73 | 27 |
| S721-4 | 69 | 31 |
| S723-1 | 84 | 16 |
| S723-2 | 79 | 21 |
| S723-3 | 76 | 24 |
| S801-1 | 88 | 12 |
| S801-2 | 76 | 24 |
| S801-3 | 84 | 16 |
| S804-1 | 65 | 35 |
| S804-2 | 74 | 26 |
| S804-3 | 72 | 28 |
| S805-2 | 79 | 21 |
| S805-3 | 55 | 45 |
| S806-1 | 67 | 33 |
| S808-2 | 76 | 24 |
| S809-1 | 70 | 30 |
| S810-1 | 71 | 29 |
| S810-2 | 74 | 26 |
| S810-3 | 71 | 29 |

Table 9. Composition of heavy mineral fraction.

| Mineral | S711-2 A | S711-2 B | S801-1 A | S801-1 B | S801-3 A | S801-3 B | S805-3 A | S805-3 B |
|---|---|---|---|---|---|---|---|---|
| Opaque minerals | 15.0 | | 14.7 | | 21.7 | | 62.3 | |
| Mineral aggregates | 7.7 | | 5.7 | | 4.7 | | 1.2 | |
| Orthopyroxene | 16.7 | 21.7 | 16.3 | 20.5 | 23.2 | 31.6 | 9.0 | 24.7 |
| Clinopyroxene | 19.7 | 25.6 | 30.0 | 37.7 | 11.7 | 16.0 | 7.8 | 21.5 |
| Aegerine-Augite | 0.2 | 0.3 | | | | | | |
| Hornblende | 19.0 | 24.6 | 16 0 | 20.1 | 20.0 | 27.2 | 7.5 | 20.5 |
| Lamprobolite | 3.5 | 4.5 | 0.3 | 0.4 | 0.5 | 0.7 | 0.3 | 0.9 |
| Epidote | 15.7 | 20.4 | 15.7 | 19.7 | 13.2 | 18.0 | 7.7 | 21.0 |
| Sphene | 0.7 | 1.0 | | | | | | |
| Garnet | 0.7 | 1.0 | 0.7 | 0.8 | 4.0 | 5.4 | 2.5 | 6.8 |
| Kyanite | | | | | | | 0.2 | 0.5 |
| Staurolite | | | | | 0.2 | 0.3 | 0.2 | 0.5 |
| Apatite | 0.5 | 0.6 | 0.7 | 0.8 | | | 0.3 | 0.9 |
| Zircon | | | | | | | 0.3 | 0.9 |
| Rutile | | | | | 0.2 | 0.3 | 0.7 | 1.8 |
| Chloritoid | 0.2 | 0.3 | | | | | | |
| Topaz | | | | | 0.2 | 0.3 | | |

A= % with opaques B= % without opaques

Table 10. Composition of light mineral fraction.

| Sample # | % Quartz | % Volcanics | % Opaques | % Lithic | % Organics | % Biogenic |
|---|---|---|---|---|---|---|
| S706-1 | 88 | 2 | 3 | 6 | 0 | 0 |
| S706-2 | 90 | 3 | 4 | 2 | 0 | 0 |
| S710-1 | 79 | 5 | 5 | 2 | 7 | 3 |
| S710-2 | 80 | 3 | 7 | 3 | 6 | 1 |
| S711-1 | 90 | 3 | 2 | 5 | 1 | 0 |
| S711-2 | 96 | 0 | 2 | 1 | 1 | 0 |
| S711-3 | 92 | 0 | 3 | 1 | 1 | 1 |
| S712-1 | 95 | 0 | 2 | 2 | 1 | 0 |
| S712-2 | 92 | 1 | 4 | 1 | 1 | 1 |
| S714-1 | 95 | 1 | 2 | 2 | 0 | 0 |
| S717-1 | 91 | 1 | 2 | 3 | 0 | 1 |
| S718-2 | 87 | 1 | 4 | 7 | 0 | 1 |
| S718-3 | 91 | 0 | 2 | 4 | 2 | 1 |
| S718-4 | 94 | 2 | 2 | 2 | 0 | 0 |
| S719-5 | 89 | 0 | 1 | 9 | 0 | 1 |
| S719-6 | 88 | 1 | 7 | 3 | 1 | 0 |
| S720-3 | 94 | 1 | 1 | 4 | 0 | 0 |
| S720-4 | 86 | 2 | 3 | 9 | 0 | 0 |
| S721-4 | 91 | 0 | 4 | 6 | 0 | 0 |
| S723-1 | 84 | 1 | 7 | 8 | 0 | 0 |
| S723-2 | 89 | 0 | 8 | 3 | 0 | 0 |
| S723-3 | 93 | 0 | 2 | 5 | 0 | 0 |
| S801-1 | 88 | 0 | 4 | 7 | 1 | 0 |
| S801-2 | 89 | 1 | 3 | 6 | 0 | 0 |
| S801-3 | 92 | 0 | 3 | 4 | 0 | 0 |
| S804-1 | 82 | 0 | 6 | 13 | 0 | 0 |
| S804-2 | 84 | 0 | 4 | 9 | 2 | 0 |
| S804-3 | 93 | 0 | 1 | 5 | 0 | 1 |
| S805-2 | 75 | 1 | 7 | 13 | 1 | 3 |
| S805-3 | 89 | 0 | 6 | 5 | 0 | 0 |
| S806-1 | 91 | 0 | 2 | 3 | 1 | 3 |
| S808-2 | 91 | 0 | 1 | 7 | 0 | 1 |
| S809-1 | 89 | 0 | 2 | 7 | 1 | 1 |
| S810-1 | 92 | 0 | 5 | 2 | 1 | 1 |
| S810-2 | 95 | 0 | 1 | 2 | 1 | 1 |
| S810-3 | 92 | 0 | 6 | 2 | 0 | 1 |
| avg. | 89.3 | 0.81 | 3.75 | 4.81 | 0.81 | 0.64 |

Table 11. Location of Foraminifera species in the study area.

| Species | Station S710-1 | S711-2 | S801-1 | S801-3 | S802-3 | S805-3 |
|---|---|---|---|---|---|---|
| *Trochammina inflata* | X | | | X | | X |
| *Ammobaculites* sp. | X | | | | | |
| *Miliammina fusca* | X | | | | | |
| *Trochammina pacifica* | X | | | | | |
| *Bathysiphon* sp. | | | X | | | X |
| *Martinotiella* sp. | | | X | | | |
| *Rhabdammina* sp | | | X | X | X | X |
| *Cyclammina* sp. | | | X | | | |

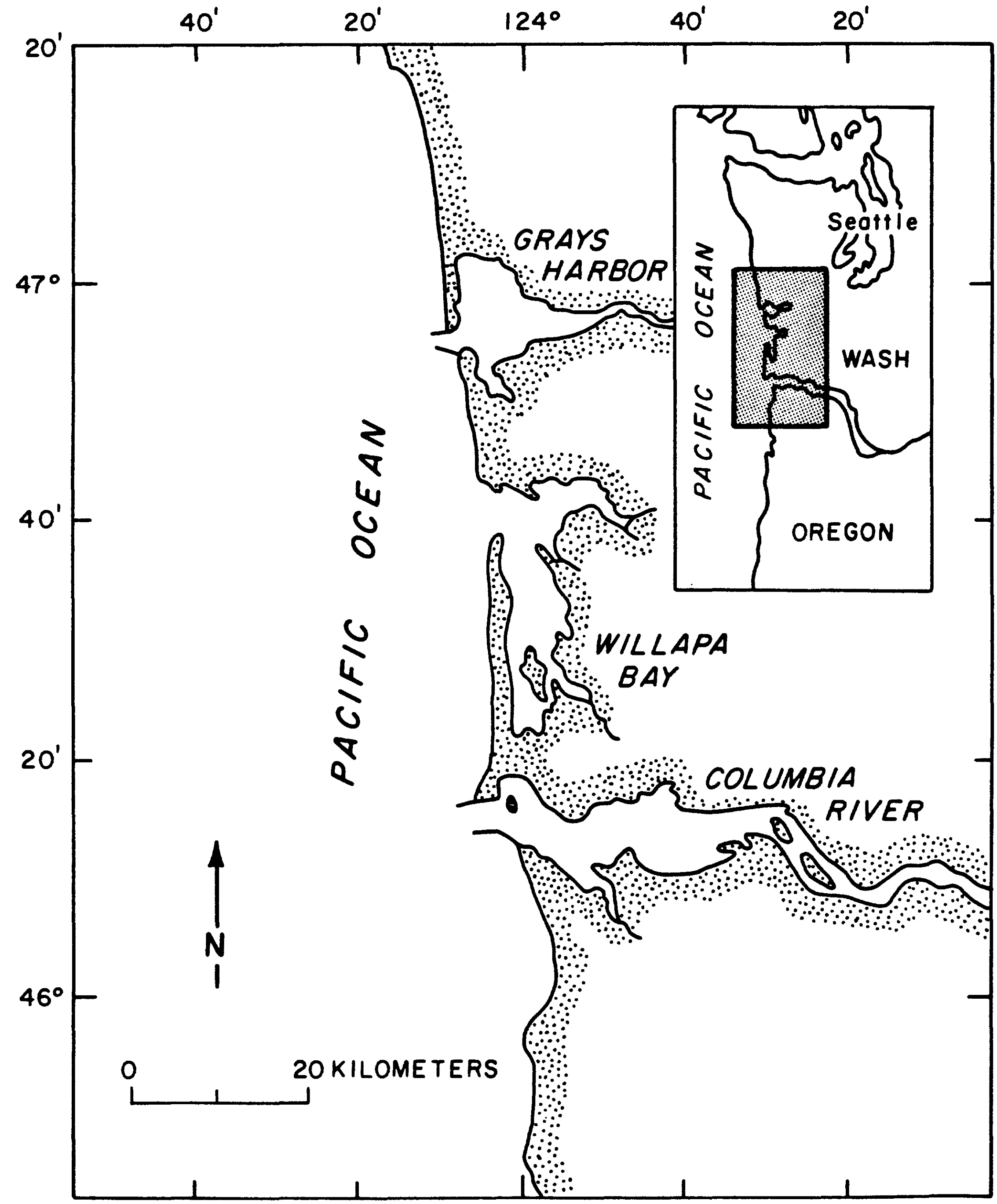
Table 12. Organic geochemistry of surficial sediments. Concentrations in parts per million (ppm).

| Sta. # | Total Carbon | Carbonate Carbon | Organic Carbon (C) | Total Nitrogen | Organic Nitrogen (N) | C/N ratio |
|---|---|---|---|---|---|---|
| S706-1 | 1900 | 0 | 1900 | 149 | 135 | 14.1 |
| S706-2 | 3100 | 1100 | 2000 | 178 | 161 | 12.4 |
| S710-0 | 11900 | 2500 | 9400 | 1563 | 1533 | 6.1 |
| S710-2 | 10500 | 5000 | 5500 | 304 | 295 | 18.6 |
| S711-2 | 14200 | 5100 | 9100 | 639 | 609 | 14.9 |
| S711-3 | 2200 | 700 | 1500 | 236 | 230 | 6.5 |
| S712-1 | 2900 | 1400 | 1500 | 135 | 116 | 12.9 |
| S712-2 | 10200 | 2200 | 8000 | 679 | 645 | 12.4 |
| S714-1 | 2900 | 1800 | 1100 | 6 | 0 | - |
| S717-1 | 2100 | 1200 | 900 | 21 | 13 | 69.2 |
| S718-2 | 2200 | 1000 | 1200 | 189 | 182 | 6.6 |
| S718-3 | 2300 | 1100 | 1200 | 132 | 125 | 9.6 |
| S718-4 | 1700 | 600 | 1100 | 180 | 173 | 6.4 |
| S719-5 | 2200 | 200 | 2000 | 192 | 175 | 11.4 |
| S719-6 | 2100 | 900 | 1200 | 174 | 164 | 7.3 |
| S720-3 | 2600 | 100 | 2500 | 331 | 302 | 8.3 |
| S720-4 | 2600 | 700 | 1900 | 234 | 211 | 9.0 |
| S721-4 | 2800 | 1200 | 1600 | 242 | 213 | 7.5 |
| S723-1 | 2600 | 1300 | 1300 | 197 | 183 | 7.1 |
| S723-2 | 3800 | 2300 | 1500 | 251 | 236 | 6.4 |
| S723-3 | 2200 | 900 | 1300 | 257 | 244 | 5.3 |
| S801-1 | 3500 | 700 | 2800 | 246 | 238 | 11.8 |
| S801-2 | 7100 | 3100 | 4000 | 8 | 0 | - |
| S801-3 | 2700 | 1000 | 1700 | 216 | 209 | 8.1 |
| S804-1 | 3000 | 1500 | 1500 | 193 | 177 | 8.5 |
| S804-2 | 6200 | 3600 | 2600 | 224 | 213 | 12.2 |
| S804-3 | 2500 | 800 | 1700 | 186 | 172 | 9.9 |
| S805-2 | 15800 | 10200 | 5600 | 439 | 424 | 13.2 |
| S805-3 | 8900 | 1250 | 7650 | 603 | 591 | 12.9 |
| S806-1 | 10700 | 4100 | 6600 | 606 | 592 | 11.2 |
| S808-2 | 3800 | 2000 | 1800 | 247 | 232 | 7.8 |
| S809-1 | 4200 | 100 | 4100 | 376 | 365 | 11.2 |
| S810-1 | 2400 | 1100 | 1300 | 159 | 142 | 9.2 |
| S810-2 | 2600 | 1800 | 800 | 209 | 197 | 4.1 |
| S810-3 | 2000 | 900 | 1100 | 190 | 175 | 6.3 |

1 ppm = 0.0001%

FIGURES

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



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

Fig. 2. Bathymetry of Willapa Bay, Washington (modified from Clifton and Phillips, 1980).

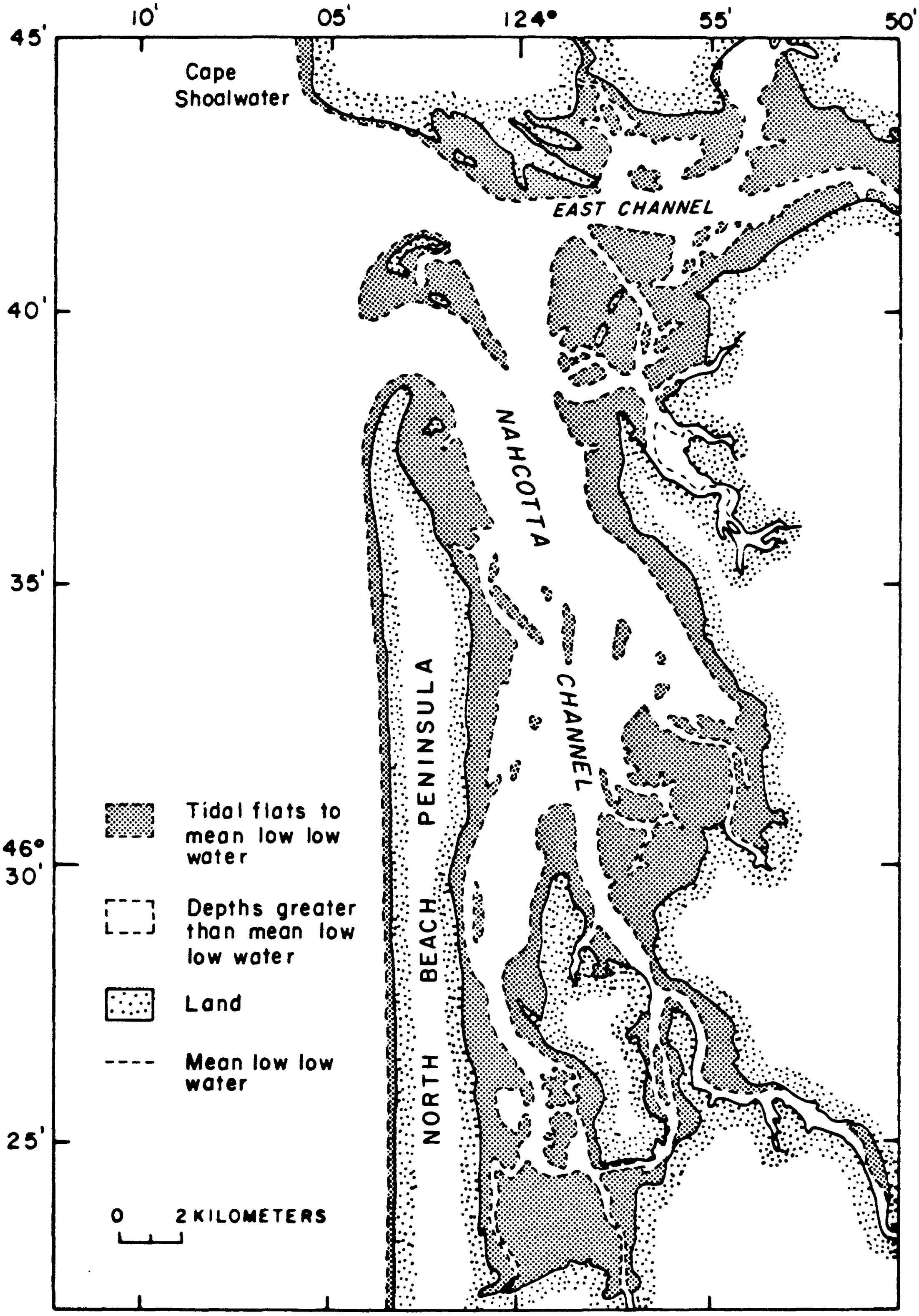

10'
05'
124°
55'
50'
45'
40'
35'
46°
30'
25'
Cape
Shoalwater
EAST CHANNEL
NAHCOTTA
CHANNEL
NORTH BEACH PENINSULA
Tidal flats to mean low low water
Depths greater than mean low low water
Land
Mean low low water
0 2 KILOMETERS

Fig. 3. Sediment texture of intertidal flats in Willapa Bay, Washington (modified from Clifton and Phillips, 1980).

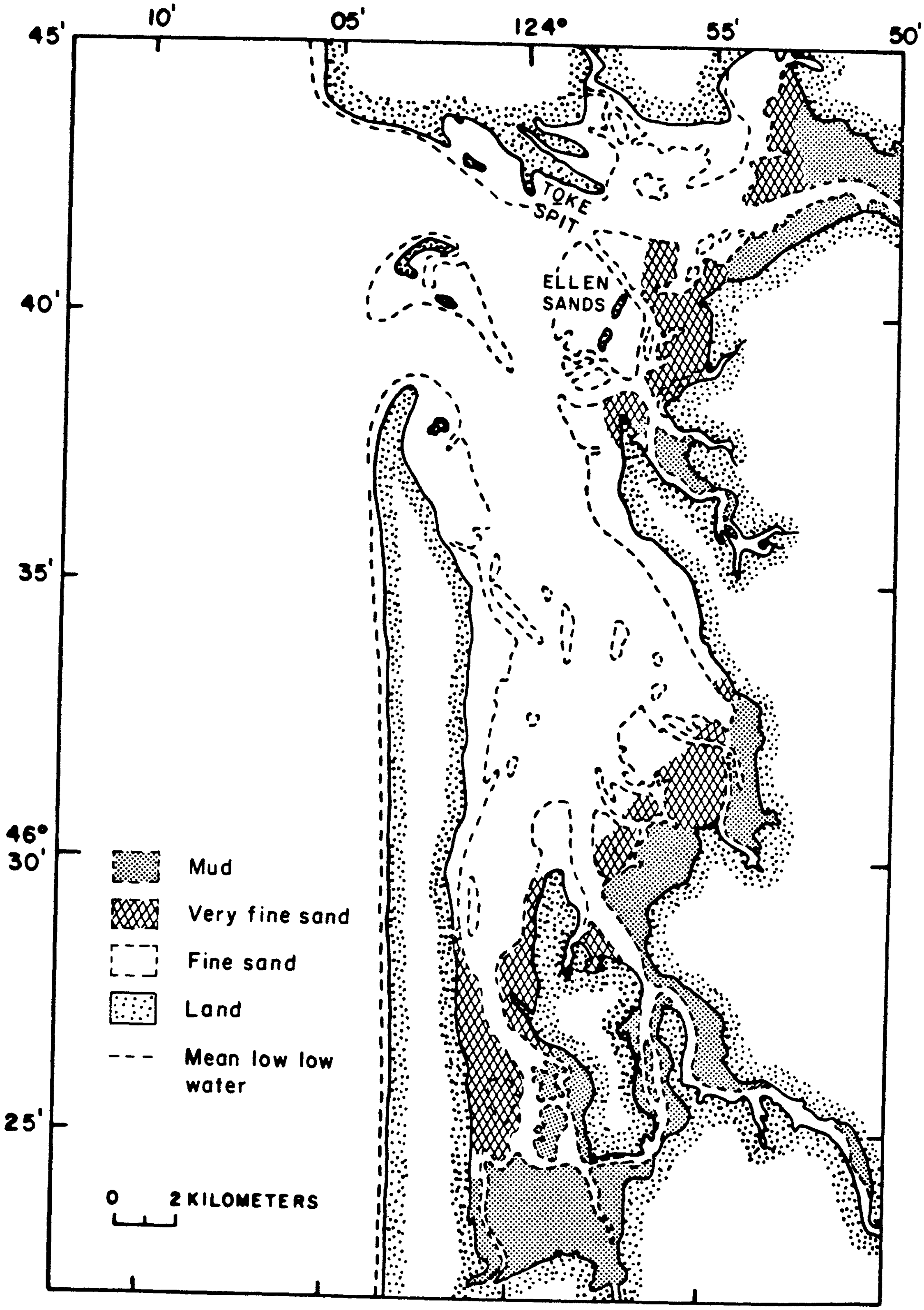
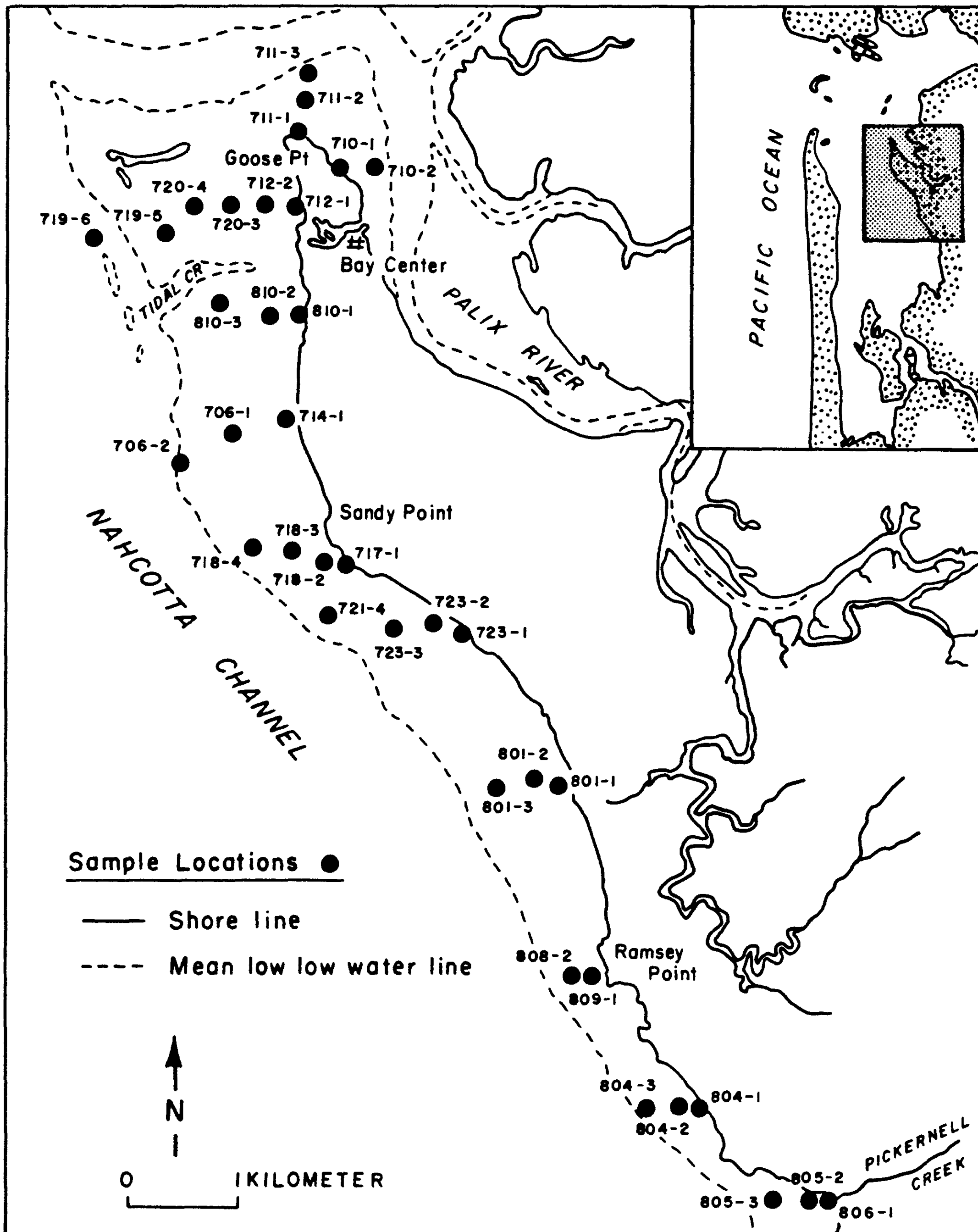

45'
10'
05'
124°
55'
50'
TOKE SPIT
ELLEN SANDS
40'
35'
46° 30'
25'
Mud
Very fine sand
Fine sand
Land
Mean low low water
0 2 KILOMETERS

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



711-3
711-2
711-1
Goose Pt
710-1
710-2
720-4
712-2
712-1
719-6
719-5
720-3
Bay Center
TIDAL CR
810-2
810-3
810-1
PALIX RIVER
PACIFIC OCEAN
706-1
714-1
706-2
Sandy Point
NAHCOTTA CHANNEL
718-3
718-4
717-1
718-2
721-4
723-2
723-3
723-1
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 within the study area.

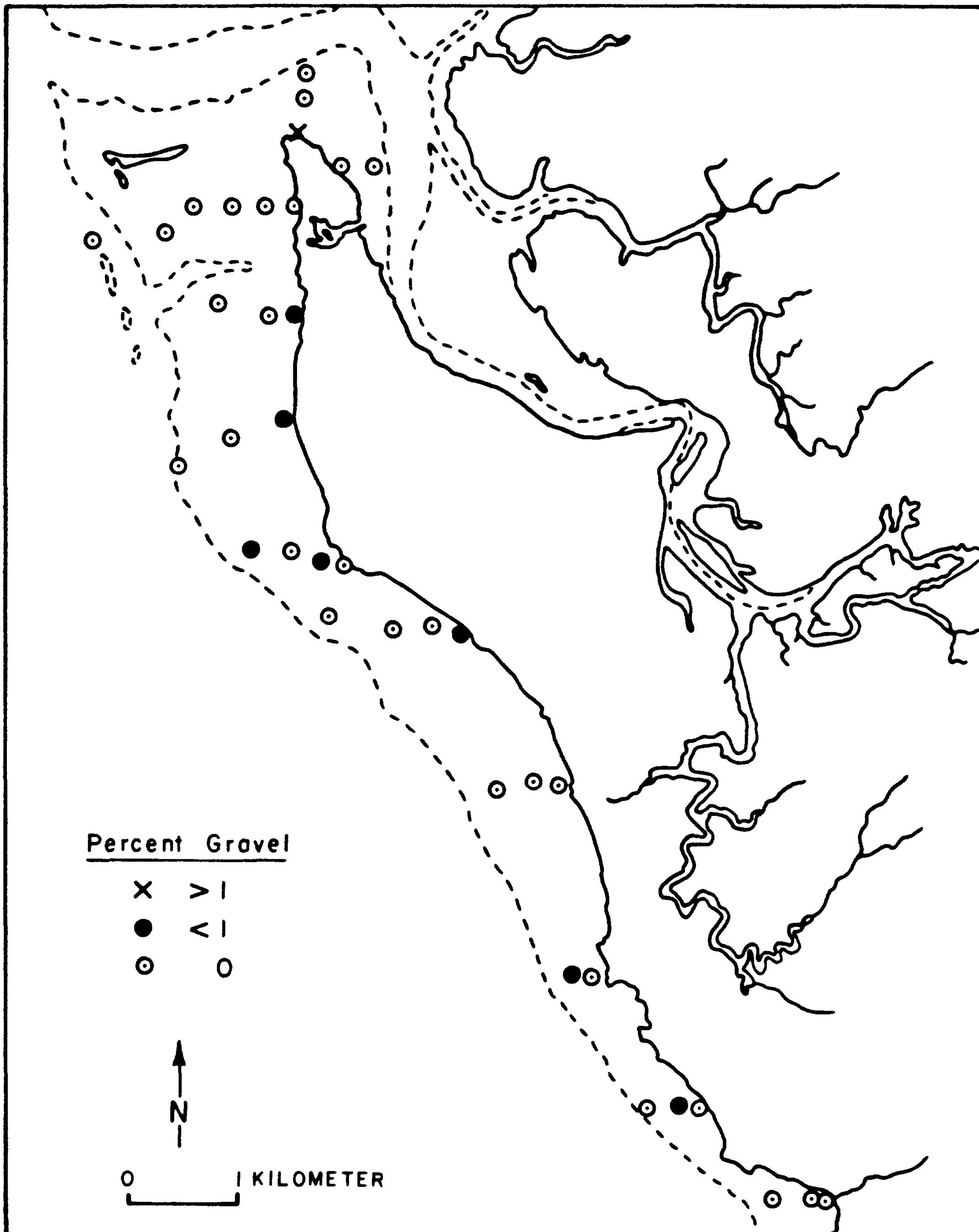
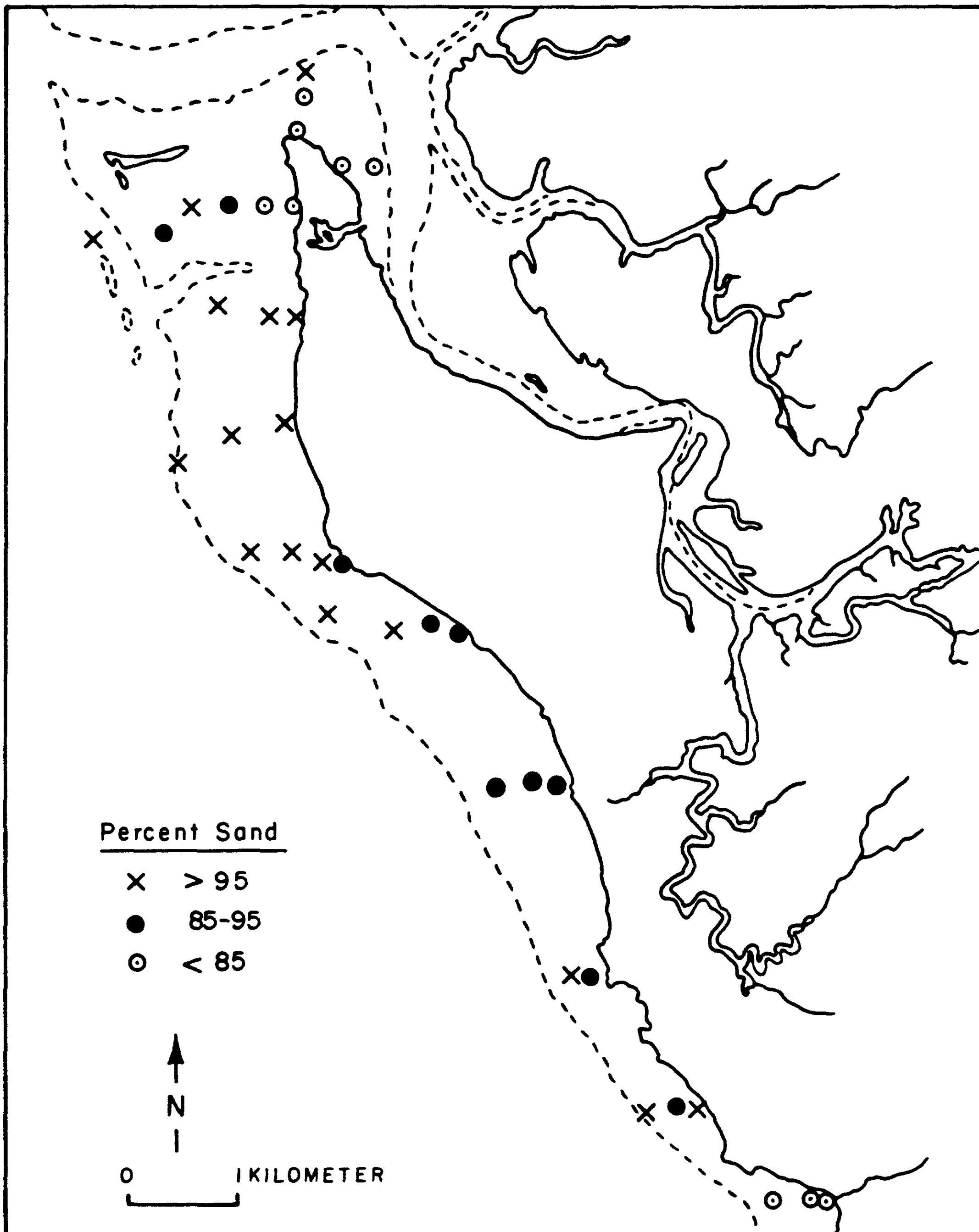

Percent Gravel
× >1
● <1
⊙ 0
N
0 1 KILOMETER

Fig. 6. Distribution of sand within the study area.



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

Fig. 7. Distribution of silt within the study area.

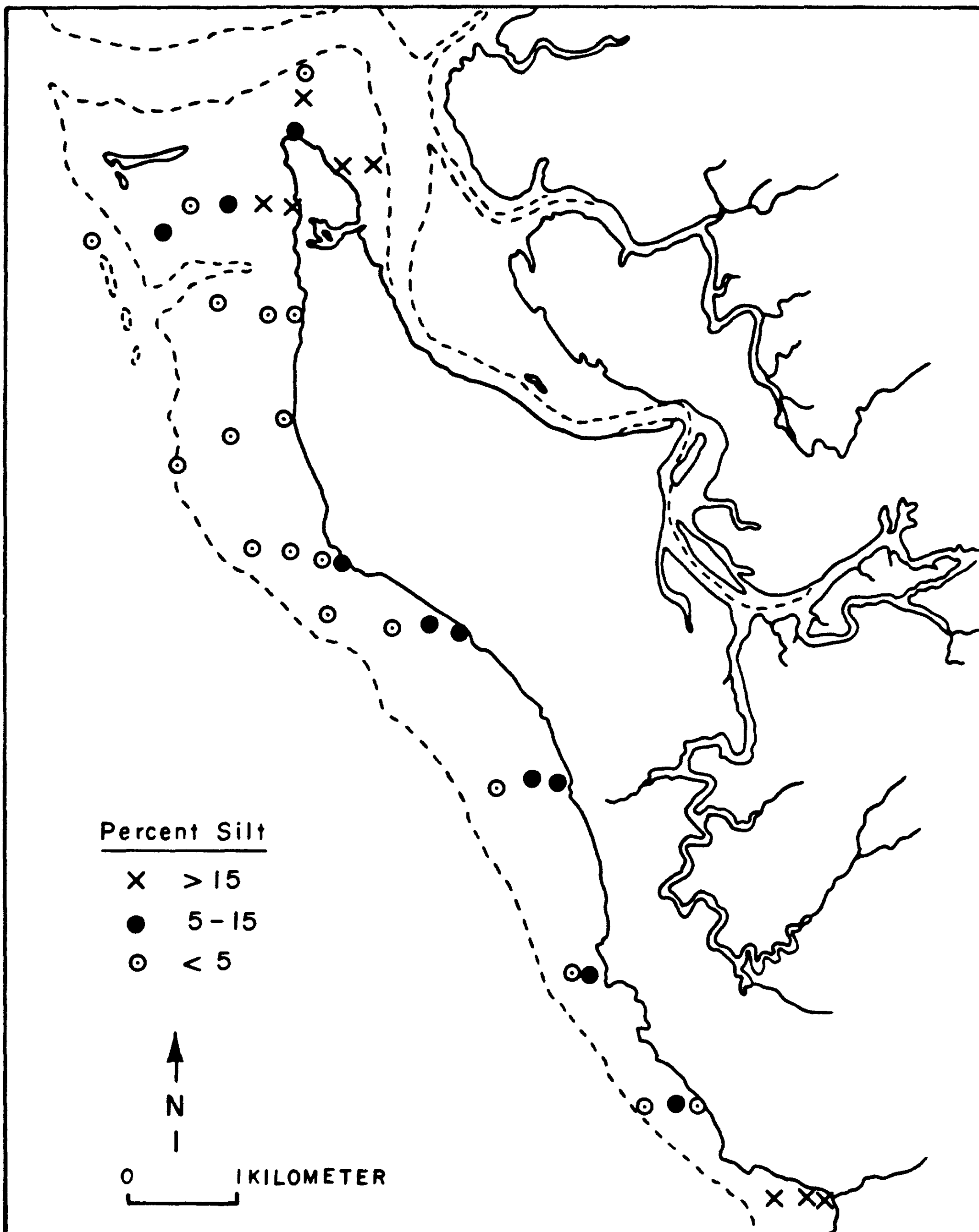

Percent Silt
× >15
● 5-15
⊙ < 5
N
0 1 KILOMETER

Fig. 8. Distribution of clay within the study area.

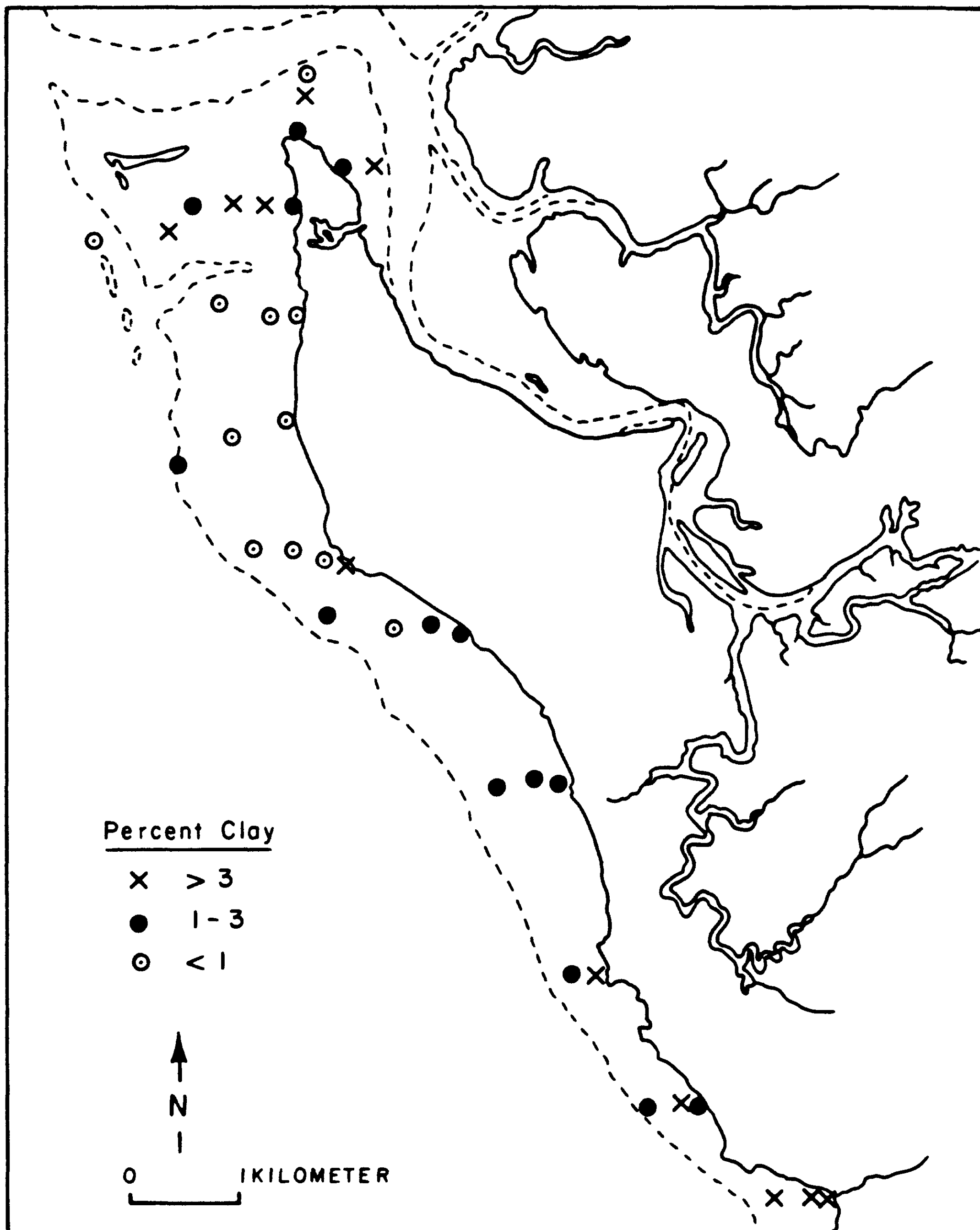

Percent Clay
> 3
1 - 3
< 1
N
0
1 KILOMETER

Fig. 9. Distribution of sand/mud ratios in the study area.

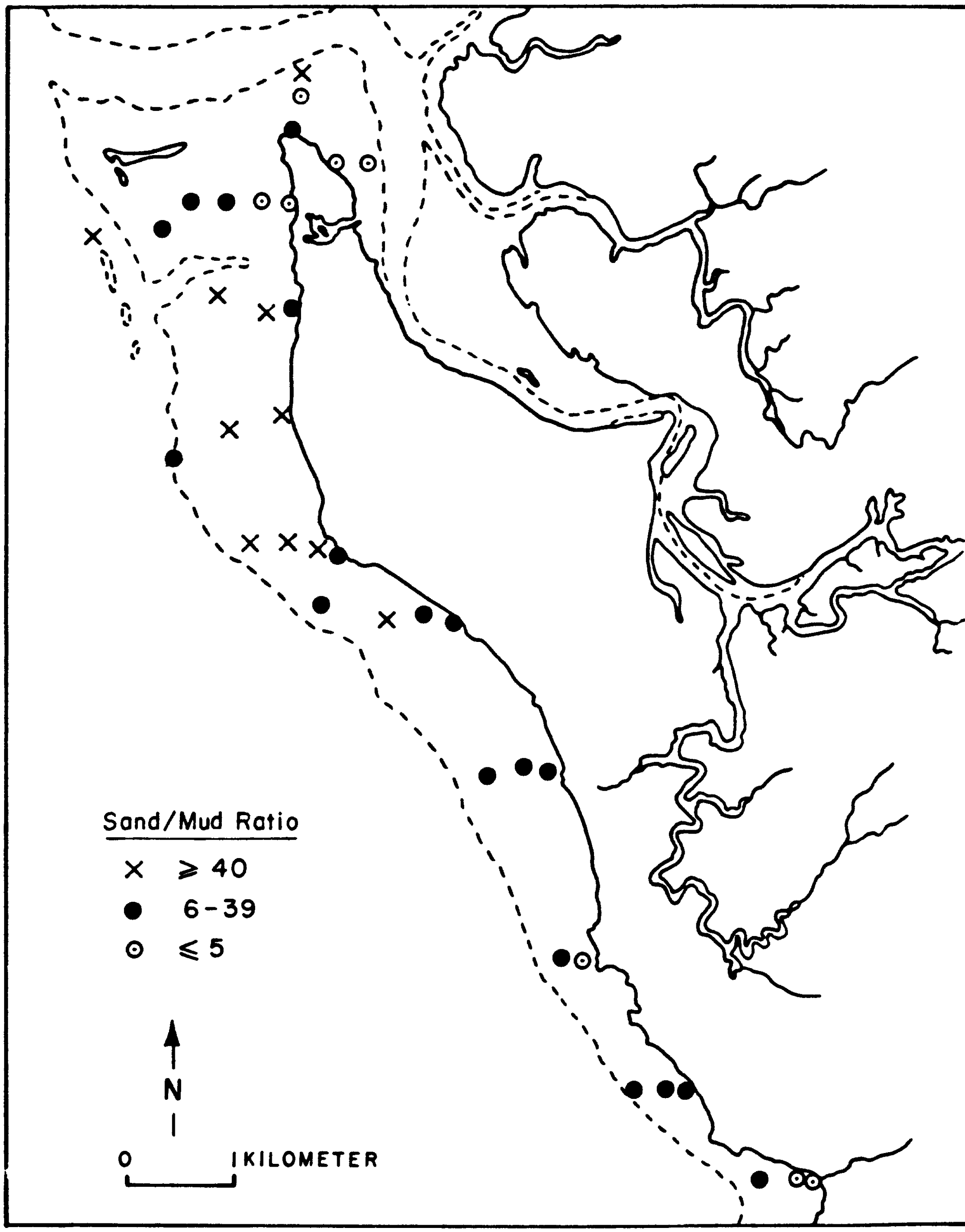

Sand/Mud Ratio
× ≥ 40
● 6-39
⊙ ≤ 5
N
0 1 KILOMETER

Fig. 10. Distribution of silt/clay ratios in the study area.

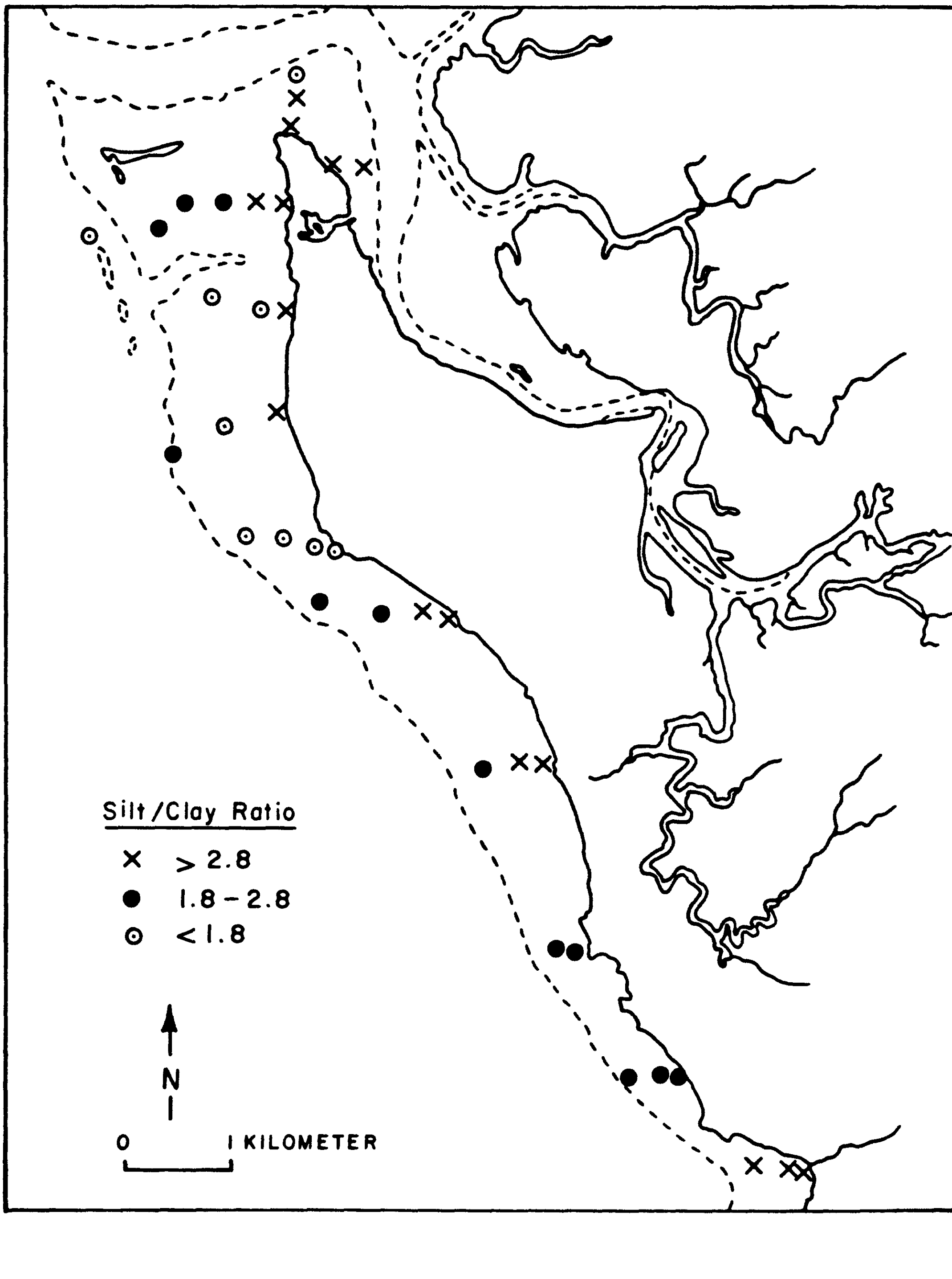

Silt/Clay Ratio
× > 2.8
● 1.8 – 2.8
⊙ < 1.8
N
0 1 KILOMETER

Fig. 11. Ternary diagram of sediment composition in the study area.

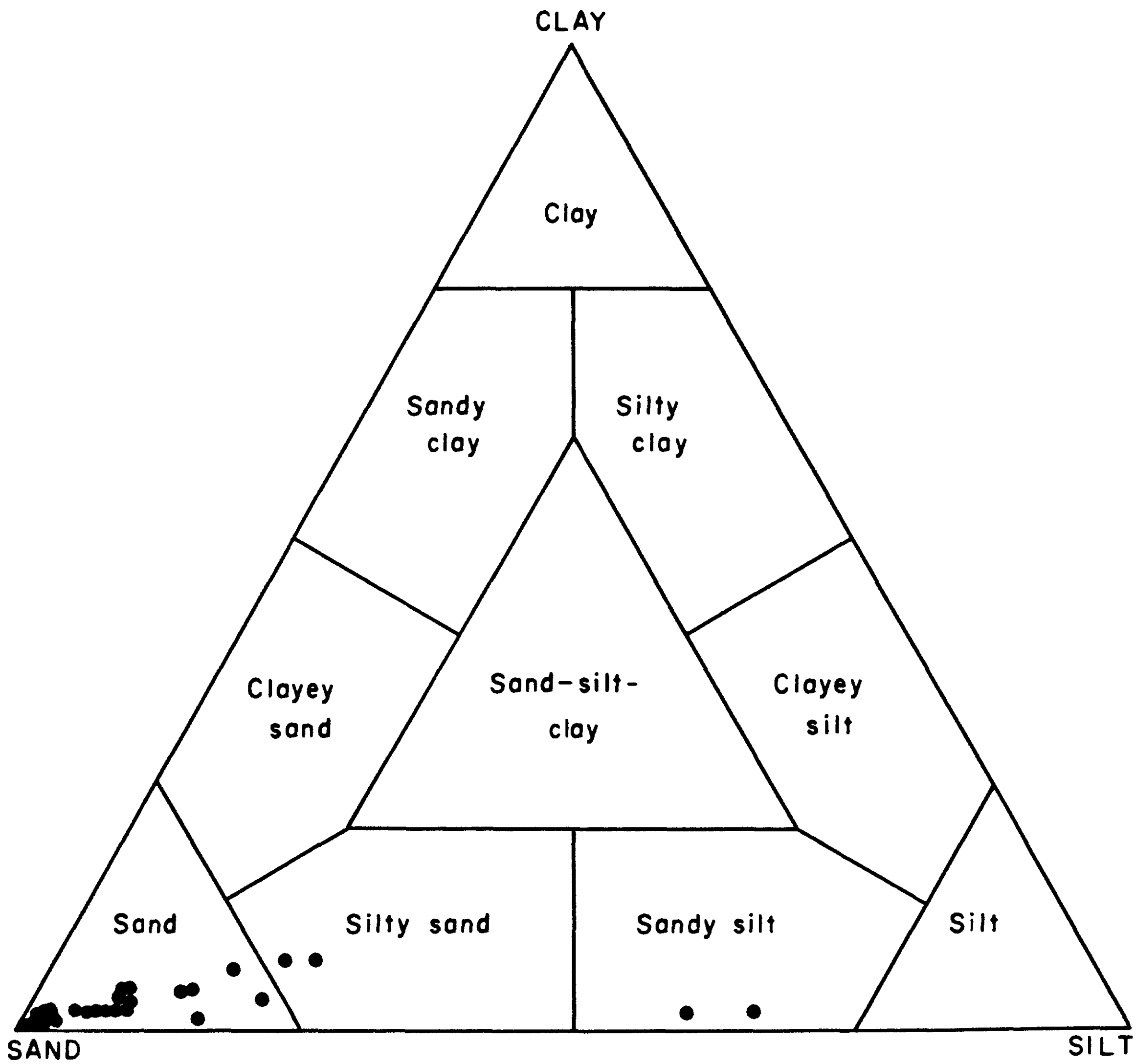

CLAY
Clay
Sandy clay
Silty clay
Clayey sand
Sand-silt-clay
Clayey silt
Sand
Silty sand
Sandy silt
Silt
SAND
SILT

Fig. 12. Distribution of sediment based on Shepard's (1954) classification system.

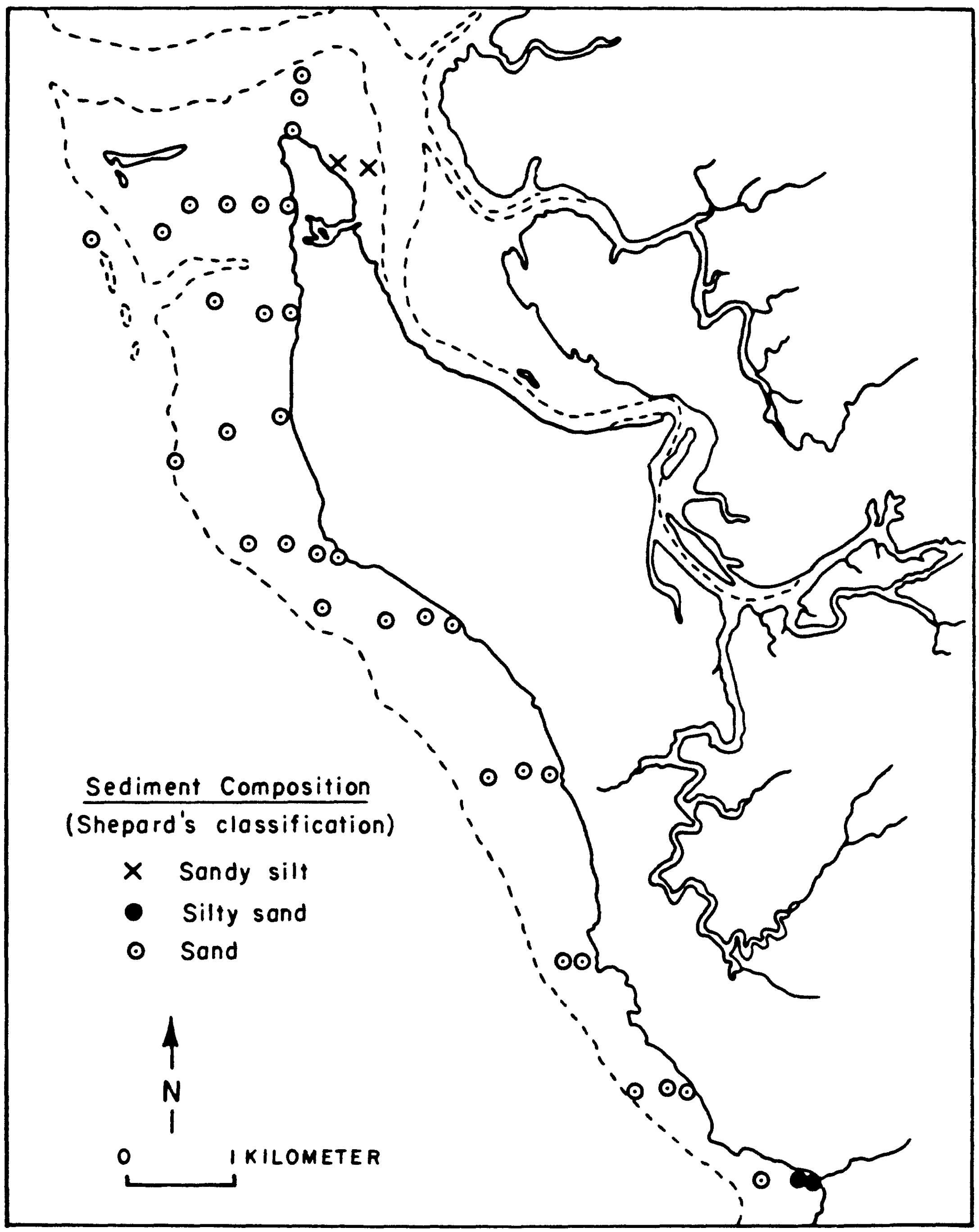

Sediment Composition
(Shepard's classification)
Sandy silt
Silty sand
Sand
N
0
1 KILOMETER

Fig. 13. Distribution of sediment in the study area by mean grain size.

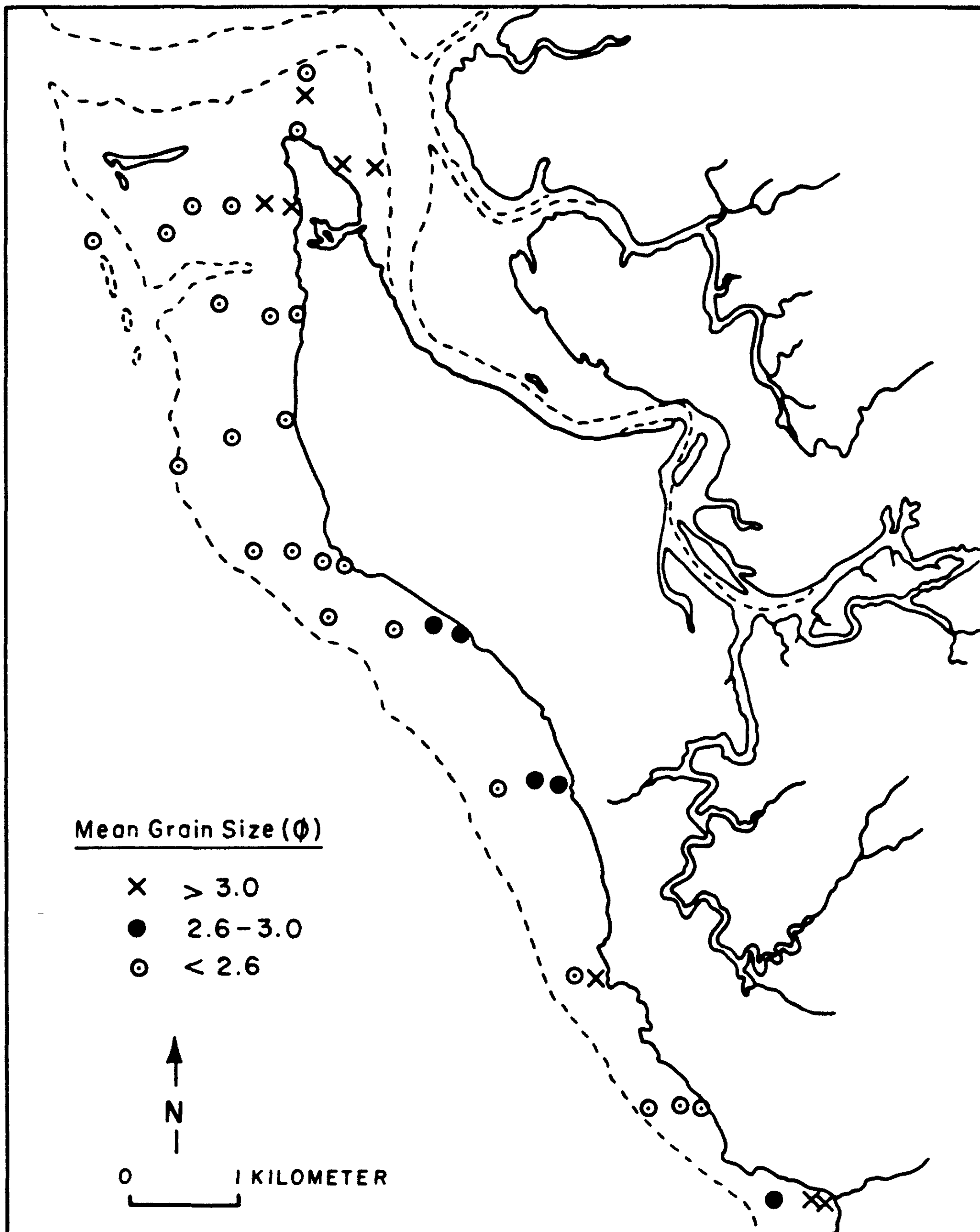

Mean Grain Size (ϕ)
> 3.0
2.6–3.0
< 2.6
N
0
1 KILOMETER

Fig. 14. Distribution of sediment in the study area by standard deviation.

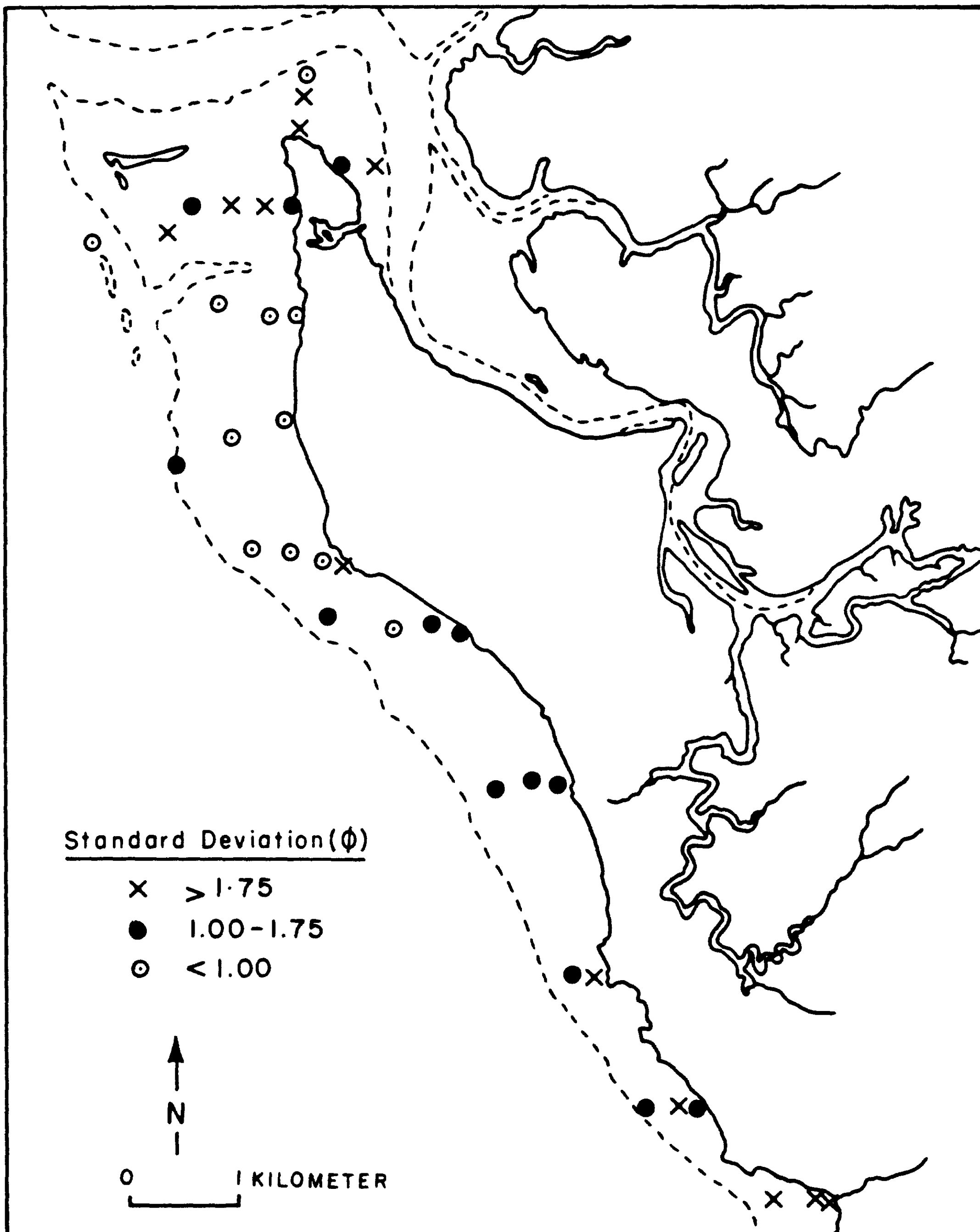

Standard Deviation(φ)
× >1·75
● 1.00-1.75
⊙ <1.00
N
0 1 KILOMETER

Fig. 15. Distribution of sediment in the study area by skewness.

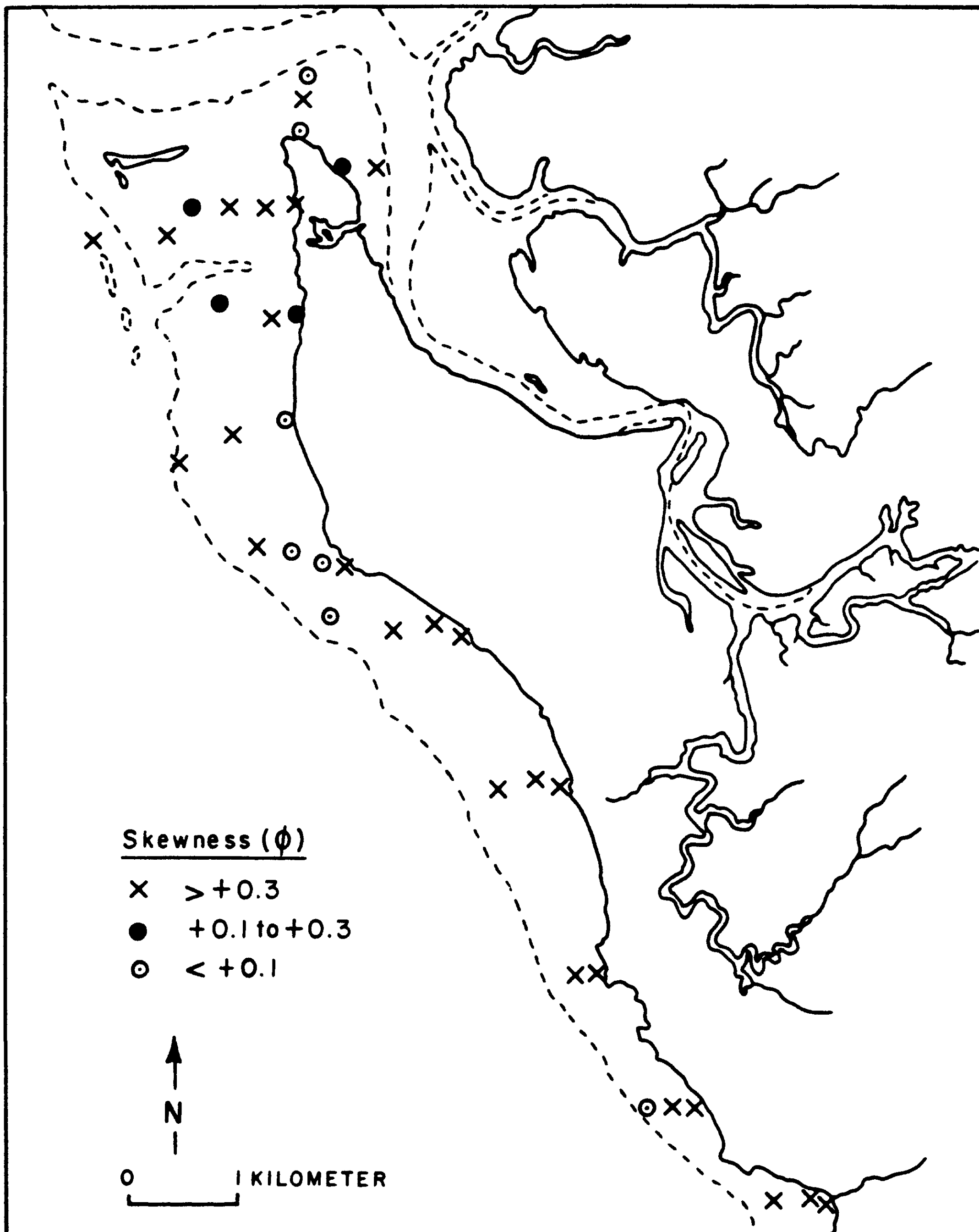

Skewness (φ)
> +0.3
+0.1 to +0.3
< +0.1
N
0
1 KILOMETER

Fig. 16. Distribution of sediment in the study area by kurtosis.

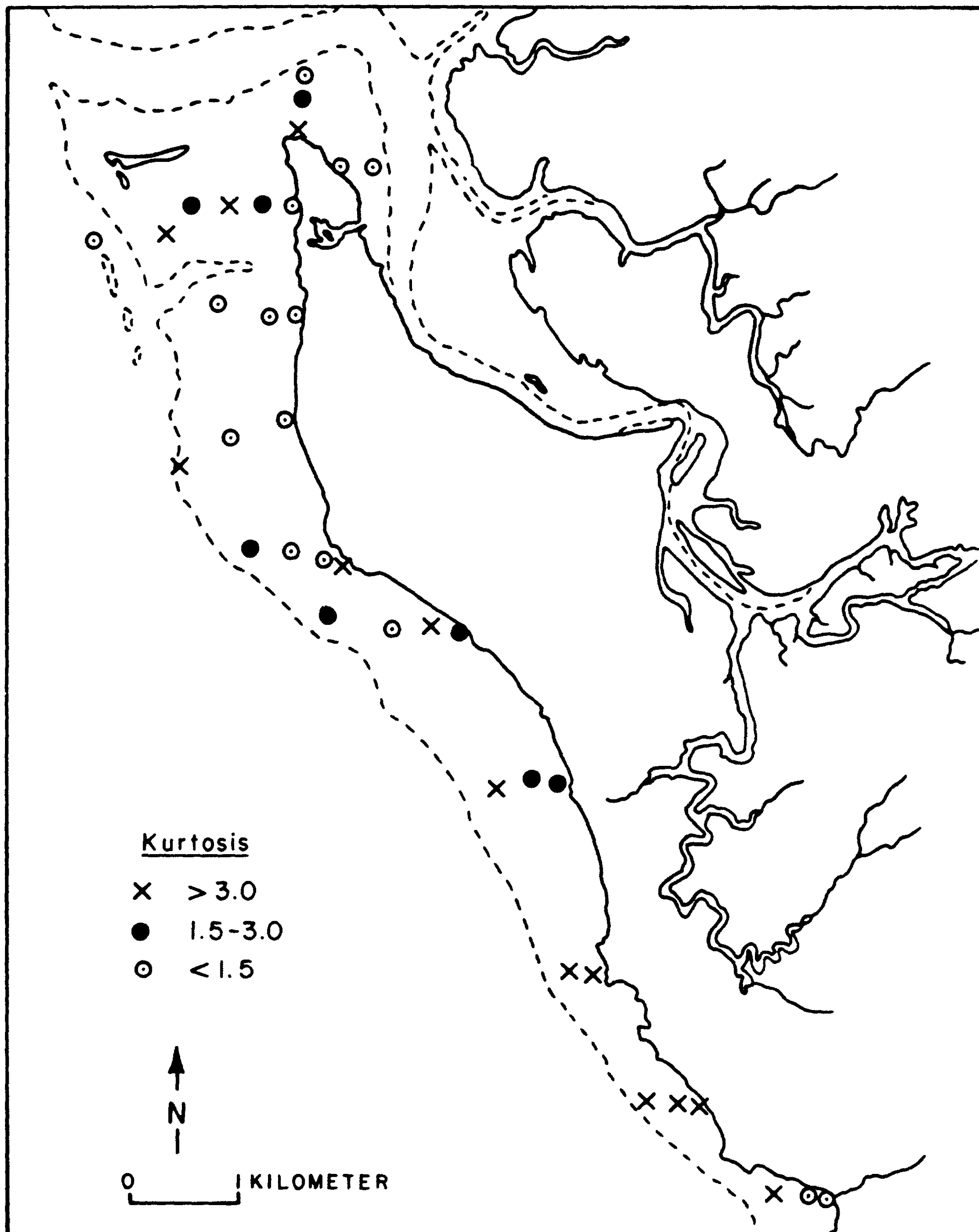
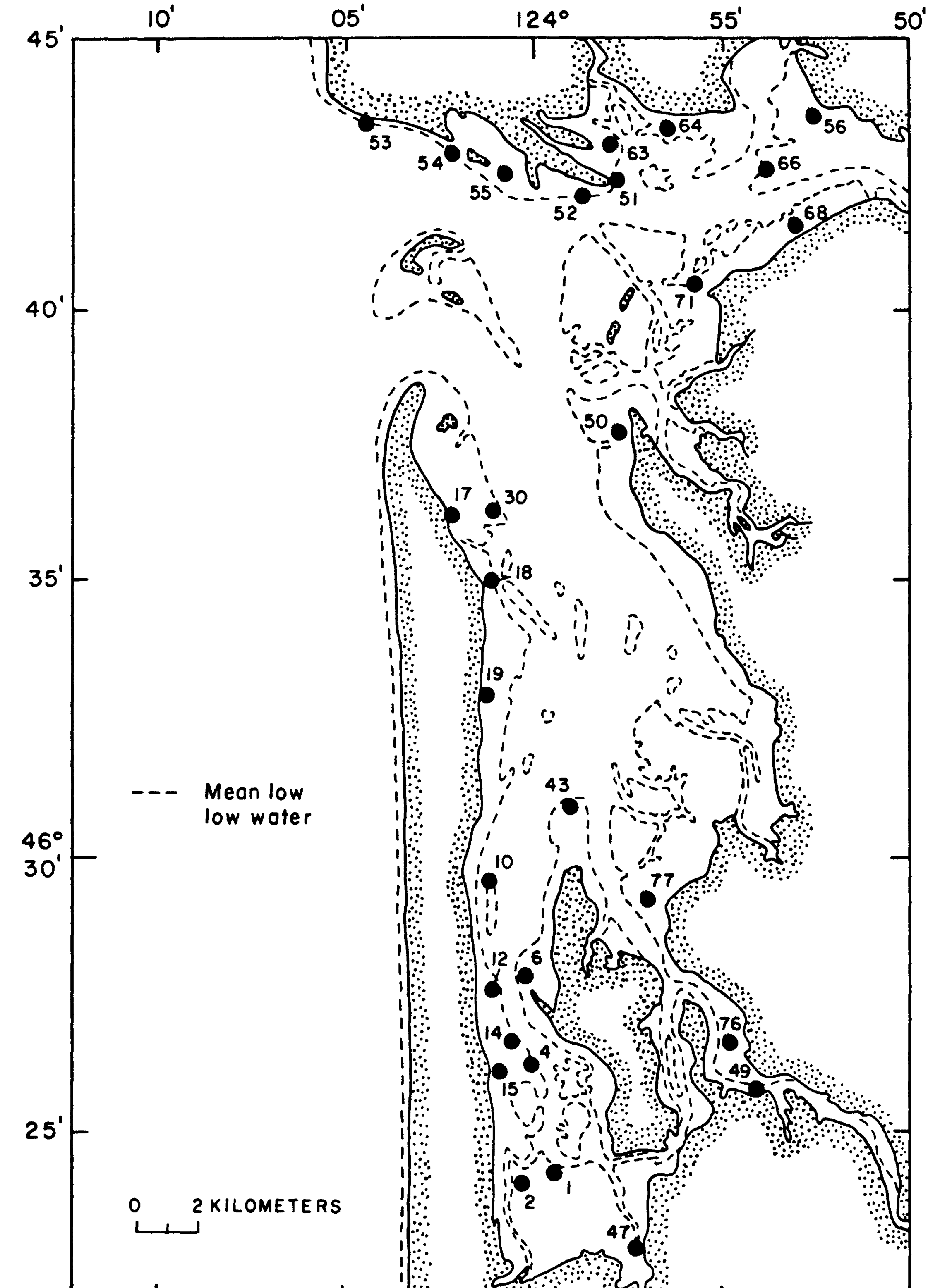
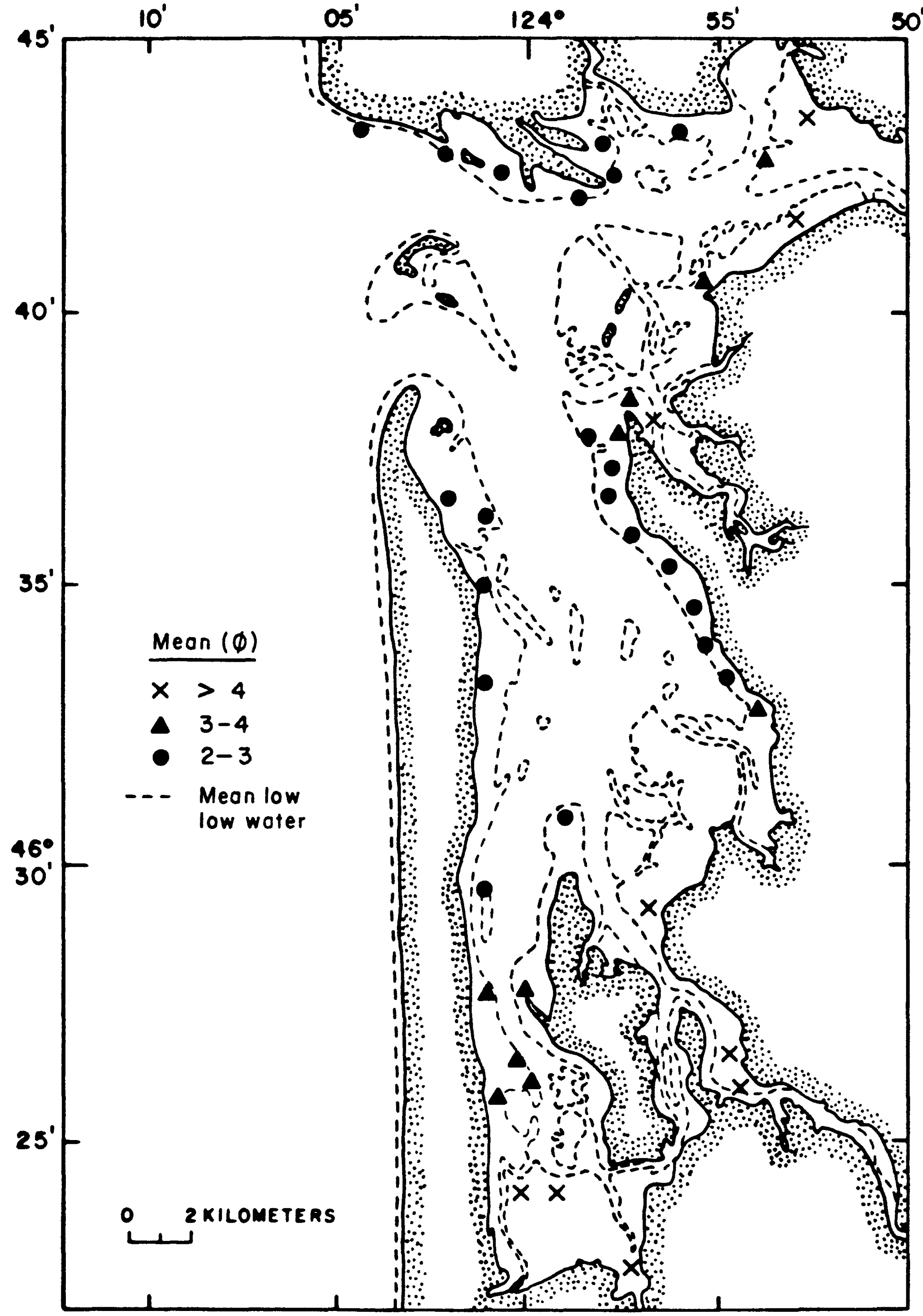

Kurtosis
> 3.0
1.5-3.0
< 1.5
N
0
1 KILOMETER

Fig. 17. Intertidal sample locations in Willapa Bay 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
2
1
47
Mean low
low water
0 2 KILOMETERS

Fig. 18. Distribution of tidal flat sediments in Willapa Bay by mean grain size using combined data from this report and Andrews (1965). Within my 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

Fig. 19. Distribution of montmorillonite in the study area.

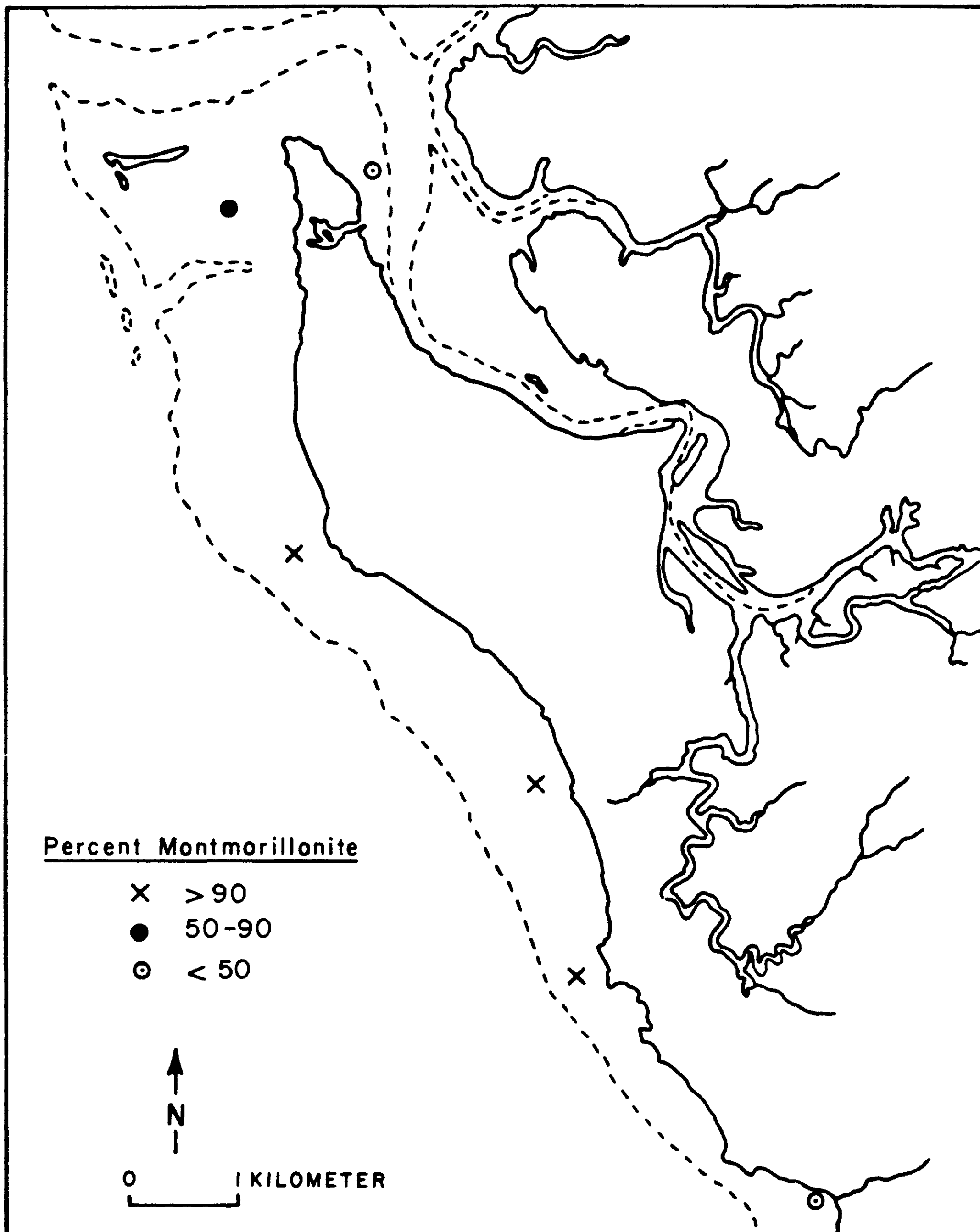

Percent Montmorillonite
× >90
● 50-90
⊙ < 50
N
0 1 KILOMETER

Fig. 20. Distribution of heavy minerals in the study area.

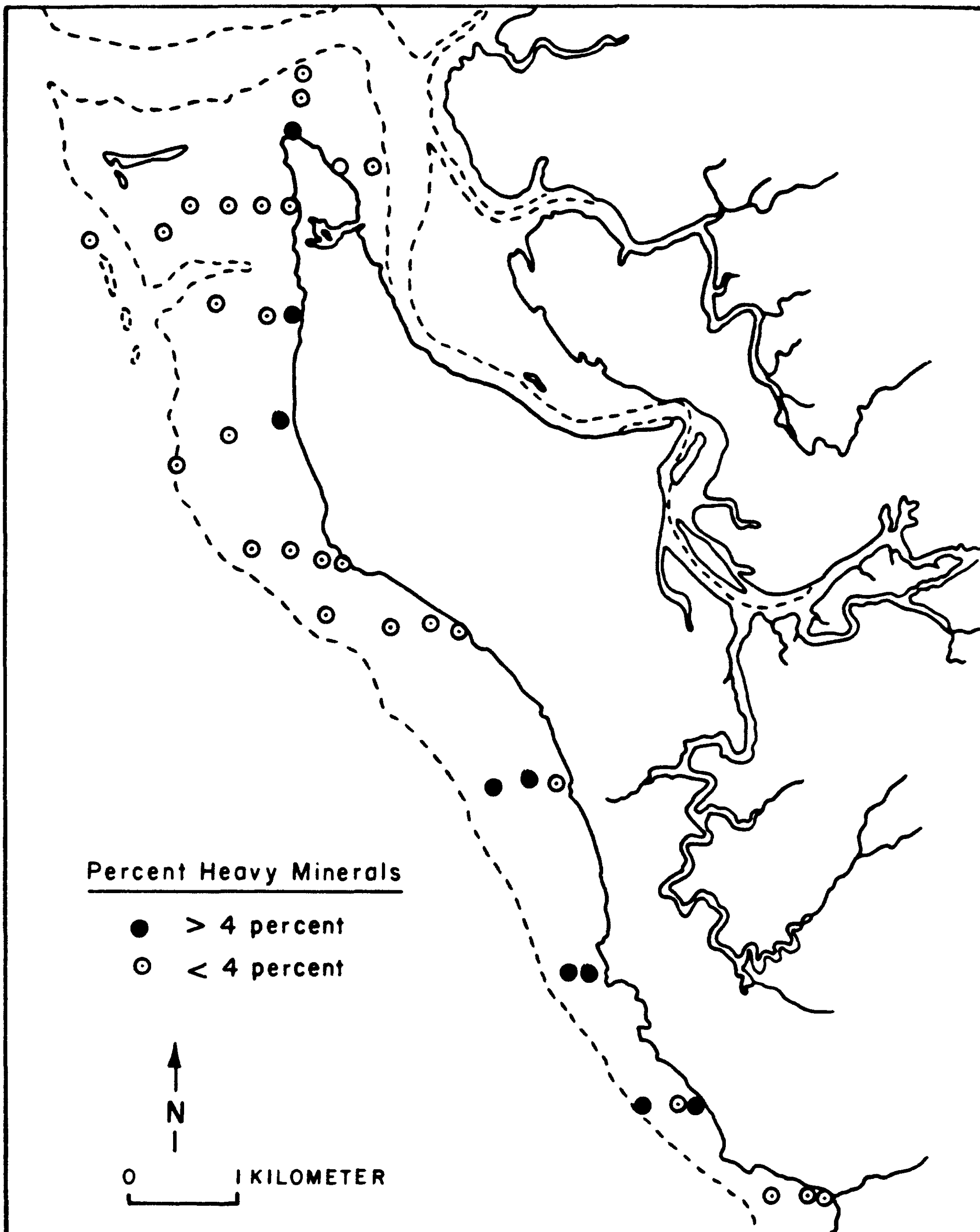
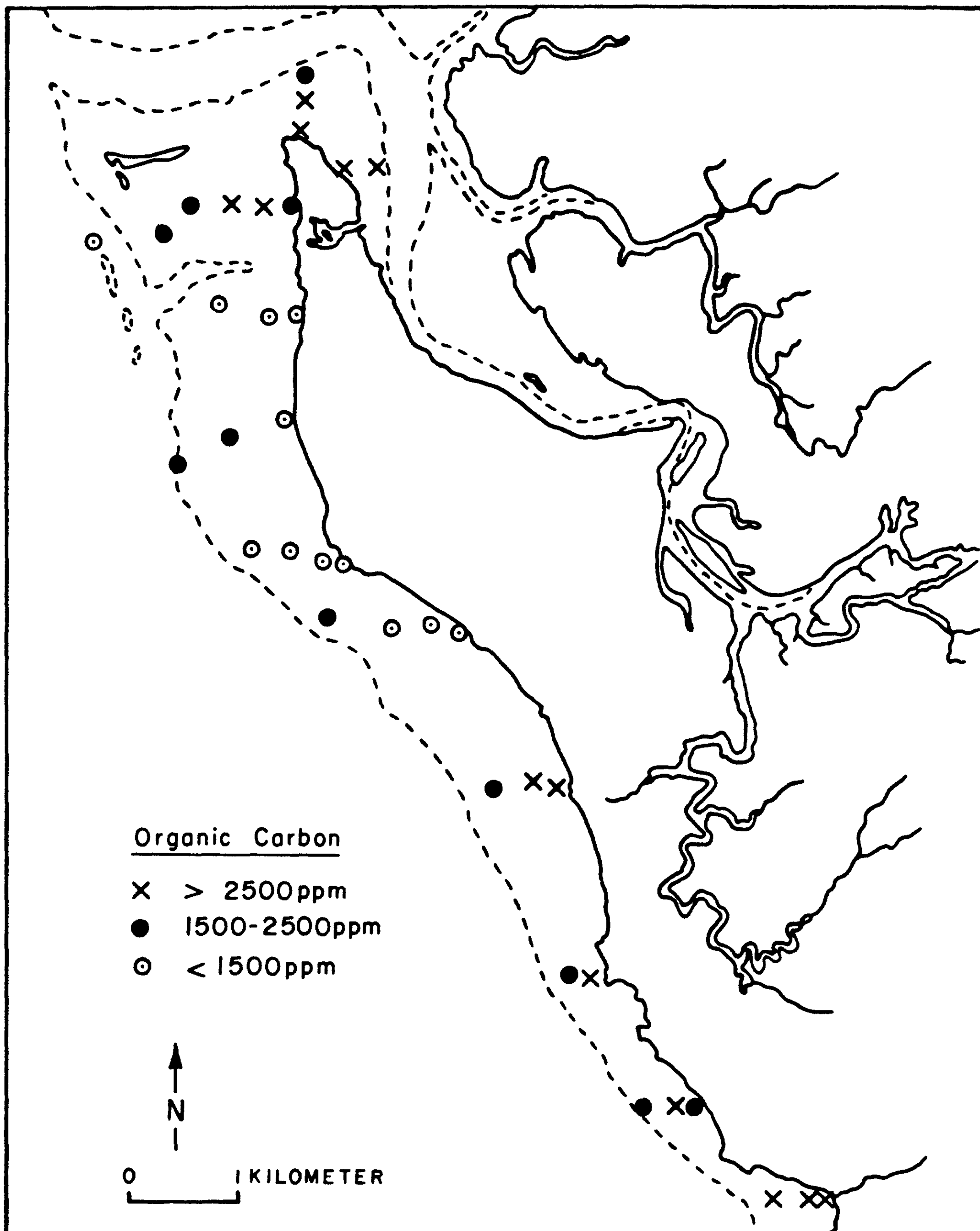
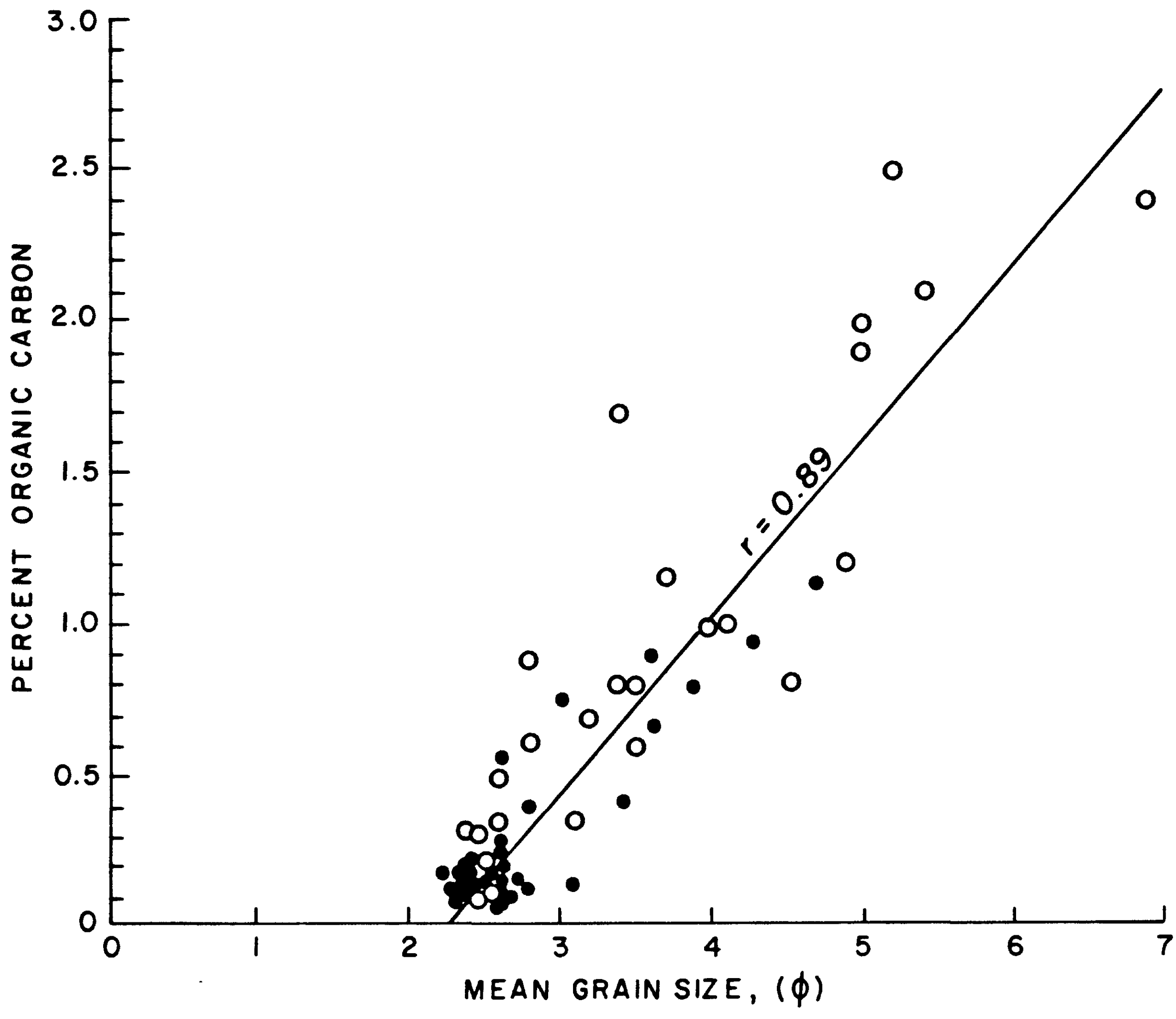

Percent Heavy Minerals
> 4 percent
< 4 percent
N
0 1 KILOMETER

Fig. 21. Distribution of organic carbon in the study area.



Organic Carbon
× > 2500ppm
● 1500-2500ppm
⊙ < 1500ppm
N
0 1 KILOMETER

Fig. 22. Percentage of organic carbon as a function of mean grain size. Data from this study are solid circles and data from Andrews (1965) are open circles.



PERCENT ORGANIC CARBON
3.0
2.5
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
MEAN GRAIN SIZE, (ϕ)
r = 0.89

Fig. 23. Distribution of organic nitrogen in the study area.

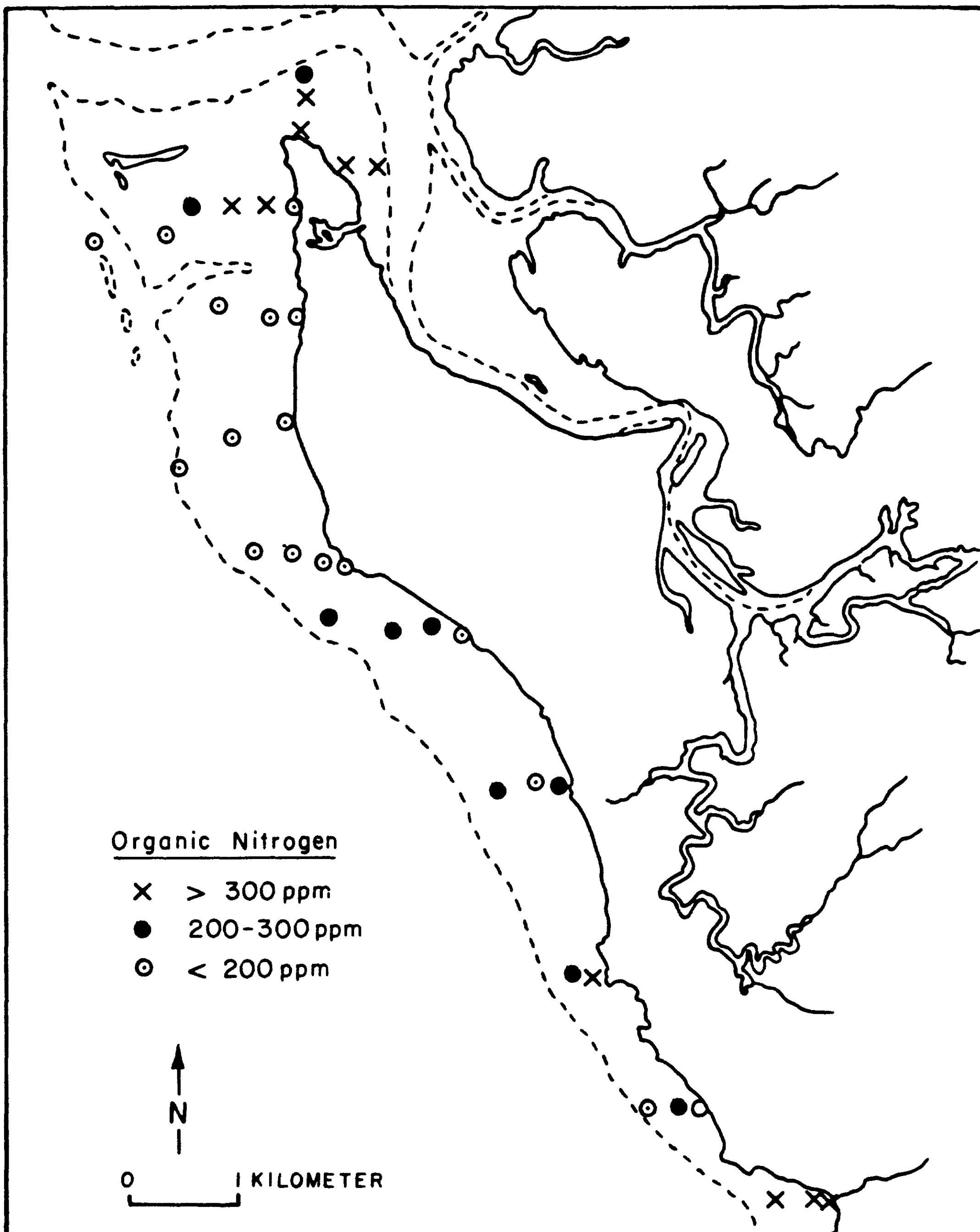
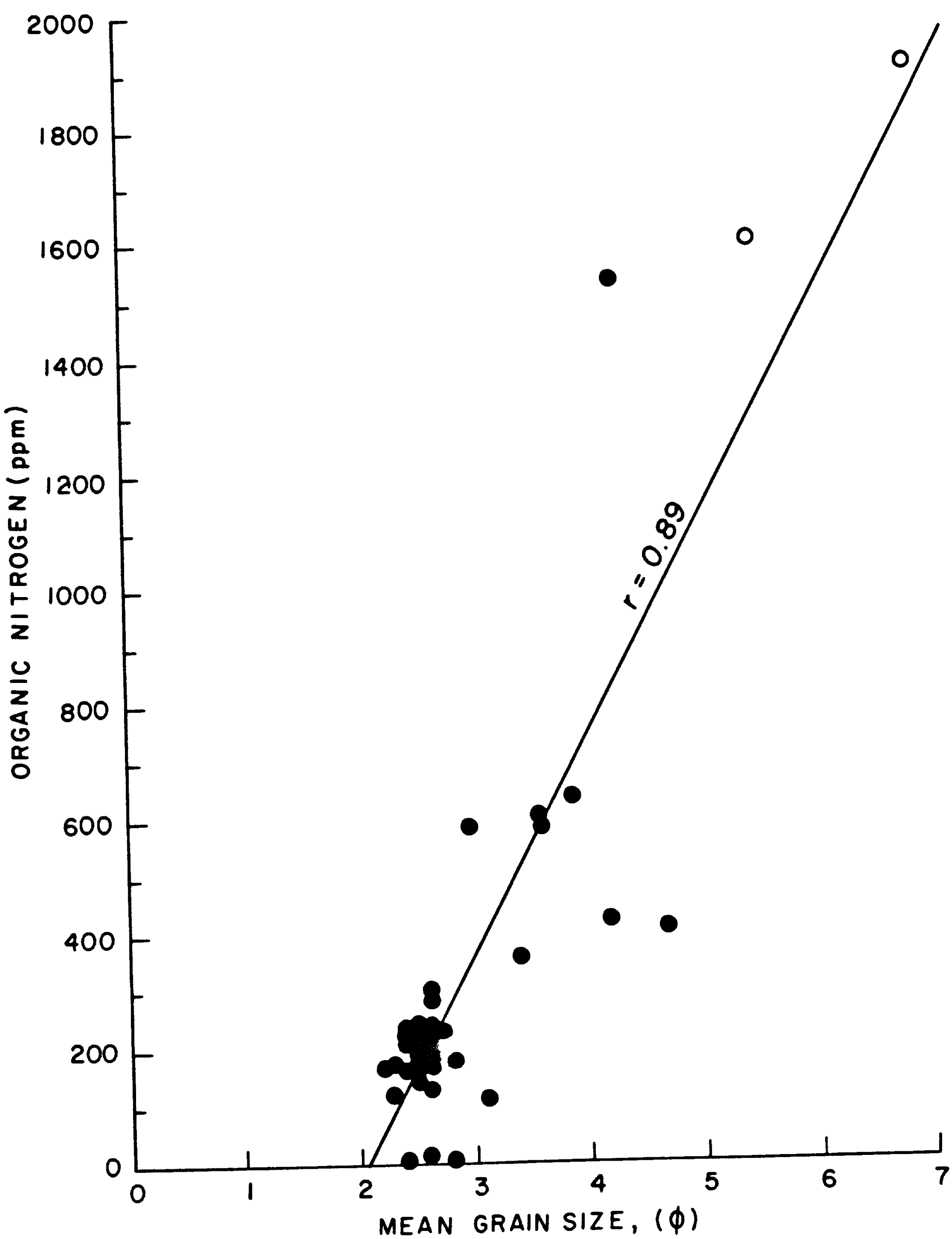

Organic Nitrogen
> 300 ppm
200-300 ppm
< 200 ppm
N
0 1 KILOMETER

Fig. 24. Percentage of organic nitrogen as a function of mean grain size. Data from this study are solid circles and data from Andrews (1965) are open circles.



2000
1800
1600
1400
1200
1000
800
600
400
200
0
ORGANIC NITROGEN (ppm)
r = 0.89
0
1
2
3
4
5
6
7
MEAN GRAIN SIZE, (ϕ)

Fig. 25. Percentage organic carbon as a function of percentage organic nitrogen. Data from this study are solid circles and data from Andrews (1965) are open circles.

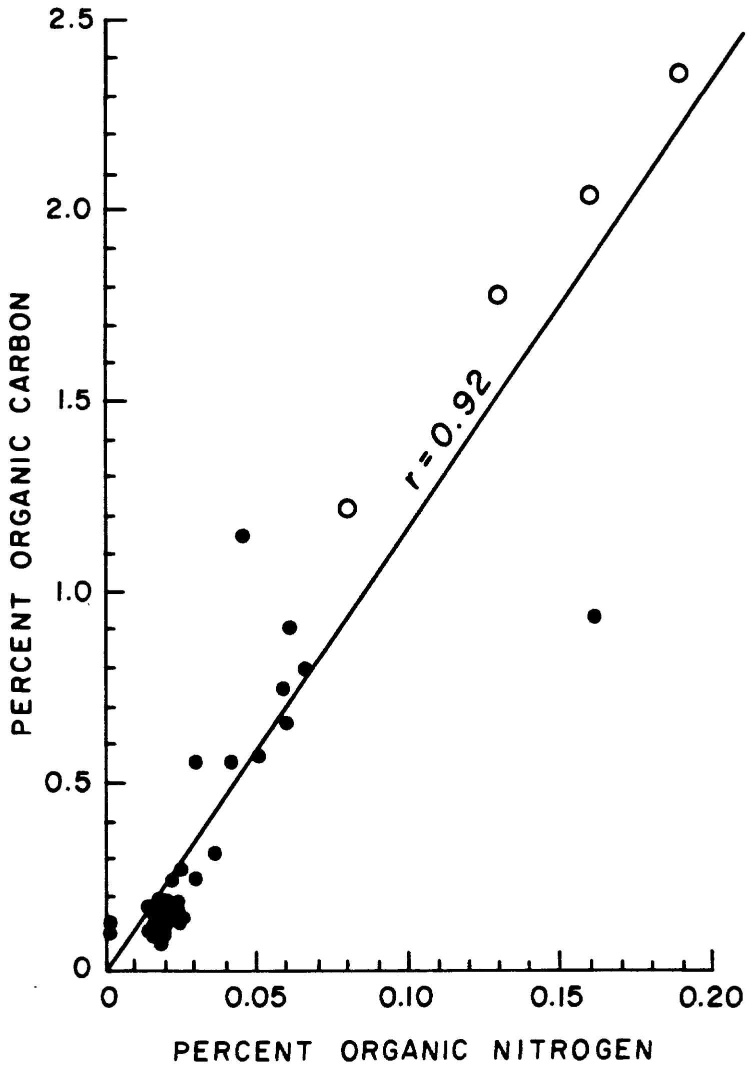

2.5
2.0
1.5
1.0
0.5
0
PERCENT ORGANIC CARBON
r=0.92
0
0.05
0.10
0.15
0.20
PERCENT ORGANIC NITROGEN

Fig. 26. Distribution of C/N ratios in the study area.

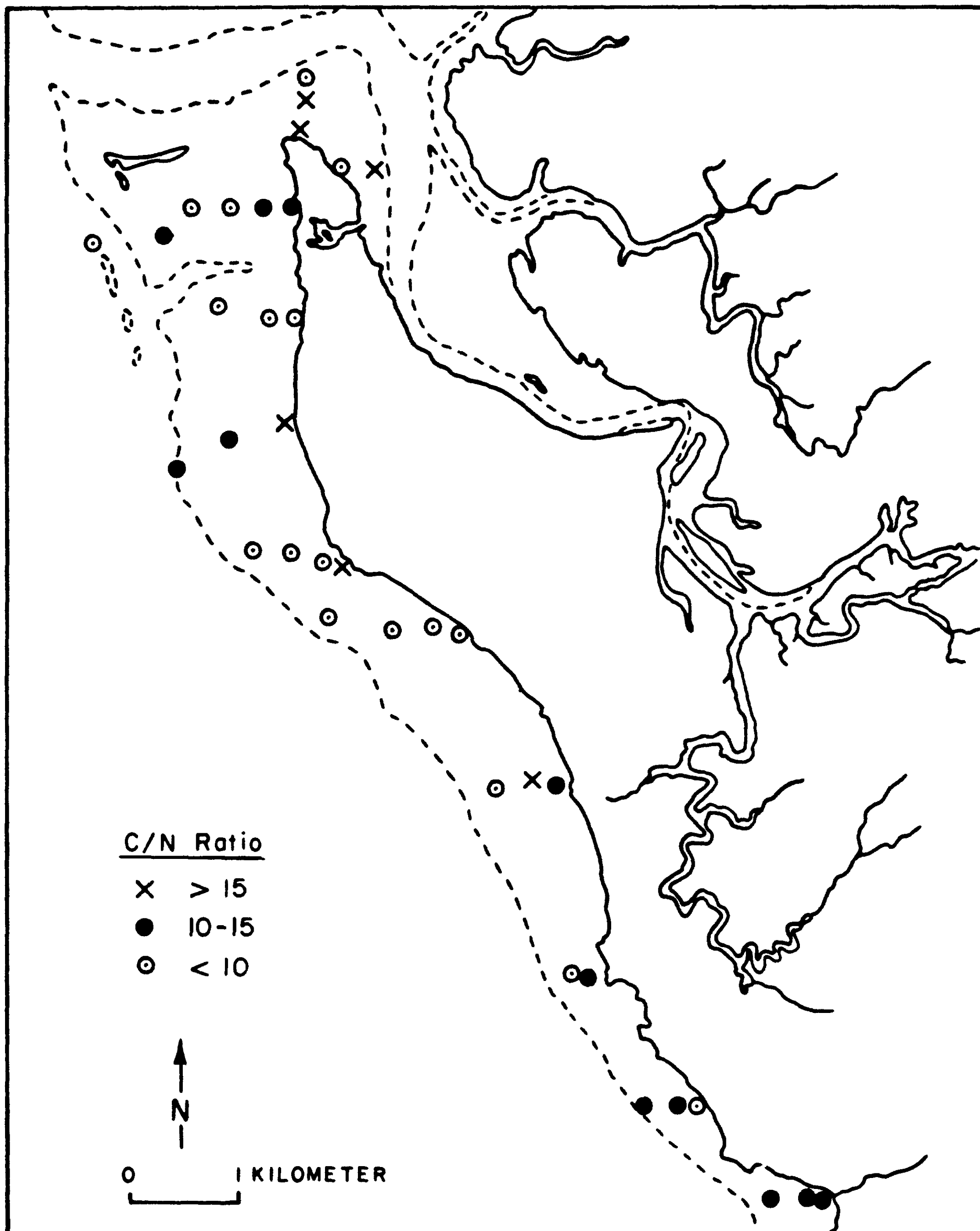

C/N Ratio
> 15
10-15
< 10
N
0
1 KILOMETER

Fig. 27. (A) Sinuous, ebb-oriented sandwaves on the lower intertidal flat off Sandy Point. (B) Trench through a sandwave showing medium scale cross-stratification. (Photographs courtesy of R. L. Phillips).

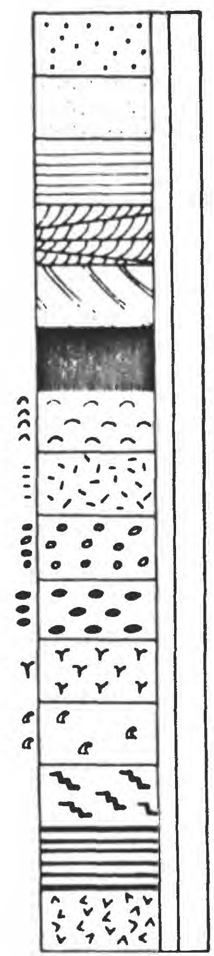
A

B

Fig. 28. Graphic display of box cores taken in the study area. Symbols indicate various sedimentary structures. Degree of bioturbation is shown in right hand column.

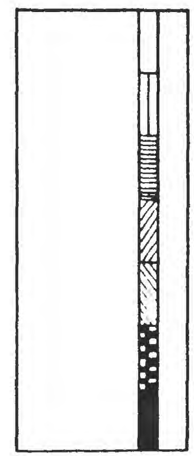
# EXPLANATION

**Sediments and Physical Structures**



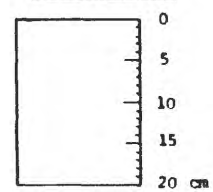
- structureless muddy coarse sand
- structureless muddy fine sand
- laminated sand
- ripple laminated sand
- trough crossbedded sand
- peaty mud
- shells
- shell fragments
- pebbles
- mud clasts
- wood and plant fragments
- crab claws
- Pleistocene mud
- laminated Pleistocene sand and mud
- cemented sand (Pleistocene?)

**Percent Bioturbation**

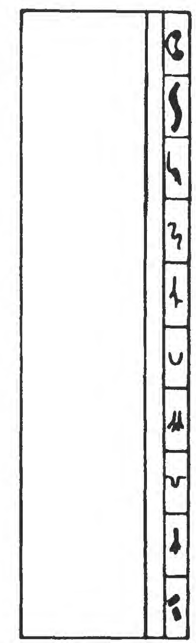


- 0
- trace
- <30
- 30-60
- 60-90
- 90-100
- 100

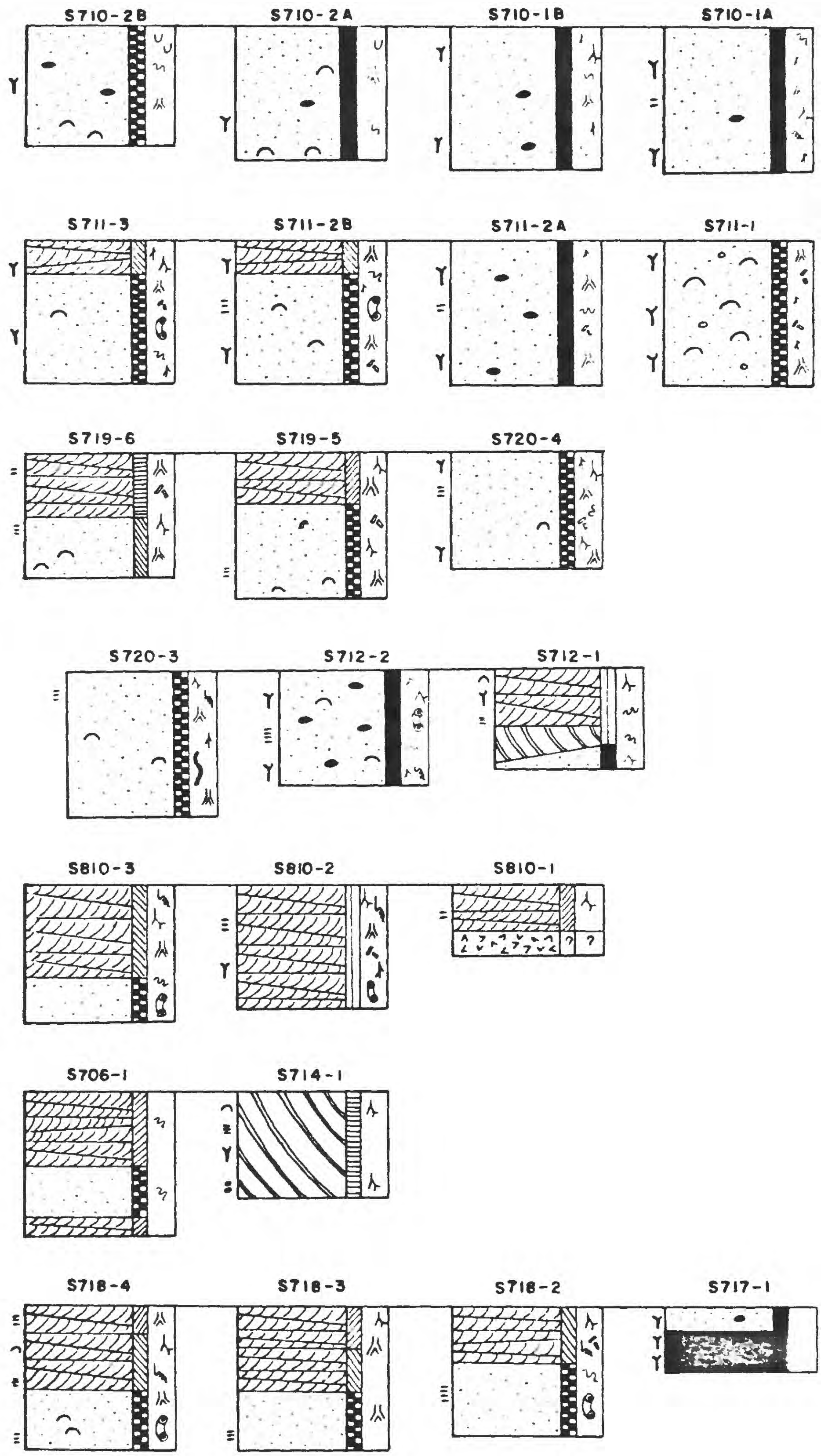
**Box Core Scale**




**Biogenic Sedimentary Structures**



- Trace A
- Trace B
- Trace C
- Trace D
- Trace E
- Trace F
- Trace G
- Trace H
- Trace K
- Callianassa fecal pellets 1 X 4 mm, rod shaped, clay composition


S710-2B
S710-2A
S710-1B
S710-1A
S711-3
S711-2B
S711-2A
S711-1
S719-6
S719-5
S720-4
S720-3
S712-2
S712-1
S810-3
S810-2
S810-1
S706-1
S714-1
S718-4
S718-3
S718-2
S717-1

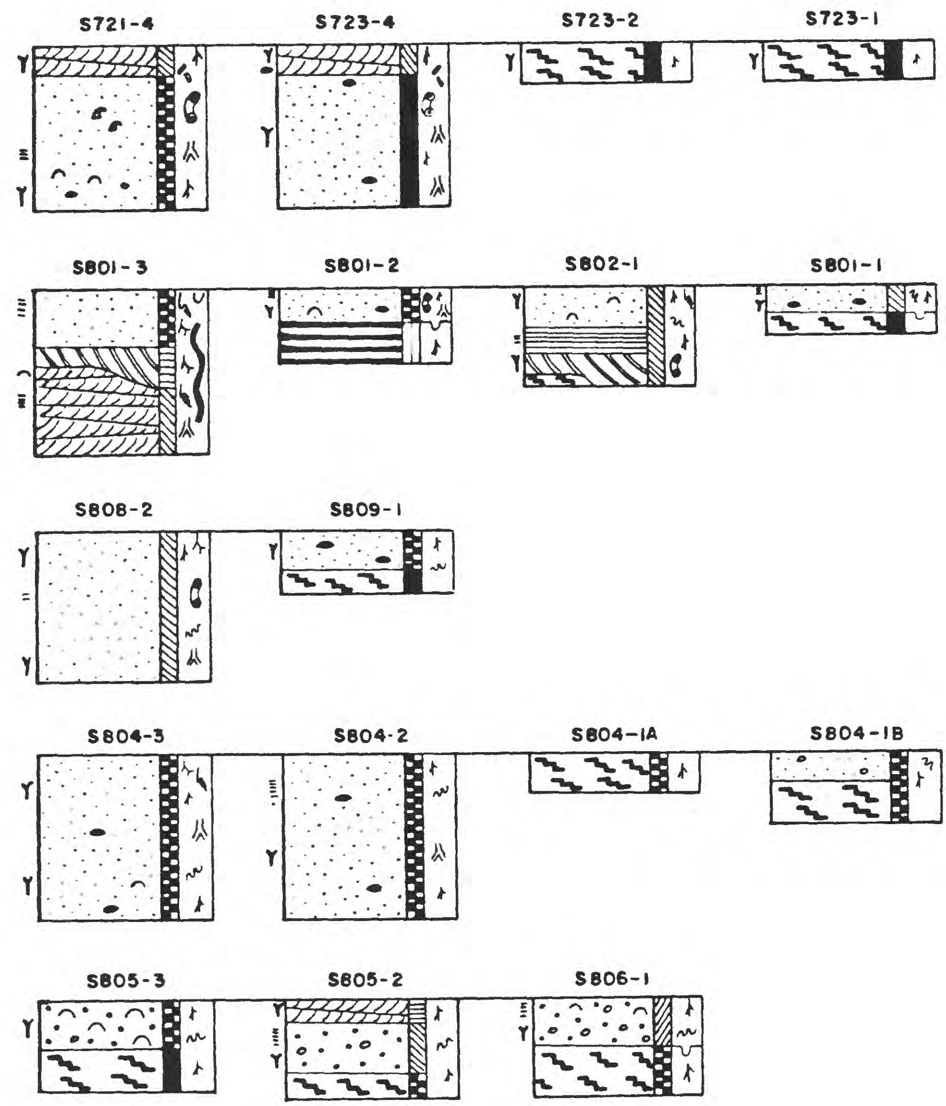
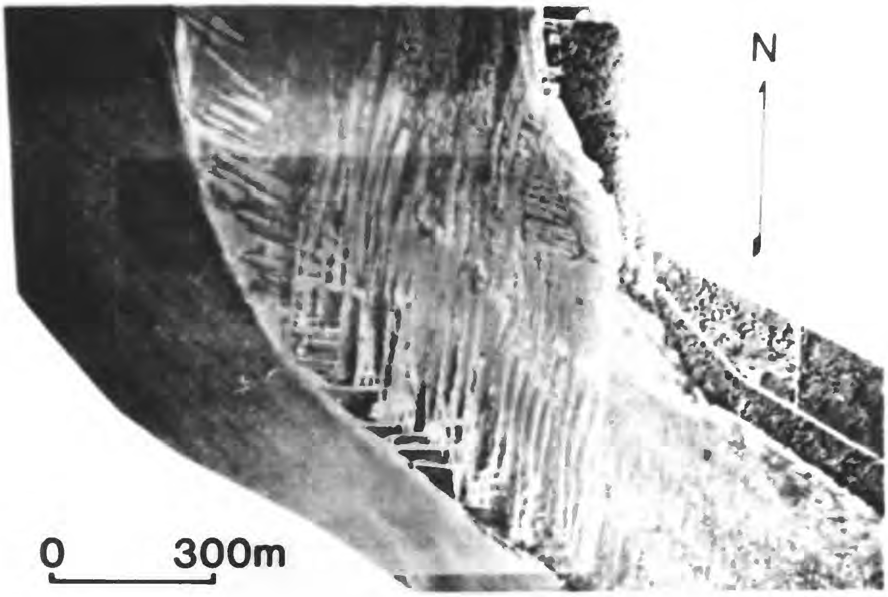

S721-4
S723-4
S723-2
S723-1
S801-3
S801-2
S802-1
S801-1
S808-2
S809-1
S804-3
S804-2
S804-1A
S804-1B
S805-3
S805-2
S806-1

Fig. 29. (A) Low-amplitude (10-20 cm) bedforms (ridges and troughs) on sandy intertidal flats between Goose Point and Sandy Point. (Photograph courtesy of R. L. Phillips) (B) X-ray radiograph of box core taken on a low-amplitude ridge showing ripple laminations.

A




B

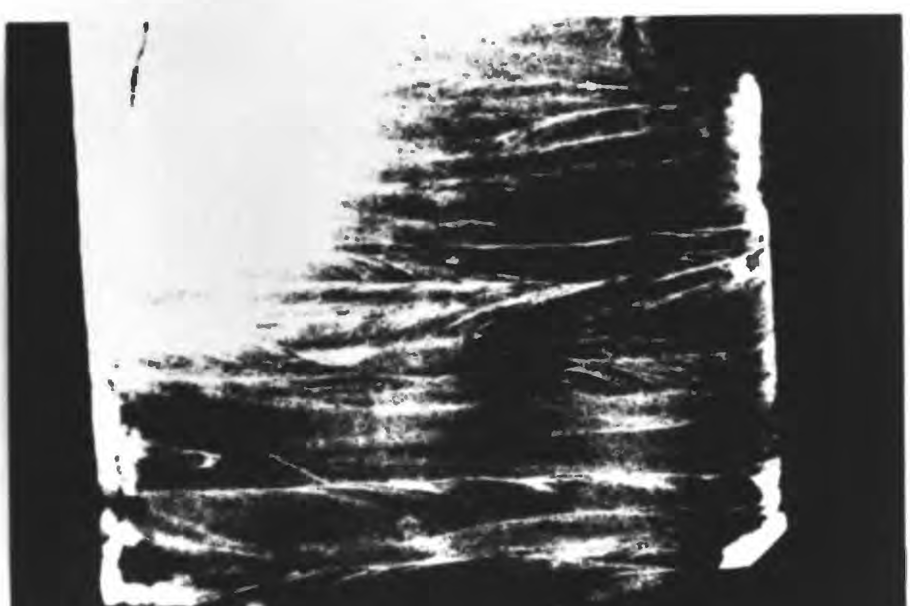
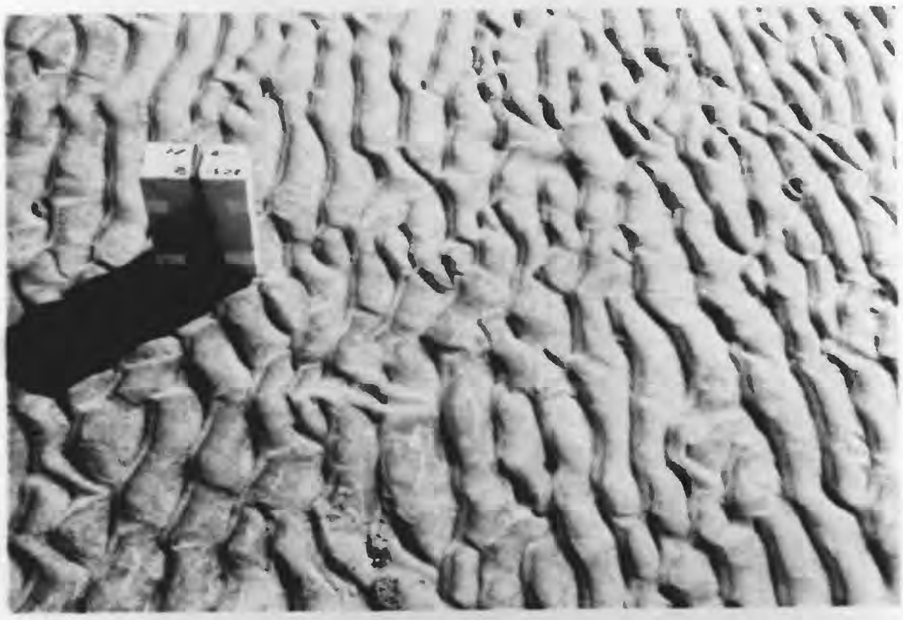


Fig. 30. Runoff channel on the intertidal flat between Goose Point and Sandy Point. (Photograph courtesy of R. J. Anima).


0 2m

Fig. 31. Types of ripples common on the tidal flats in the study area: (A) asymmetrical current ripples, (B) irregular linguoid ripples, (C) long-crested symmetrical ripples. (Photographs courtesy of R. L. Phillips and H. E. Clifton)

A



B

C

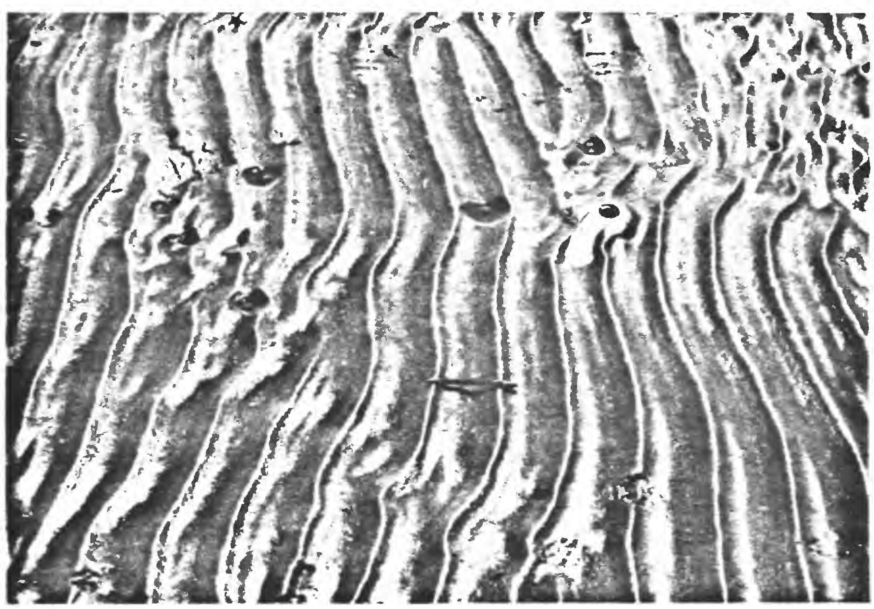
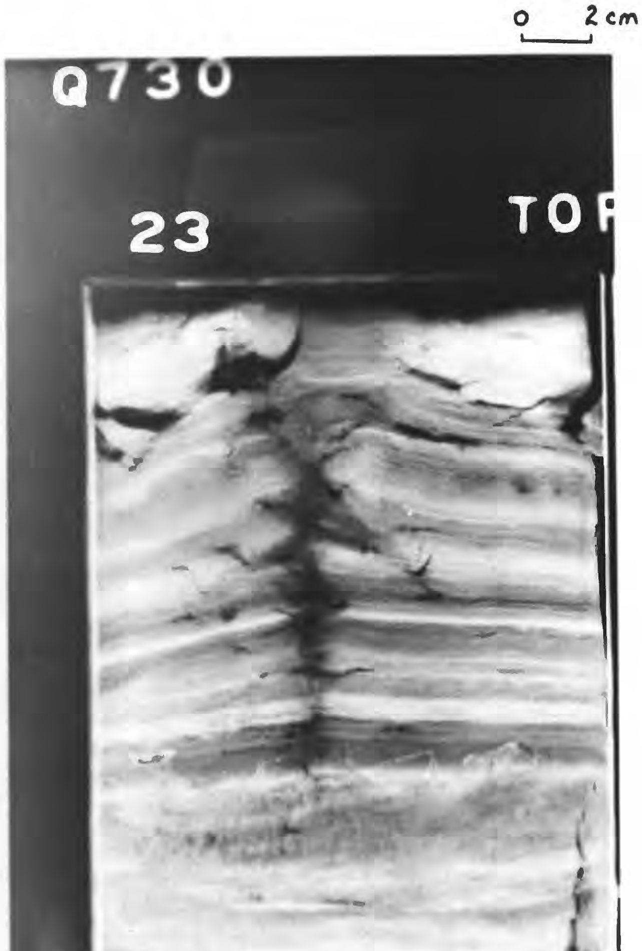


Fig. 32. Indurated mudstone ("bedrock") flooring intertidal flat off Goose Point. Thin sand veneer occurs locally. Openings to borings made by Upogebia are common.

Fig. 33. (A) Intertidal mud flat surface; note lack of physical sedimentary structures but abundance of biogenic sedimentary structures such as bird tracks. (B) X-ray radiograph of box core taken on mud flat showing bioturbate texture of sediment.

Fig. 34. X-ray radiographs of box cores taken (A) on section of tidal flat covered by algal mound; anoxic conditions beneath algal mound inhibits biogenic activity, thereby reducing the degree of bioturbation, and (B) on supratidal flats where the deposits are characterized by repeated, thin laminations of silt and clay (deposited during storms or floods) with abundant root traces. (Photographs courtesy of R . L. Phillips and H. E. Clifton)

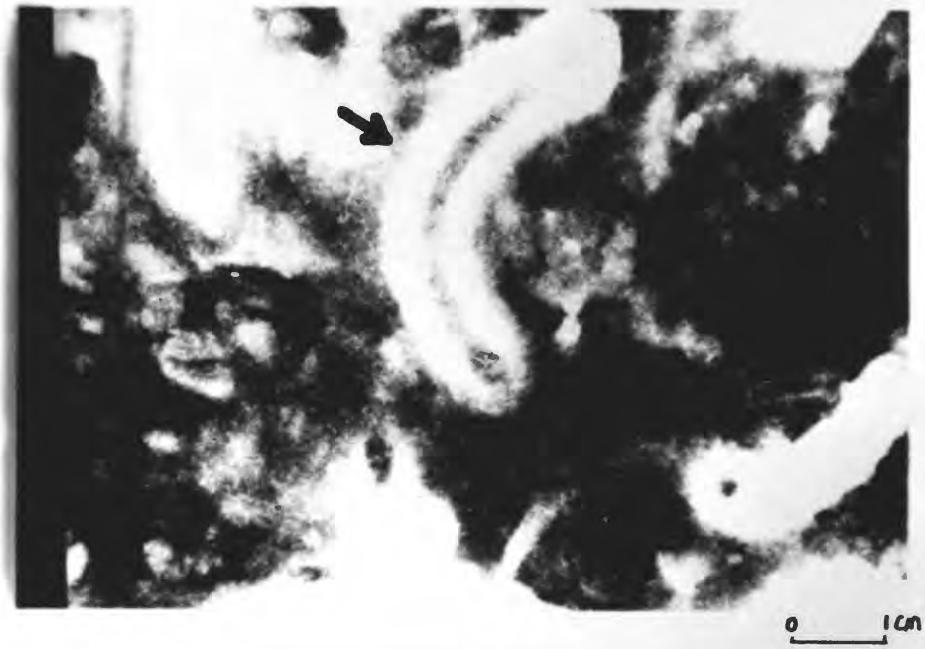
A



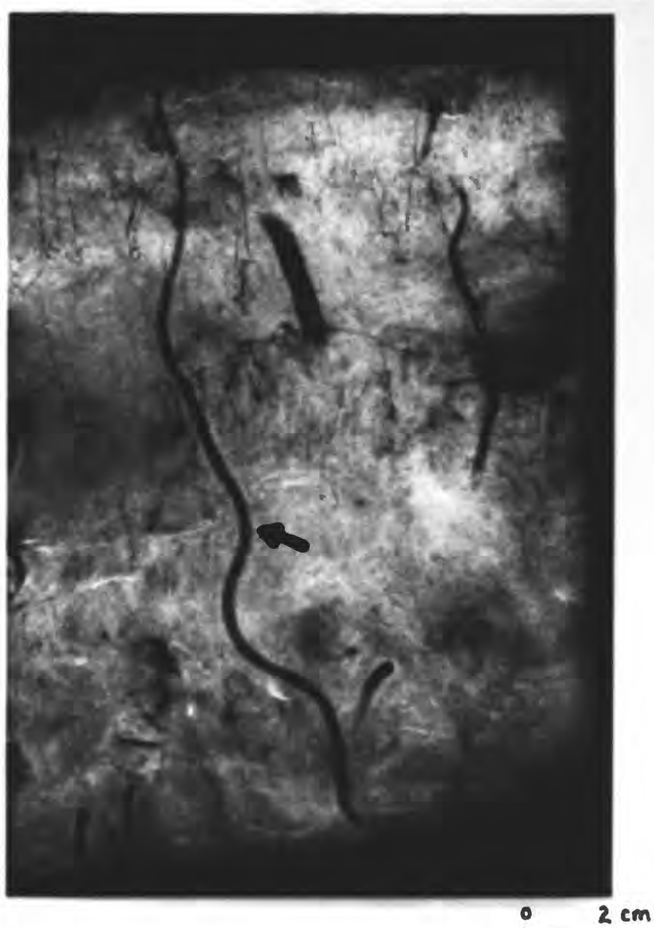

B

Fig. 35. Examples of specific biogenic sedimentary structures observed in box cores. These are X-ray radiographs where mud is black, sand is white, and sandy mud is a mottled grey. See text for description of traces.

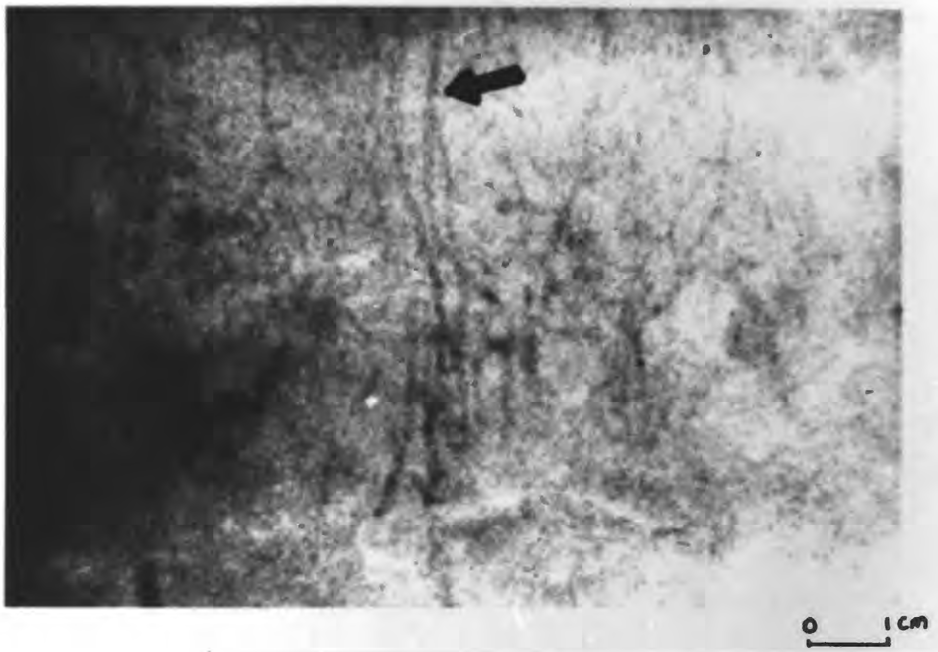
A



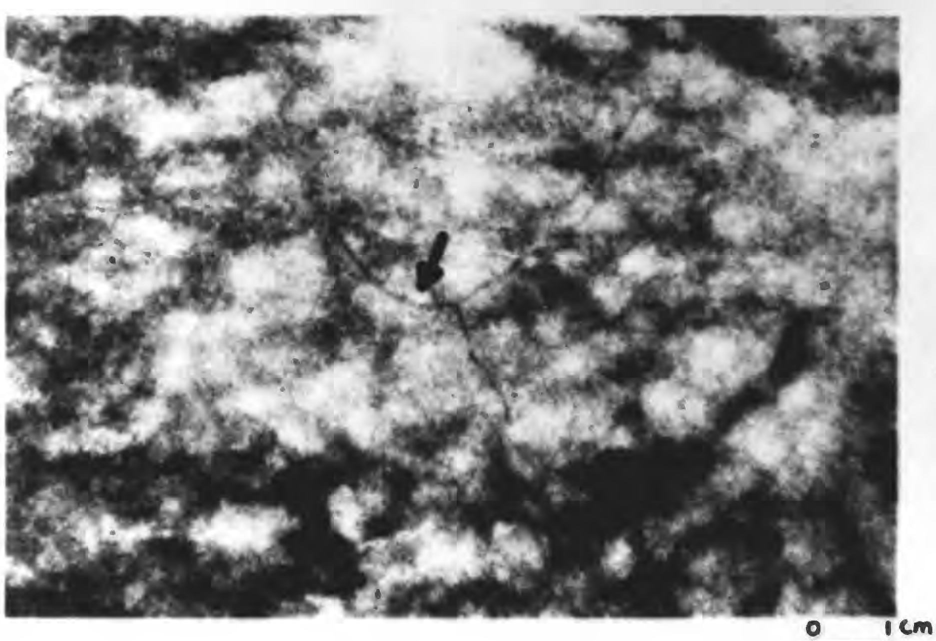

B



D




E



F

Fig. 36. Fiberglass cast of _Callianassa_ burrow showing (A) overall burrow configuration and (B) "turn-a-round" (junction of branches).

A

B

Fig. 37. Distribution of *Callianassa* burrow opening in the study area.

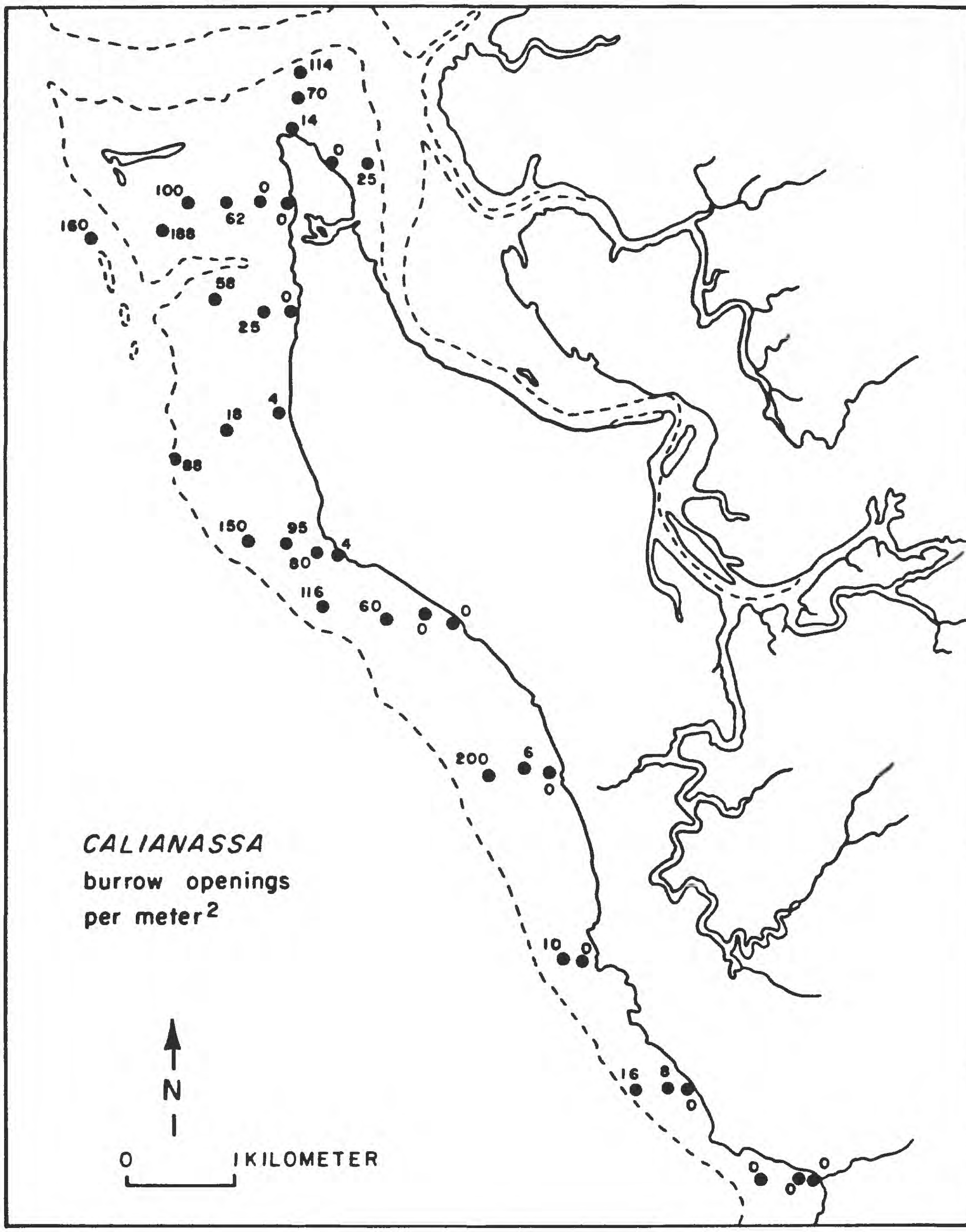
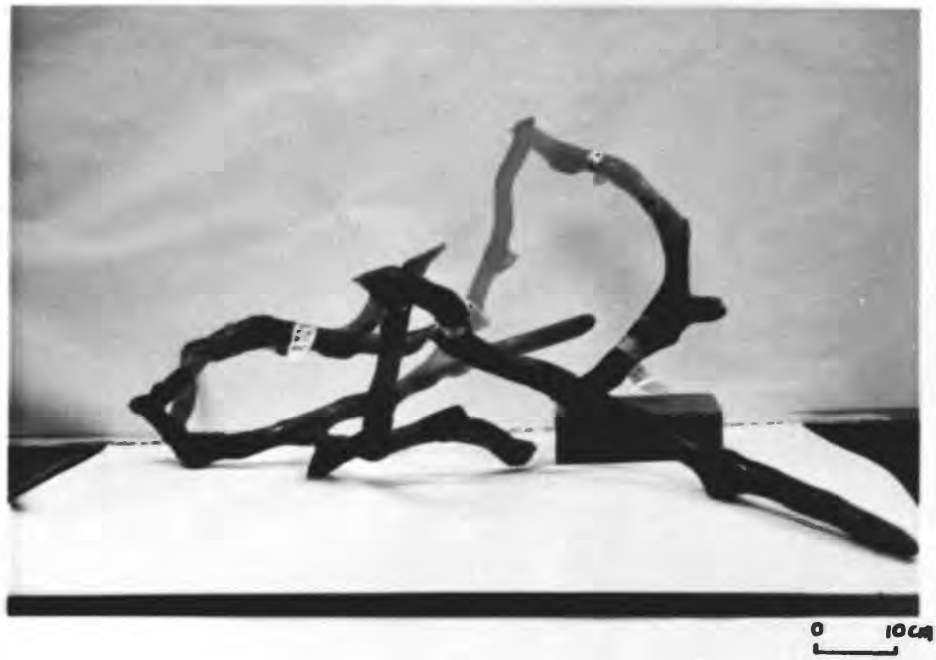

CALIANASSA
burrow openings
per meter²
N
0
1 KILOMETER

Fig. 38. (A) Fiberglass cast of *Upogebia* boring showing configuration. (B) Fossil analog of *Upogebia* boring from Pleistocene terrace deposits adjacent to tidal flats in the study area.

A




B

Fig. 39. Intrastratal trail produced by *Ophelia*. (Photograph courtesy of J. K. Thompson).

Fig. 40. X-ray radiographs of box cores showing root casts produced by (A) *Triglochin* (photograph courtesy of H. E. Clifton) and (B) *Zostera*.

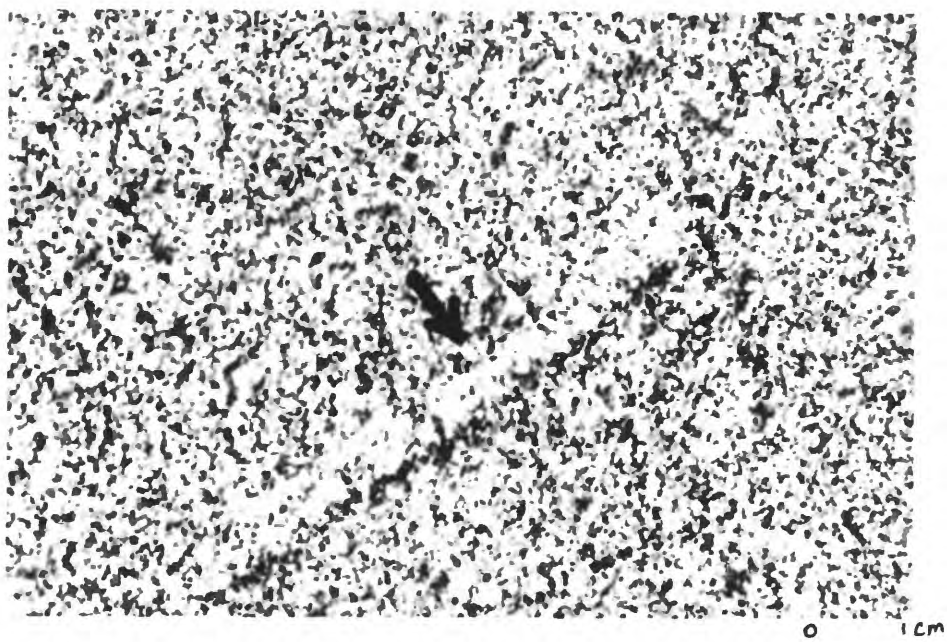

0
1 cm

Fig. 41. Fiberglass cast of _Saccoglossus_ burrow from sandy intertidal flat.

A

B