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GEOLOGICAL SURVEY

COMPOSITION OF TIDAL FLAT SEDIMENTS, WILLAPA BAY, WASHINGTON

By

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ABSTRACT

The purpose of this study was to characterize the modern sediments of sandy tidal flats in Willapa Bay, Washington based on their composition.

Generally, clay comprises less than five percent of the sediment. Clay content increases upslope and up-estuary. Principal clay minerals are montmorillanite, illite, and chlorite; two clay mineral suites are present: (1) muddy flat suite with clay containing 44% montmorillonite, and (2) sandy flat suite with clay composition of 88% montmorillonite.

Heavy minerals make up approximately four percent of the tidal flat sediment. Distribution of heavy minerals reflect their source with (1) heavy minerals most abundant near the beach on flats to the north where they were eroded out of terrace deposits, and (2) relatively greater heavy mineral concentrations (supplied by the Naselle River) across the entire flat to the south. The composition of the heavy mineral suite is mainly clinopyroxene, orthopyroxene, hornblende, epidote, and opaque minerals. This mineral suite represents several sources including rivers, ocean and ocean beaches, and reworked local Tertiary and Quaternary deposits.

Tidal flat sediments are approximately 90% light minerals, mostly quartz. The light fraction also contains small quantities of lithic fragments, pumice, vegetation, and biogenic shell fragments. Tertiary and Quaternary terrace deposits are the major source of most of the light material.

Fossils make up less than one percent of the bottom sediment. Two foram assemblages are present: (1) a modern shallow-water assemblage characterized by <u>Trochammina inflata,</u> found mainly in muddy flats near rivers, and (2) a relic deep-water assemblage (Eocene to Cretaceous) characterized by such

species as Bathysiphon and Cyclammina found predominantly on the sandy flats. Macrofossils consists of shells of the modern tidal flat mollusc assemblage.

Organic sediments were mostly carbon (1%). The highest concentations of organic carbon are associated with muddy sediments near the Palix River and Pickernell Creek; overall, organic carbon concentration increased up-estuary. C/N ratios are transitional between open marine environments and marsh deposits of estuaries.

INTRODUCTION

As part of a larger investigation into depositional processes and facies characteristics of modern estuarine deposits, a study was made of the tidal flats in Willapa Bay, Washington. The purpose of this paper is to report on that part of the Bay study which characterizes intertidal sediments based on their composition.

Andrews (1965) made the first significant sedimentological study of Willapa Bay. In the last five years, however, several studies by U.S. Geological Survey geologists into modern and ancient environments in or near the Bay have been conducted: examples include Clifton and others, 1976; Hill and Chin, 1979; Luepke and Clifton, 1979; Phillips, 1979; Clifton and Phillips, in preparation. Textural characteristics of intertidal sediments in Willapa Bay are reported on by Hill and Chin (1980).

STUDY AREA

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

Geographic Location

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

Geomorphology

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

Surrounding the Bay on three sides, Willapa Hills reach elevations of 3 to 9 km. These hills are a northwest-trending major anticline and are the southern extension of the Olympic Mountains. The hills are composed of dark gray, coarse- to fine-grained basalt flows and breccia. Included locally are sedimentary beds, altered palagonite beds, and pillow basalts; all these beds are Eocene in age.

Tertiary sedimentary rocks (Eocene to Miocene) flank the Willapa Hills in the central and southern Bay area. These sedimentary beds are consolidated sandstone, shale, and lenses of conglomerate. Origins of these sediments are both continental and marine. Quaternary terrace deposits lie immediately adjacent to Willapa Bay. The deposits consist of silt, sand, and local gravel and conglomerate lenses consolidated to the extent that vertical cliffs are produced by wave action. The upper surface of the terraces is several tens of meters above sea level.

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

The Bay entrance is about 8 km across and generally obstructed by large sandshoals. The main channel runs adjacent to Cape Shoalwater. Over the past hundred years, this channel migrated causing extensive erosion to the north. Willapa Bay has two main channels (Fig. 2). The south channel (Nahcotta), about 29 km long, is protected from open water by the North Beach Peninsula. The other channel, running east from the Bay mouth for approximately 19 km, is the mouth of the Willapa River, the largest tributary flowing into the bay. Water depths in the main channels vary from about 6 to 25 meters; widths range approximately from 90 to 2200 meters. Both channels show a somewhat sinuous configuration which is influenced by the tides.

Intertidal flats rim the shoreline of the Bay. The sediments of the flats range from well sorted sand near the main channels to clay toward the upper reaches of the tide flats. In the southern part of the Bay, tidal flats are muddier due to decreases in water circulation and well-developed salt marshes. Sections of the north Bay also have dense vegetation on the flats.

Climate

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

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

Mean annual precipitation is about 220 cm. Monthly precipitation is least in July/August (4 cm) and greatest in December (38 cm). However, only a few precipitation records are available for the basin with only rare records from higher elevations. The mean annual air temperature varies from approximately 11 °C (July) to 4.5 °C (January). Extreme temperatures are infrequent and of short duration; overall, the moderating influence of the ocean is noticed in the air temperatures of the area. Relatively high humidities (70-85% in winter, 25-70% in summer) result in low water losses to evaporation. The annual evaporation is about 51-63 cm.

Tides, Currents, and Wave Climate

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

The average current velocity during ebb and flood tides is about

2.5 knots. The greatest currents (4-6 knots) occur on the ebb tide at the Bay mouth. Even greater velocities may occur during periods of strong south winds due to the northward flow of the ebbing tide coupled with the wind effects. Waves generated offshore have little effect on the inner Bay because of the protection afforded by North Beach Peninsula. An exception is at the Bay entrance where bottom sediment is intensively reworked by waves. Local winds are the most significant agent generating waves in the inner Bay.

Water Properties

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

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

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

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

Runoff

Willapa Bay receives runoff from about 2400 km^2 of land area (principally the west flank of the Willapa Hills). The major tributaries are:

Willapa River	668 km^2
North River	653 km^2
Naselle River	344 km^2
Smith Creek	174 km^2
Palix River	96 km^2
North Nemah River	88 km^2
Bear River	57 km^2
Cedar Rvier	34 km^2
Middle Nemah River	31 km^2

Each of the other tributaries to the Bay drains an area less than 25 km^2.

Runoff is variable due to seasonal variation in precipitation and lack of snow or other surface storage to maintain summer flow. Runoff during July to September accounts for less than two percent of the average annual runoff. Runoff maps show a large variation in average runoff between tributary basins. For example, average runoff for the North River basin is about 150 cm, whereas it is over 250 cm in the Naselle River basin. Overall, the runoff figures are generally higher than would be anticipated from the available precipitation records.

Sediments

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

The Pacific Ocean supplies most of the sand deposited in the Bay and on the tidal delta at the Bay entrance (Fig. 3). A combination of littoral drift and tides causes extensive erosion along Cape Shoalwater. The eroded sediment is carried onto the tidal delta and into the Bay; in the Bay it is deposited along Toke Spit and Ellen Sands.

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

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

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

Flora and Fauna

Flora

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

Fauna

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

METHODS

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

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 (-1 to 4 Ø) obtained during textural analysis (Hill and Chin, 1980). This subsample was separated into heavy and light fractions using tetrabromoethane (specific gravity: 2.92-2.94). Both mineral fractions were weighed and slide mounted for petrographic analysis. For heavy minerals, a 300 to 600 point count was used due to the large amount of opaque minerals, whereas a 100 point count was used for the light minerals.

Clay Minerals

Clay mineral samples were obtained from original, unanalysed surface samples. A small representative sample was taken and run through an ultrasonic disperser. Sediment in suspension was then poured off and centrifuged to separate 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. Quantitative calculations were then made after all x-rays had been completed. Due to logistic problems in the lab, only six samples could be analyzed to date.

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 of organic carbon, total nitrogen, and organic nitrogen.

Paleontology

For micropaleontology analysis, a subsample of the sand fraction 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 obtained through a 0.5 mm mesh sieve. Macrofossils were collected from the sieves and identified.

Mapping

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

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

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

$$\frac{\text{distance along straight shorelines from harbor to intercept}}{\text{distance along straight shorelines from harbor to Pickernell Ck.}}$$

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

DISCUSSION OF RESULTS

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 (less than 3.9 μm) detritus is shown by figure 5. Percentage of clay in bottom sediments at individual stations range from 0.3% to 7.1% (Hill and Chin, 1980). Clay content increases upslope and up-estuary with major concentrations (greater than 10 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 1. The principal clay minerals are montmorillonite, illite, and chlorite. Areal distribution of montmorillonite is shown in figure 6. 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 composition 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.

Heavy Minerals

Distribution: The percentages of heavy minerals in each sample are tabulated in Table 2 and the areal distribution shown in figure 7. 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 high on the tidal flat near the vertical cliffs. To the south, relatively high percentages of heavy minerals (greater than 4%) occur across the entire intertidal 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 channel sediments in Willapa Bay, he found an increase in abundance of heavy minerals in the Nahcotta Channel and attributed this to sediment supplied by the Naselle River. The abundance of heavy minerals on the flats south of Sandy Point could be explained, therefore, as (1) being closer to the source area (i.e., Naselle River), and (2) being distributed across the entire flat due to tidal action.

Composition: Mineralogical analysis of all samples show that opaque minerals composed 6 to 40% of the heavy fraction in the 2-4 Ø size range; average value 23% (Table 3). 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 minerals in 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 4). 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 heavy minerals but a proportionately greater amount of the lighter minerals.

Light Minerals

Distribution: Tidal flat samples consist of 88-99% material with a specific gravity less than 2.92 (= light fraction). Most samples (89%) had a light mineral fraction equal to or greater than 95% of the total composition (Table 2). The average light fraction content is 96.4%.

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

Composition: Analysis of the light fraction was conducted for all bottom samples. The average compositon 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 5). 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. The composition of the terrace deposits along the study area is mainly siliceous sand (Clifton and Phillips, 1978) although significant mud beds do occur. As discussed earlier, other 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; diatoms and ostracods are relatively rare. Only the forams were identified for this study; results are tabulated in Table 6.

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 modern assemblage consists of *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; 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 were represented by individuals that were 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 exception of the oyster *Ostrea lurida* which thrives 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 occasionally become incorporated into the tidal flat deposits. Large logs are preserved in the terrace deposits; however, they are mainly in channel deposits.

Organic Geochemistry

Carbon

The concentration (ppm) of total carbon, organic carbon, and carbonate carbon for each sample is given in Table 7, the areal distribution and isopleth map of organic carbon is shown in figures 8 and 9A respectively. Organic carbon concentrations ranged from 1.15% (11450 ppm) to 0.08% (800 ppm), the average was 0.3% (3122 ppm).

The greatest concentration of organic carbon is on the tidal flat adjacent to the Palix River and Pickernell Creek with organic carbon concentrations generally greater than 2500 ppm (Figs. 8 and 9A). Relatively low concentrations (less than 1500 ppm) of organic carbon are generally restricted to the upper tidal 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. 10). 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. 10).

The distribution pattern of organic carbon within the study area reflects the relation of organic carbon to hydraulics. The Palix River and Pickernell Creek supply 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 (Hill and Chin, 1980). Even though substantial organic material is produced locally on the sandy flats (e.g., macrobenthic infauna and marine grasses), tidal currents and 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 7 and the distribution of organic nitrogen is shown in figures 11 and 9B. Concentrations of organic nitrogen ranged from 6 ppm to 1563 ppm with an average value of 280 ppm. Most of the nitrogen is organic (Table 7).

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

As the sediment becomes muddier, the total nitrogen content increases (Fig. 12). This relationship is similar to that observed for grain size versus organic carbon (Fig. 10). A correlation exists between organic carbon and total nitrogen; as organic carbon increases so does organic nitrogen (Fig. 13). However, concentration of organic carbon is on the average several times greater than total nitrogen. 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 7; distribution of ratios in the study area is shown in Figure 14; isopleth map of C/N ratios is figure 9C. 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 commonly to characterize and identify different types of organic matter. For example, higher plant forms characteristic 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 ranges from 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) average C/N ratio of 6.1 associated with coarser channel sediments.

C/N ratios on the sandy tidal flats are in the range of Scholl's (1963) values for shelf deposits. They are intermediate relative to Andrews (1965) data (i.e., values lie between those for marine influenced channels and fresh-water 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.

CONCLUSIONS

Compositionally, the tidal flat within the study area is composed predominantly of quartz sand (approximately 90%); subordinate fractions include other light minerals, heavy minerals, clay minerals, fossils, 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, while 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 freshwater sources, 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 a mixing of material eroded from the terrace deposits and finer material supplied by the rivers. In comparison, the dominant 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 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 a greater diversity of modern brackish-water forams, and contain significantly more organic matter. Distribution of sediment components reflect increasing contribution of freshwater sources up-estuary to tidal flats near the Palix River and Pickernell Creek. Upslope trends are weak or nonexistent for most materials.

Sediment composition suggests the major sediment source for the sandy flats is the Tertiary and Quaternary terrace deposits. Evidence for this includes (1) reduced amounts of "modern" clays and organic material, and (2) "relic" mineral (clay, heavy, and light) suites and foram assemblages derived from adjacent terrace deposits.

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REFERENCES CITED

Andrews, R. S., 1965, Modern sediments of Willapa Bay, Washington: a coastal plain estuary: Univ. Washington Dept. Ocean. Tech. Rep. No. 118, 43 p.

Anima, R. J., 1979, Sedimentation and processes of a sandy intertidal runoff channel in Willapa Bay, Washington: Univ. Calif. Santa Cruz Senior Thesis, 79 p.

Ballard, R. C., 1964, Distribution of beach sediment near the Columbia River: Univ. Washington Dept. Ocean. Tech. Rep. No. 98, 82 p.

Clifton, H. E., and Phillips, R. L., 1978, Walking guide to Willapa Bay, Washington: U.S.G.S. Geologic Div., Office of Marine Geology Rep., unpublished.

Clifton, H. E., and Phillips, R. L., 1980, Lateral trends and vertical sequences in estuarine sediments, Willapa Bay, Washington: Quaternary Depositional Enviroments of the Pacific Coast, Pacific Coast Paleogeographic Syposium 4, SEPM, p. 55-71.

Clifton, H. E., Phillips, R. L., and Scheihing, J. E., 1976, Modern and ancient estuarine-fill facies, Willapa Bay, Washington (abs.): AAPG-SEPM Ann. Mtg. Prog., Abst., p. 50-51.

Cooper, W. S., 1958, Coastal sand dunes of Oregon and Washington Geol. Soc. Am. Mem. No. 72, 169 p.

Garrett, A. A., Haushild, W. L., Kennedy, V. C., Laird, L. B., Richardson, D., and Rorabaugh, M. I., 1962, Evaluation of Willapa Bay as a site for marine hydrology investigations: unpublished U.S.G.S. Water Resources Div. Rep., 15 p.

Gross, M. G., Carey, A. G., Jr., Fowler, G. A., and Kulm, L. D., 1972, Distribution of organic carbon in surface sediment, northeast Pacific Ocean, in Pruter, A. T., and Alverson, D. L., eds., The Columbia River estuary and adjacent ocean waters: Seattle, Univ. Washington Press, p. 254-264.

Hill, G. W., and Chin, J. L., 1979, Graphic display of box cores collected from tidal flats in Willapa Bay, Washington: U.S.G.S. Open File Rep. No. 79-1501.

Hill, G. W., and Chin, J. L., 1980, Tidal flat sediments - texture, Willapa Bay, Washington: U.S.G.S. Open File Rept., in review.

Luepke, G., and Clifton, H. E., 1979, Heavy minerals as indicators of source and depositional environments in Willapa Bay, Washington (abs.): Geol. Soc. America Abstracts with Programs, v. 11, no. 7, p. 89.

Muller, P. J., 1977, C/N ratios in Pacific deep-sea sediments: Effect of inorganic ammonium and organic nitrogen compounds sorbed by clays: Geochim. Cosmochim. Acta, v. 41, p. 765-776.

Parker, F. L., and Athearn, W. D., 1959, Ecology of marsh Foraminifera in Poponesset Bay, Massachusetts: J. Paleontol., v. 33, no. 2, p. 333-343.

Phillips, R. L., 1979, Bedforms and processes on an estuarine tidal current ridge, Willapa Bay, Washington (abs.): Am. Assoc. Petroleum Geologists Bull., v. 63, no. 3, p. 509.

Pinet, P. R., and Frey, R. W., 1977, Organic carbon in surface sands seaward of Altamaha and Doboy Sounds, Georgia: Geol. Soc. Am. Bull., v. 8, p. 1731-1739.

Sayce, C. S., 1976, The oyster industry of Willapa Bay: Proc. Sym. on Terrestrial and Aquatic Ecol. Studies of the Northwest: East. Washington State College Press, Cheney, Washington, p. 347-356.

Scholl, D. W., 1963, Sedimentation in modern coastal swamps, Southwestern Florida: Bull. Am. Assoc. Petrol. Geologists, v. 47, no. 8, p. 1581-1603.

Trask, P. D., 1932, Origin and environment of source sediments of petroleum: Houston, Texas, Gulf Pub. Co., 323 p.

Vinogradov, A. P., 1953, The elementary chemical components of marine organisms: Mem. Sears Found. Mar. Res. II.

Waters, A. C., 1962, Basalt magma types and their tectonic associations: Pacific Northwest of the United States, in MacDonald, G. A., and Kuno, H., eds., The crust of the Pacific Basin: Washington, D. C., Am. Geophys. Univ. Monogr. 6, p. 158-170.

Table 1. 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 2. 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 3. 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 4. 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 5. 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 6. 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 7. 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%

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

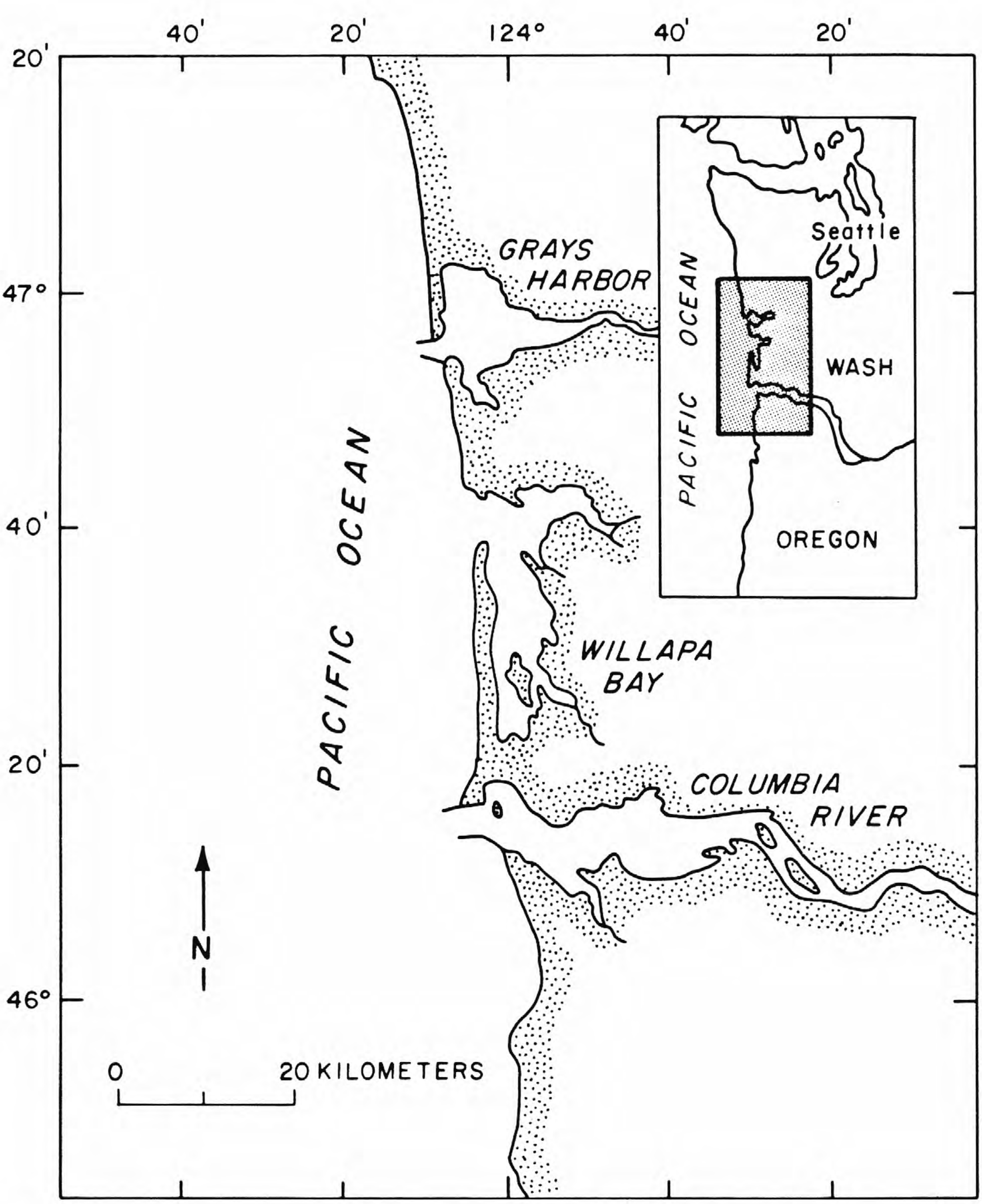
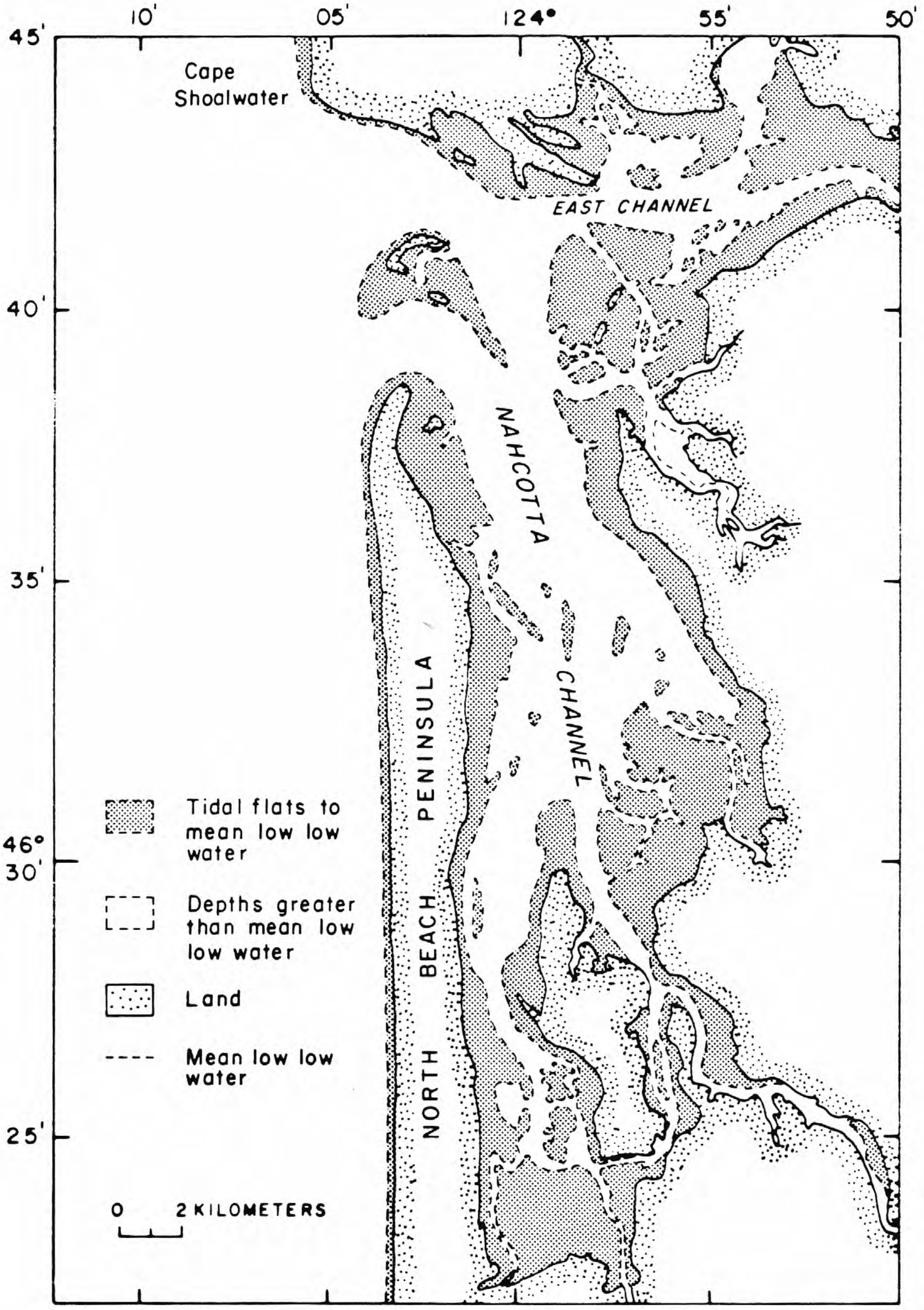
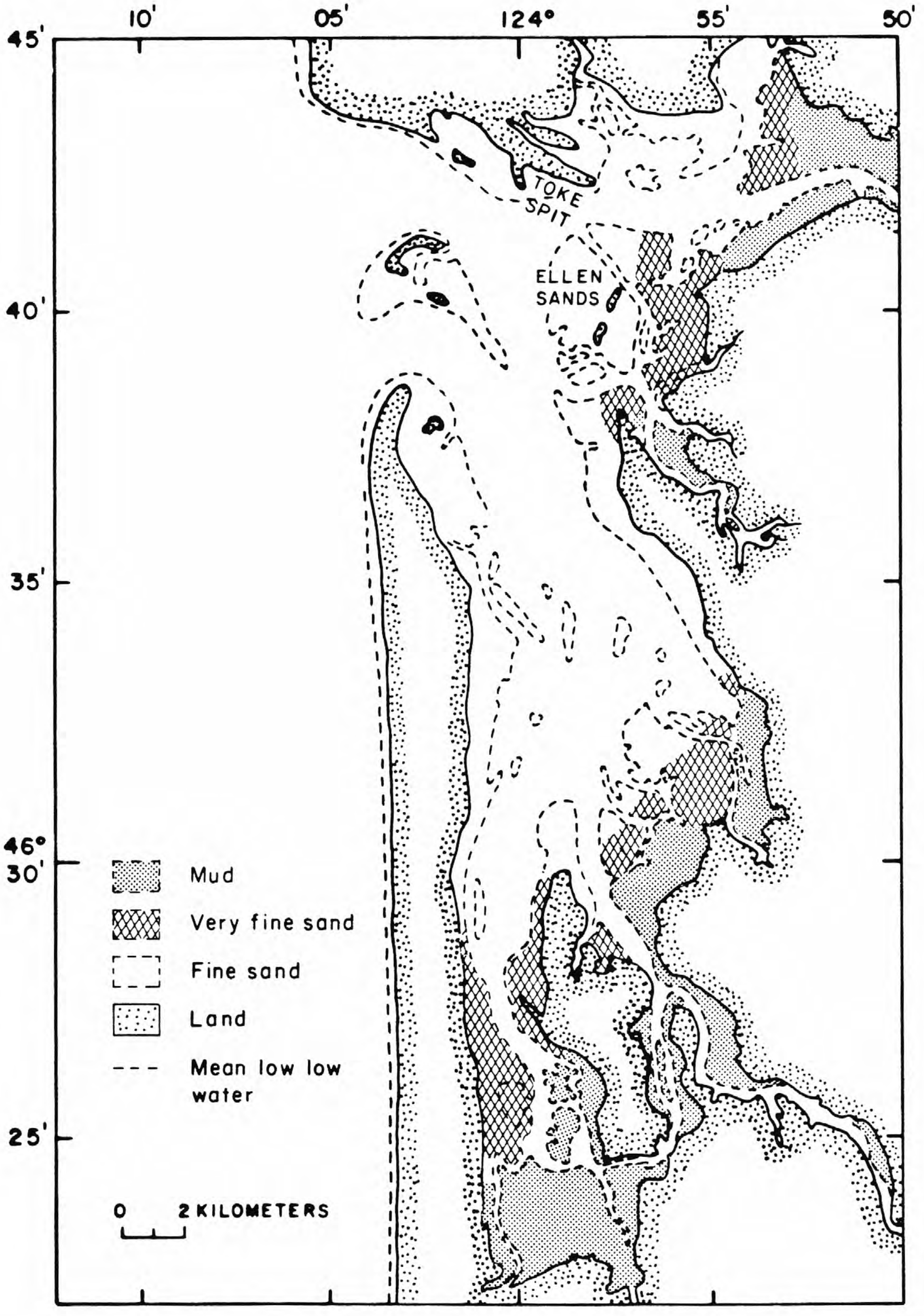

40'
20'
124°
40'
20'
20'
47°
40'
20'
46°
GRAYS
HARBOR
PACIFIC OCEAN
WILLAPA
BAY
COLUMBIA
RIVER
N
0
20 KILOMETERS
Seattle
WASH
OREGON
PACIFIC OCEAN

Fig. 2. Bathymetry of Willapa Bay, Washington.



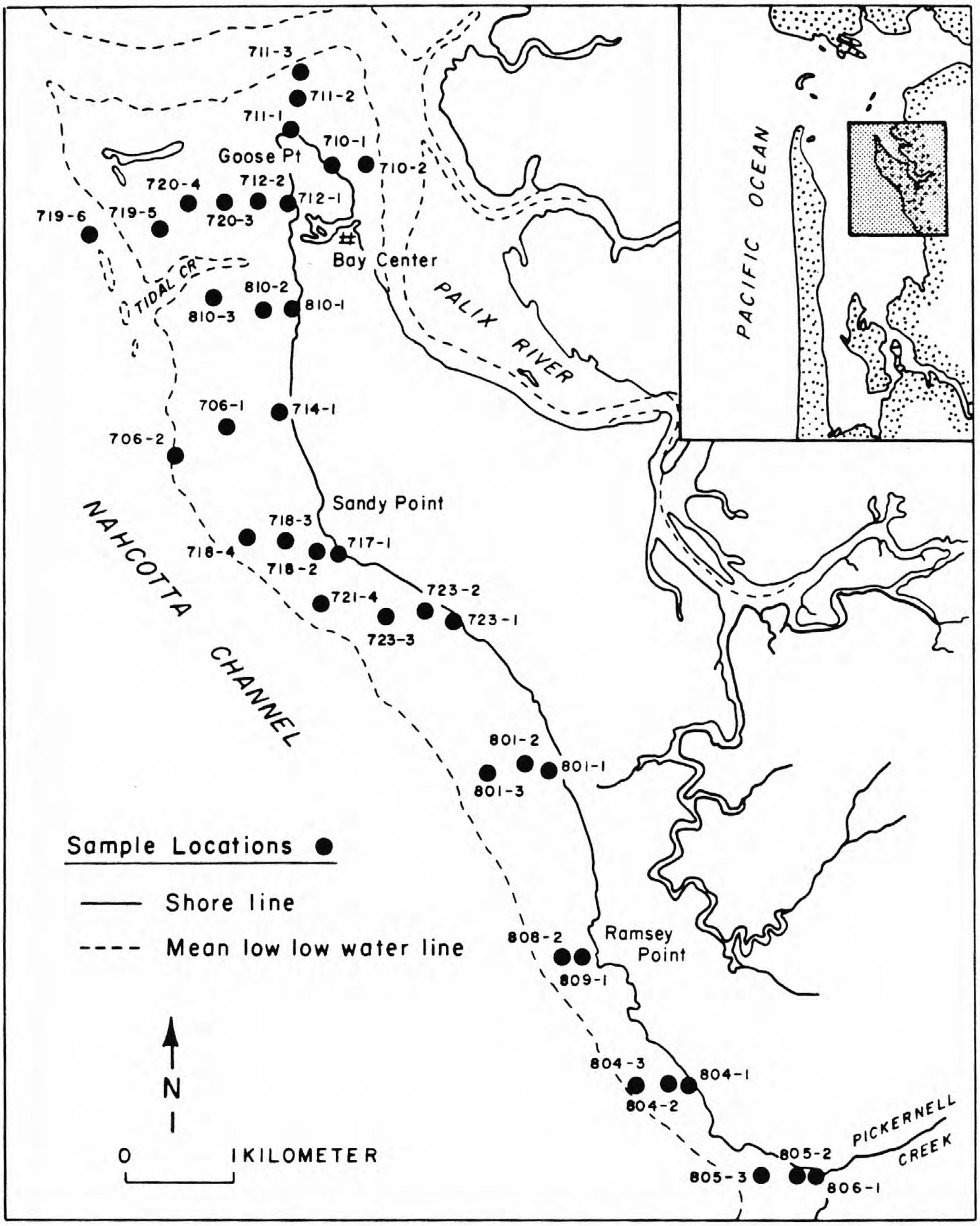
10'
05'
124°
55'
50'
45'
40'
35'
46°
30'
25'
Cape
Shoalwater
EAST CHANNEL
NAHCOTTA
CHANNEL
NORTH BEACH PENINSULA
Tidal flats to mean low low water
Depths greater than mean low low water
Land
Mean low low water
0 2 KILOMETERS

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



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

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



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

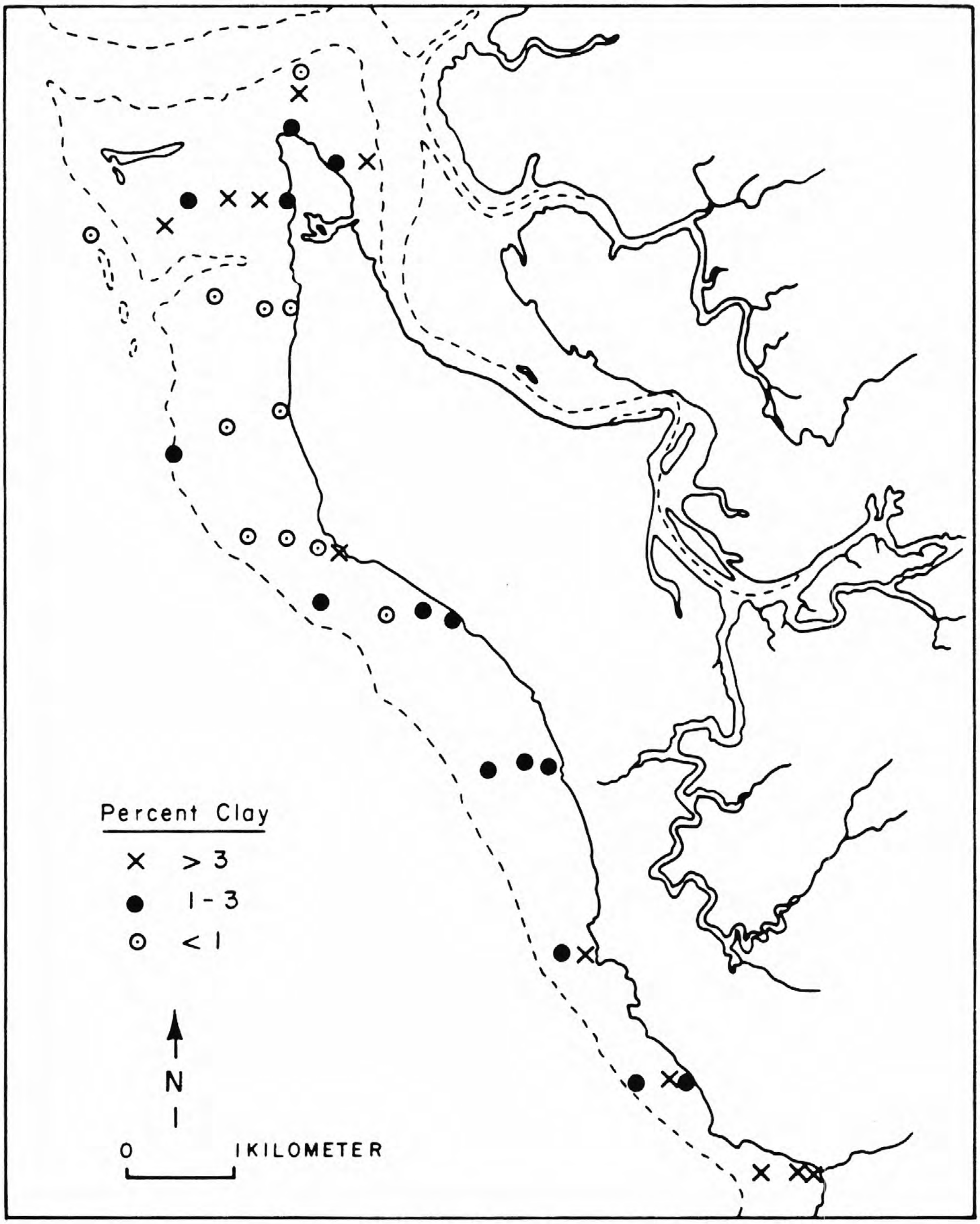

Percent Clay
> 3
1 - 3
< 1
N
0
1 KILOMETER

Fig. 6. Distribution of montmorillonite in study area.

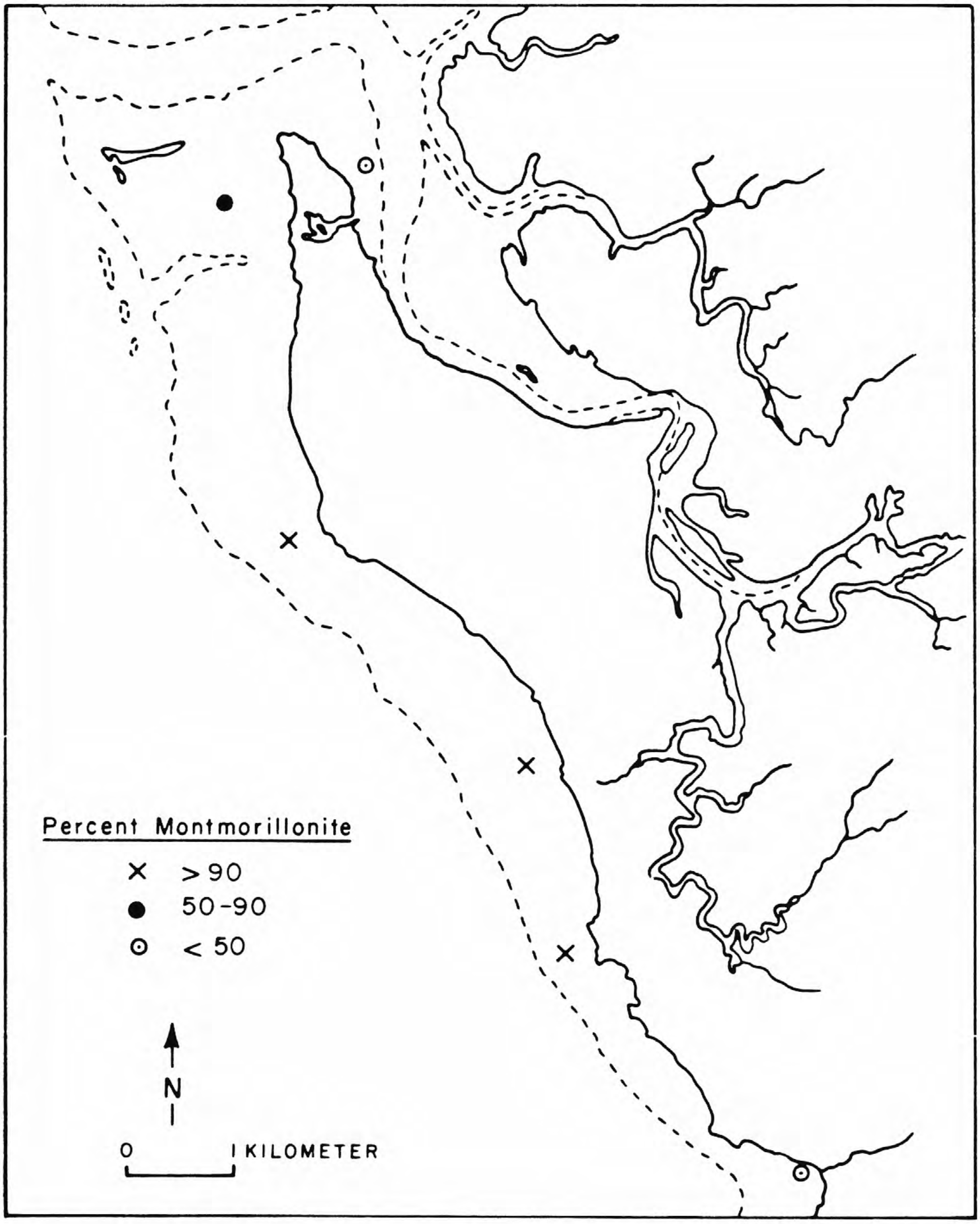

Percent Montmorillonite
× >90
● 50-90
⊙ <50
N
0 1 KILOMETER

Fig. 7. Distribution of heavy minerals in study area.

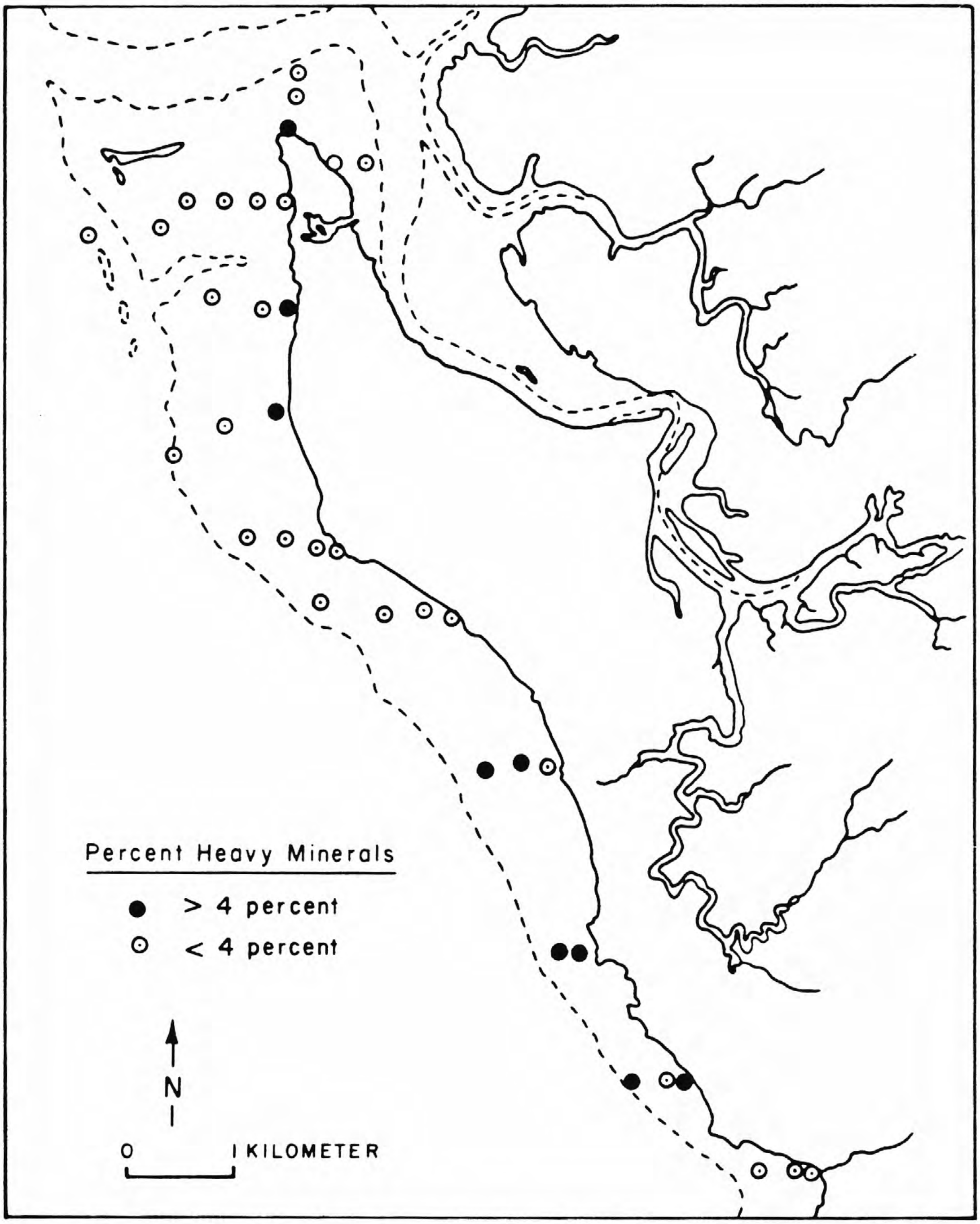

Percent Heavy Minerals
> 4 percent
< 4 percent
N
0
1 KILOMETER

Fig. 8. Distribution of organic carbon in study area.

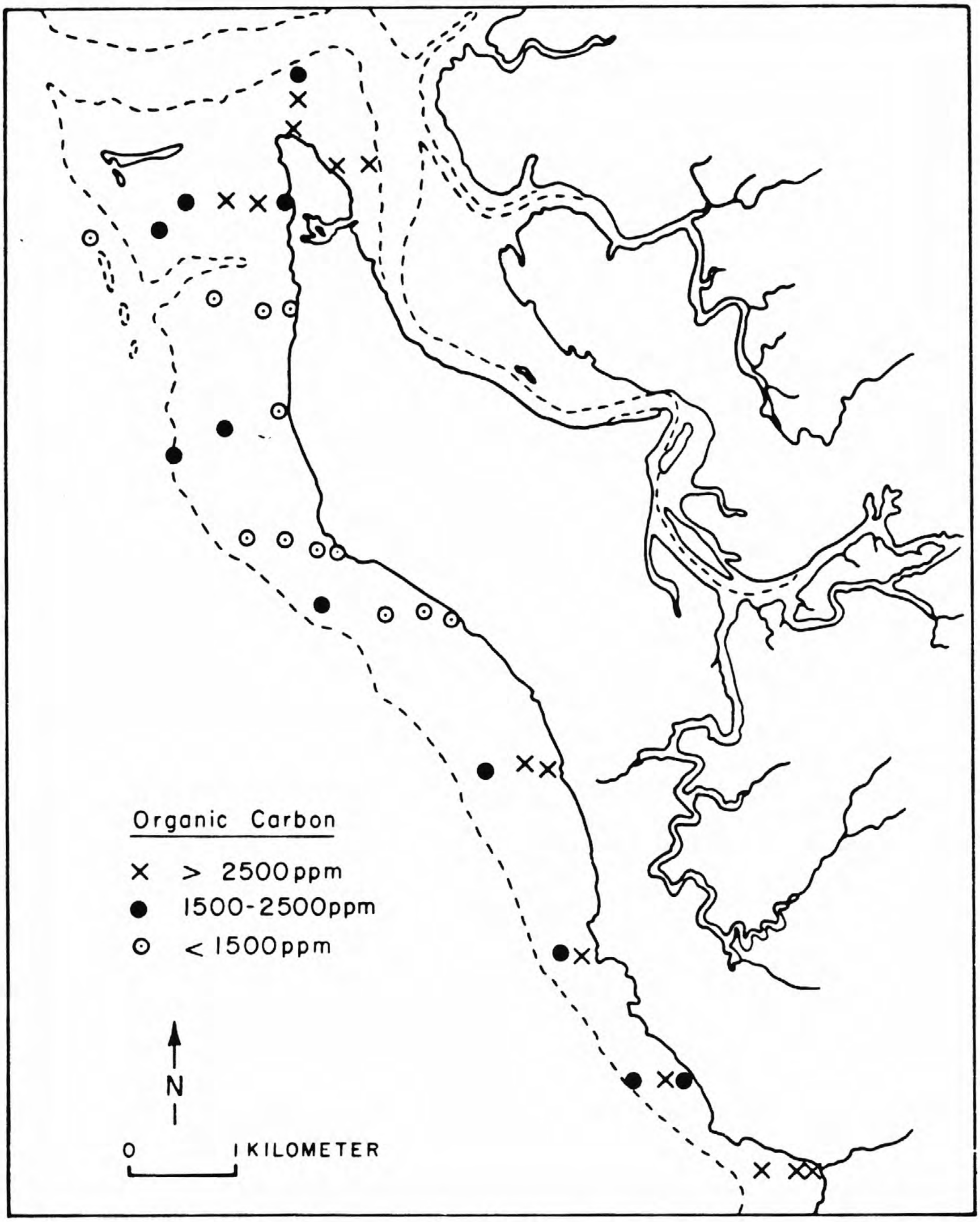
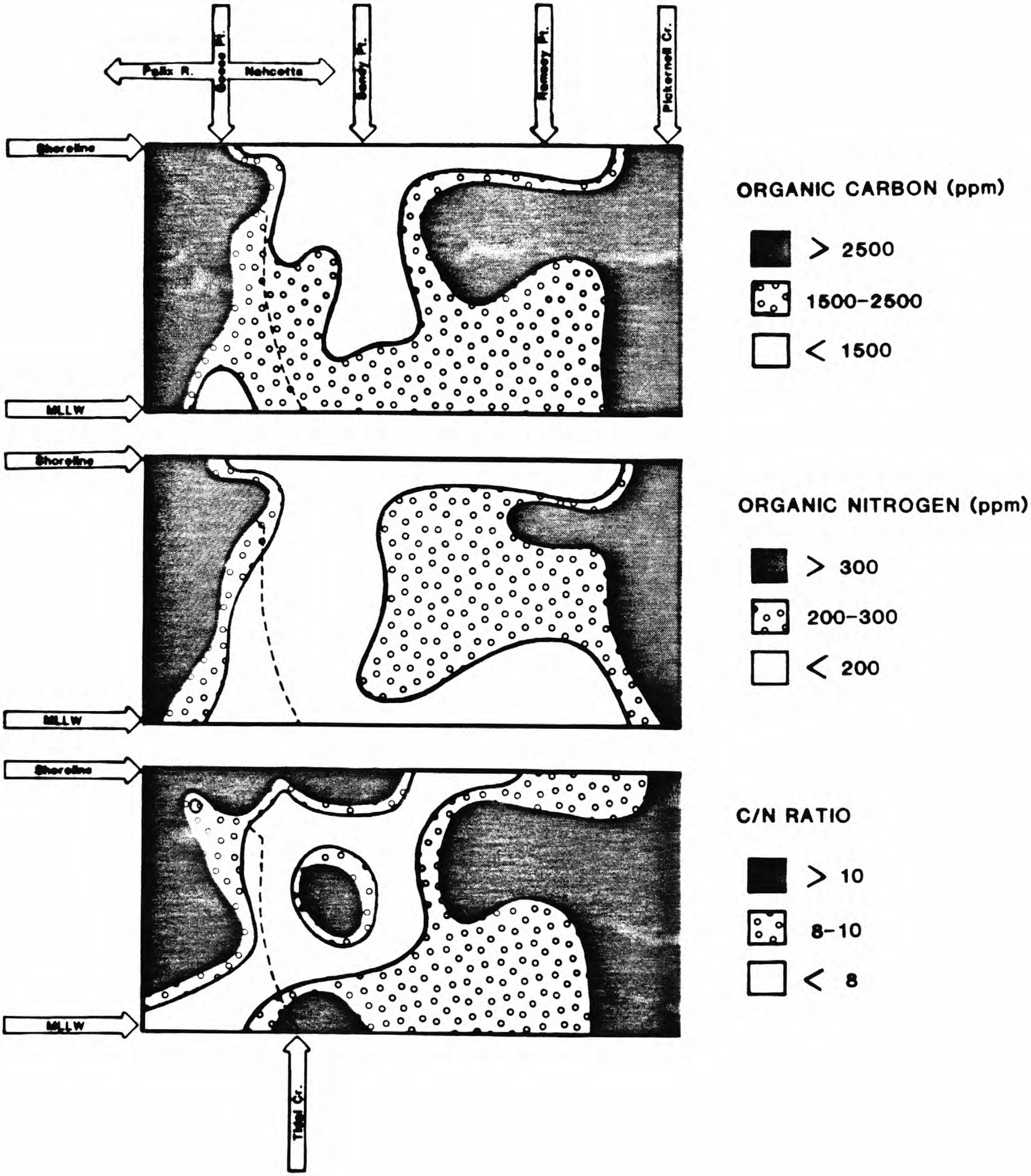
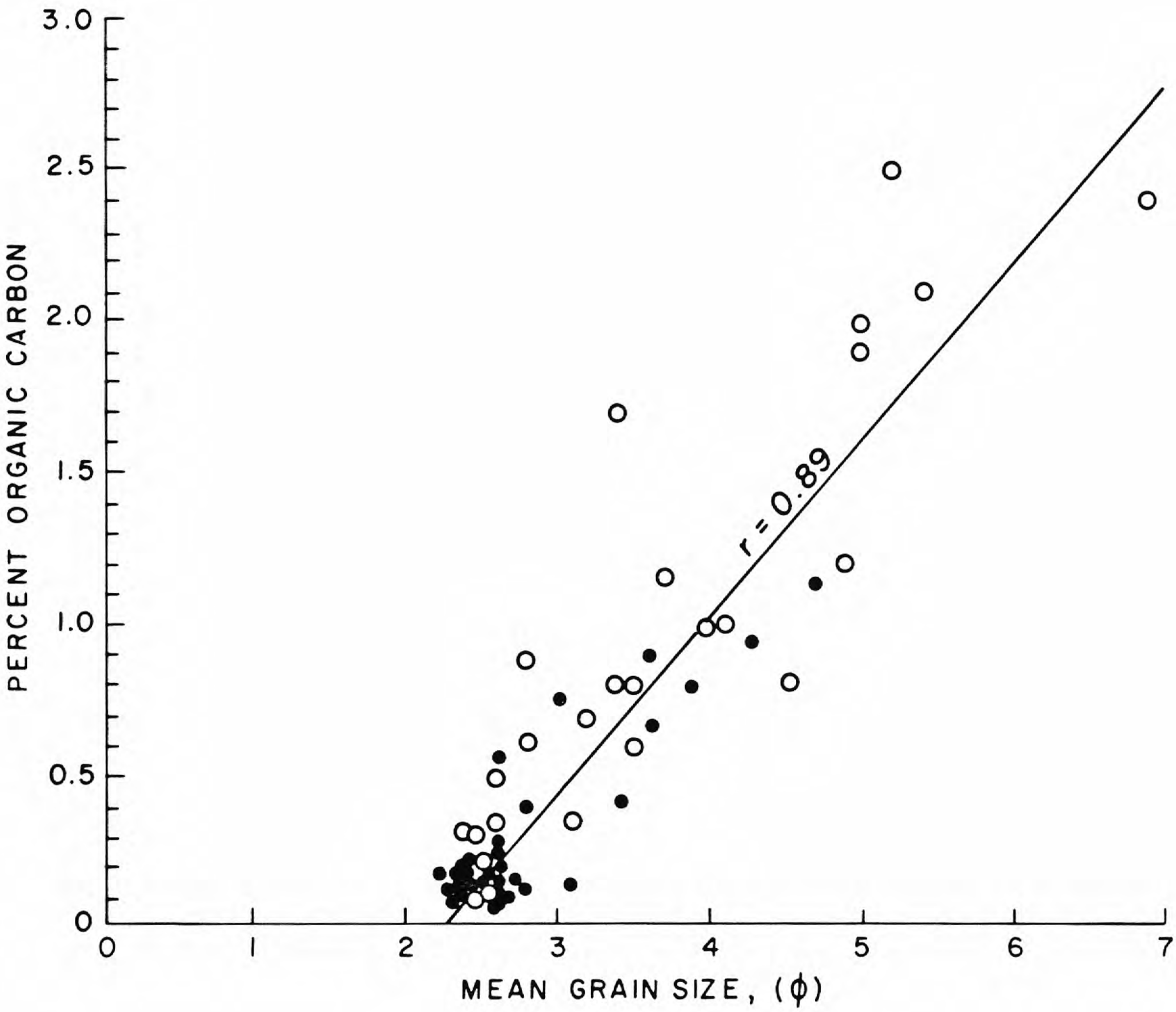

Organic Carbon
× > 2500 ppm
● 1500-2500 ppm
⊙ < 1500 ppm
N
0 1 KILOMETER

Fig. 9. Isopleth maps showing distribution of (A) organic carbon, (B) organic nitrogen, and (C) C/N ratios.



Palix R.
Goose Pt.
Nahcotta
Sandy Pt.
Ramsey Pt.
Pickernell Cr.
Shoreline
MLLW
ORGANIC CARBON (ppm)
> 2500
1500-2500
< 1500
Shoreline
MLLW
ORGANIC NITROGEN (ppm)
> 300
200-300
< 200
Shoreline
MLLW
C/N RATIO
> 10
8-10
< 8
Tidal Cr.

Fig. 10. Percentage of organic carbon as a function of mean grain size.



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

Fig. 11. Distribution of organic nitrogen in study area.

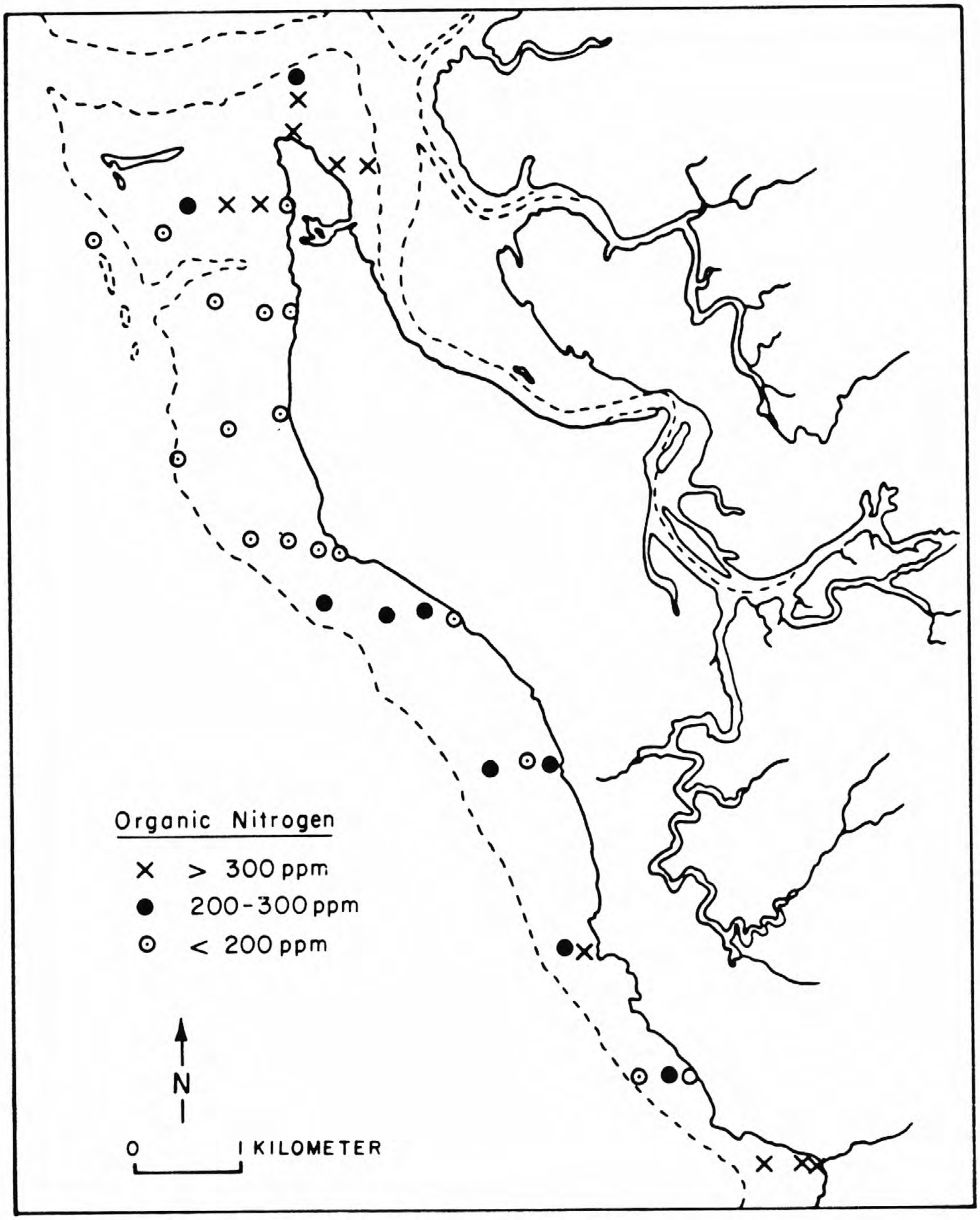

Organic Nitrogen
× > 300 ppm
● 200-300 ppm
⊙ < 200 ppm
N
0 1 KILOMETER

Fig. 12. Percentage of organic nitrogen as a function of mean grain size.

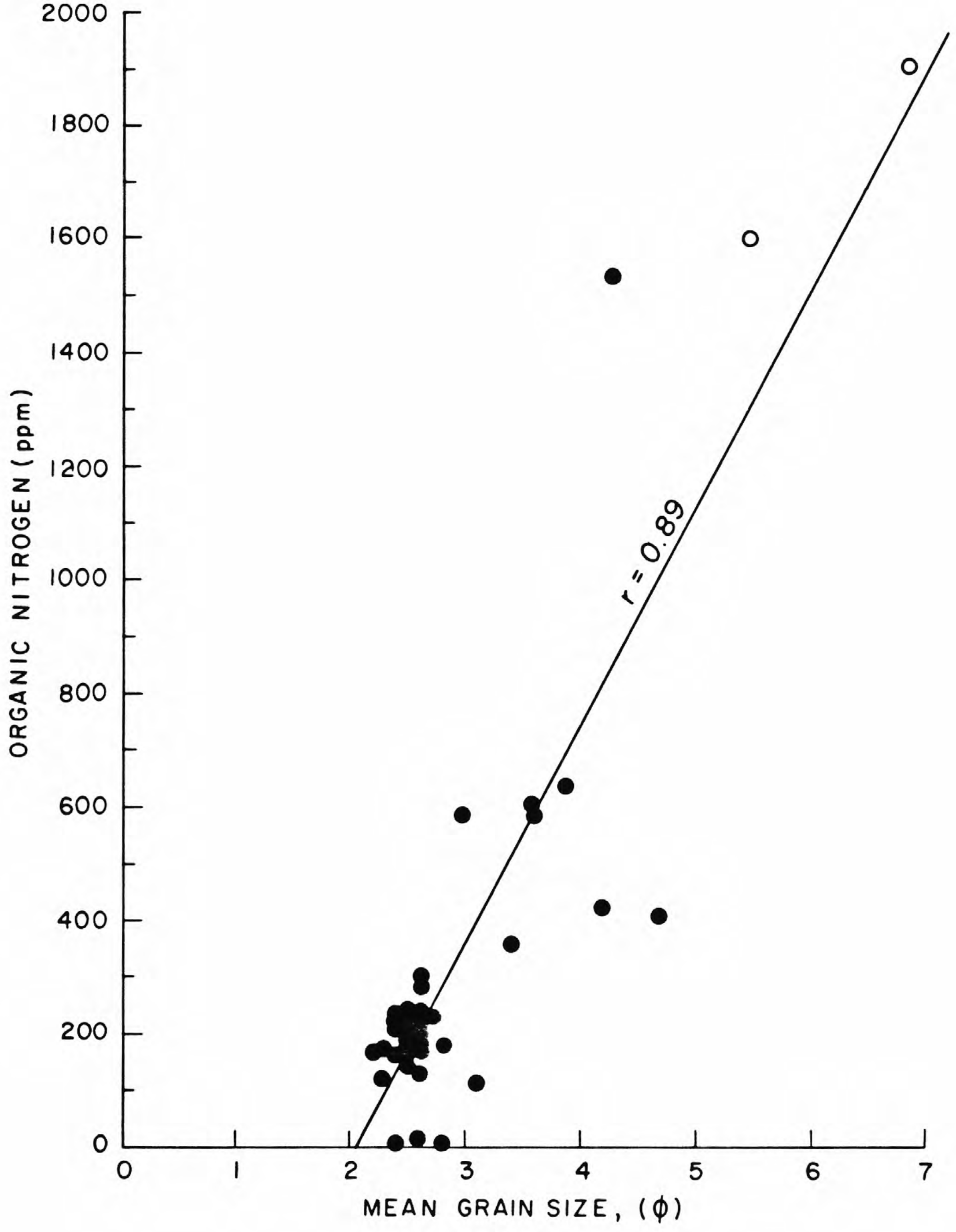

ORGANIC NITROGEN (ppm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
MEAN GRAIN SIZE, (ϕ)
r = 0.89

Fig. 13. Percentage organic carbon as a function of percentage organic nitrogen.

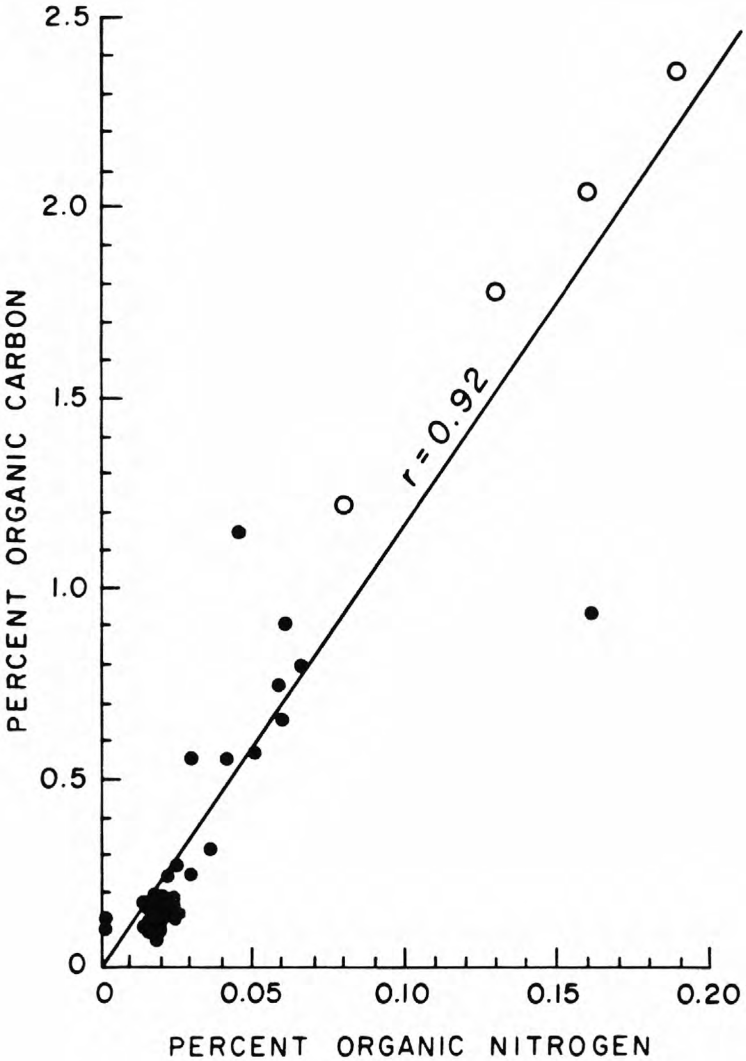
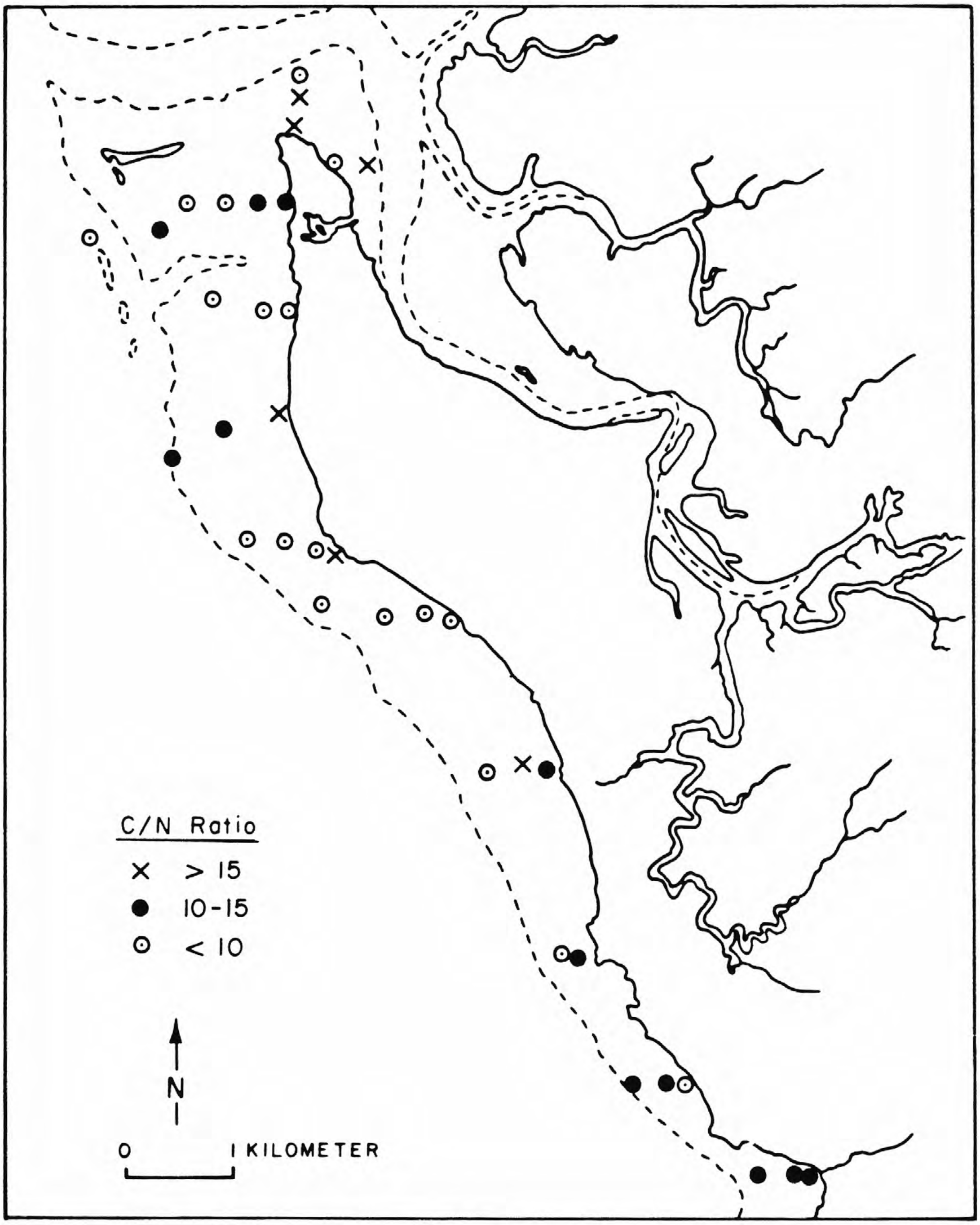

2.5
2.0
1.5
1.0
0.5
0
PERCENT ORGANIC CARBON
r=0.92
0
0.05
0.10
0.15
0.20
PERCENT ORGANIC NITROGEN

Fig. 14. Distribution of C/N ratios in the study area.


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