

**Report for the
Tillamook Bay National Estuary Project**

**SEDIMENT ACCUMULATION IN
TILLAMOOK BAY, OREGON, A LARGE
DROWNED-RIVER ESTUARY**

Paul D. Komar

*College of Oceanic & Atmospheric Sciences
Oregon State University
Corvallis, Oregon 97331*

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SUMMARY

Tillamook Bay is a drowned-river estuary that formed about 9,000 years ago when the rising level of the sea inundated the lower reaches of the Trask, Wilson, Tillamook, Kilchis and Miami Rivers. The Bay is separated from the ocean by Bayocean Spit, except for the natural inlet that permits an exchange of water and sediment with the ocean. The Bay experiences the full range of estuarine circulation patterns from well stratified to well mixed, depending on the season and variations in river discharge. The watersheds of the rivers have been affected by human activities, including the occurrence of major forest fires, the draining of marshes, and the construction of dikes and levees, activities that altered river discharges and sediment delivery to the Bay. The inlet connecting the Bay with the ocean has been controlled by the construction of jetties, the primary significance of which is that the north jetty caused extensive erosion of Bayocean Spit, leading to its breaching in 1952 and the transport of over one million cubic meters of sand into the Bay during the four years the breach remained open. There have been only limited studies of the sediments in Tillamook Bay, with one investigation providing partial documentation of mineralogical compositions and grain sizes of surface sediments, while a second study focused primarily on the early history of sediment accumulation within the Bay soon after its formation. These studies were not sufficiently detailed to document the effects of human activities on Bay sedimentation, or to establish whether there has been accelerated rates of sediment accumulation.

INTRODUCTION

The processes of sediment transport in estuaries are extremely complex, and this can make it difficult to understand the observed patterns of sediment accumulation. The primary sediment input into an estuary generally comes from the river, with the grain sizes potentially ranging from gravel through sand, to fine silt and clay. Another important sediment source is sand carried into the estuary from the marine environment—from the ocean beach—transported into the estuary by tidal currents flowing through the inlet. In some estuaries and bays this marine source of sediment can dominate over the river supply.

Sediments contributed by rivers and the marine source mix within the estuary. This mixing is controlled by the sediment transport resulting from the continued river flow, by reversing tidal currents, and by the particular circulation pattern of water within the estuary. These sediment-transport processes vary hourly to seasonally, depending on the stage of the tide and the discharge of the river. The resulting spatial distribution of sediments within the estuary, their varying grain sizes and compositions, are the result of the long-term integration of these processes.

For a particular estuary it is important to understand the processes of sediment transport and to document the resulting spatial patterns of sediment accumulation. The types of sediments in large part control the locations of biological habitats, with the organisms in turn affecting the properties of the sediments and even the processes of transport. Human activities commonly impact all components of the estuary, activities that include dredging and harbor construction within the estuary itself, and distant activities such as the damming of rivers or deforestation of watersheds that alter sediment delivery to the estuary and affect processes such as the water circulation. Predictions of the resulting alterations of processes and sedimentation within the estuary are based on research that includes a large effort toward field measurements.

The objective of this report is to review the extent of our understanding of sedimentation processes in Tillamook Bay, located on the north coast of Oregon. Tillamook Bay is unusually complex due to the presence of five significant rivers that enter the Bay, rivers whose watersheds have had varying degrees of human impacts. Furthermore, sediment input into the Bay from the marine realm has been important, through the inlet but also when Bayocean Spit breached during 1952 and remained open for

four years. Processes within Tillamook Bay leading to the mixing of the sediments from the several sources are also complex due to the large size of the Bay, a factor that results in a three dimensionality of tidal movements and water-circulation patterns.

This report begins with a review of the physical characteristics of Tillamook Bay and the processes of tides and water-circulation patterns. Also included is information concerning the five major rivers that drain into Tillamook Bay — the seasonality of discharges, the nature of the drainage basins, and how human activities have altered these drainages and the expected delivery of sediment to the Bay. Probably due to its large size, relatively little research has been undertaken in Tillamook Bay to document sediment distributions and transport processes. The thesis research of Avolio (1973) provides partial documentation of surface sediment mineralogical compositions and grain sizes, while the USGS report by Glen (1978) focuses primarily on the early history of sediment accumulation within the Bay during the first several thousand years following formation of the estuary by the Holocene rise in sea level. The report concludes with a summary, together with suggestions for additional research to better understand the sedimentation processes and the possible role of human activities in causing increased rates of sediment accumulation in Tillamook Bay.

CHARACTERISTICS OF TILLAMOOK BAY

Tillamook Bay is located on the north coast of Oregon, 80 km south of the Columbia River. The Bay is approximately 10 km long on its north-south axis, Figure 1, and averages 3.4 km in width, making it the second largest estuary on the Oregon coast (the Columbia River estuary is the largest). The average surface area is approximately 34 km² (8,500 acres), of which 50 to 60% is tideland (Percy et al., 1974). The Bay is shallow, averaging only about 2 m depth.

Tillamook Bay is a drowned-river estuary, formed initially about 9,000 years ago when the rising level of the sea at the end of the Quaternary ice age inundated the lower reaches of the Trask, Wilson, Tillamook, Kilchis and Miami Rivers. It is separated from the ocean by Bayocean Spit, Figure 1, except for the natural inlet at the north end of the Bay that permits an exchange of water and sediment with the ocean.

While being a drowned-river estuary like other estuaries along the Northwest coast, Tillamook Bay is unusual in having several rivers of significance, Figure 2, each of which carries large quantities of fresh water and sediment into the Bay. The characteristics of these rivers and their watersheds are given in Table 1, derived from Percy et al. (1974) who summarized available information for Oregon estuaries based on reviews of previous reports. In total, watersheds draining into Tillamook Bay have a combined area of 1,400 km² (345,000 acres). About 80% of this drainage is accounted for by the three largest rivers (Wilson, Trask and Tillamook), which combine to yield an average annual fresh-water discharge of 3.45×10^{12} m³ (2,203,000 acre-feet). Precipitation over the watershed, Figure 3, ranges from an annual average of 230 cm (90 inches) along the coast to a maximum of 380 cm (150 inches) in the elevated north-central portion of the watershed. Most of this precipitation occurs as rain during the winter months of November through March, and this results in significant increases in river discharge during those months compared with the relatively dry summer. This seasonality in river discharge is illustrated in Figure 4 for the Wilson and Trask Rivers, showing a 10-fold increase from the summer to the winter. Major floods have occurred on the rivers entering Tillamook Bay during 1972, 1964, and most recently during February 1996.

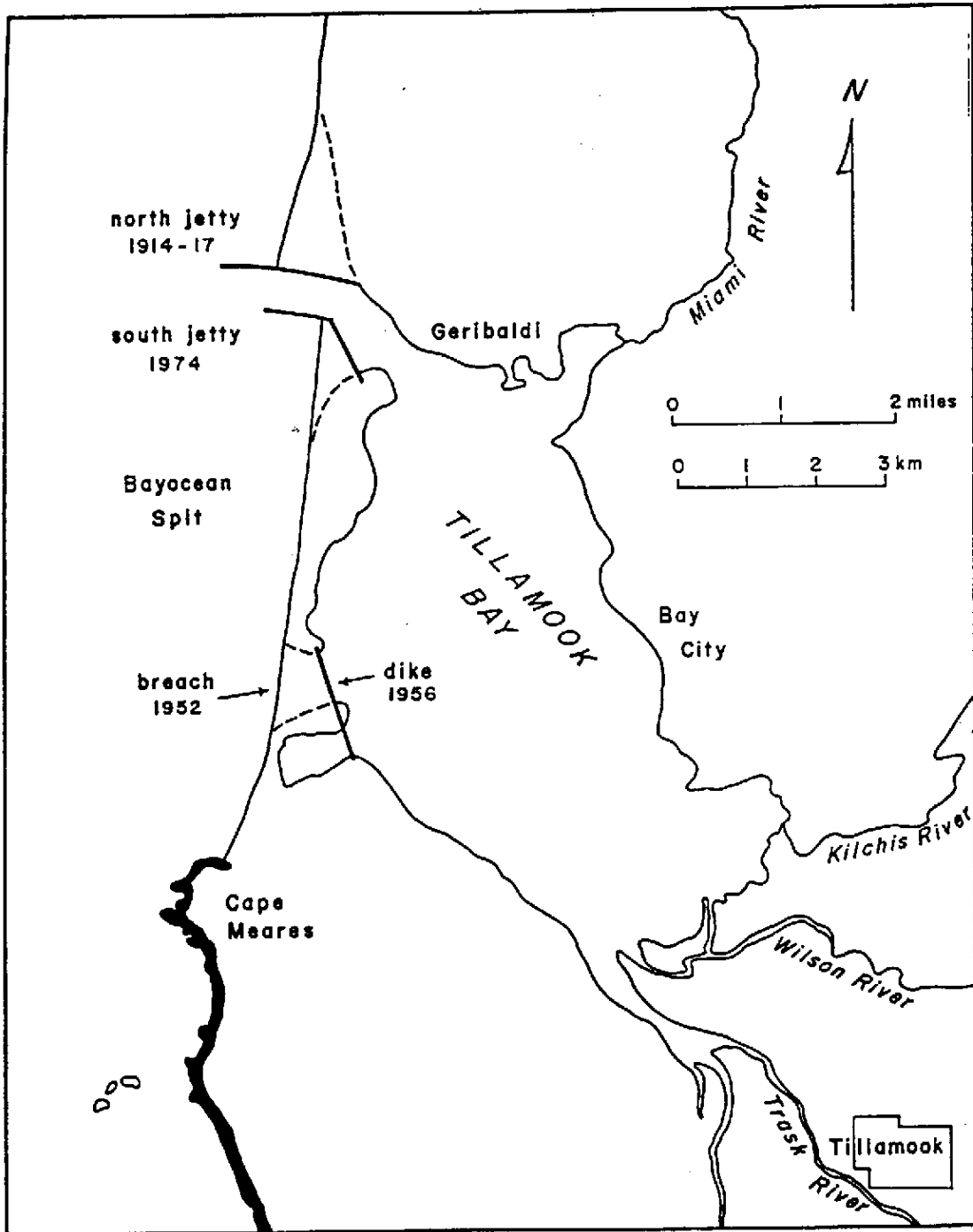


FIGURE 1: Tillamook Bay, separated from the ocean by Bayocean Spit except for the open inlet at the north which is controlled by jetties. Five significant rivers flow into the Bay, with the three largest entering at its southeast corner.

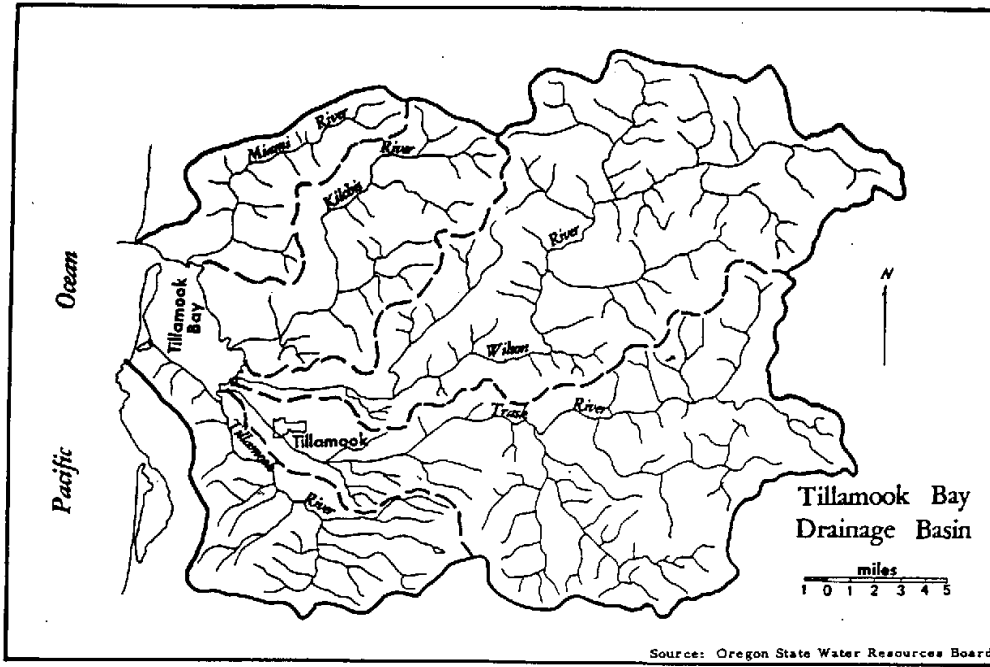


FIGURE 2: Drainage basins of the five rivers that flow into Tillamook Bay. Characteristics of these rivers and their drainage basins are given in Table 1. [Source: Oregon State Water Resources Board]

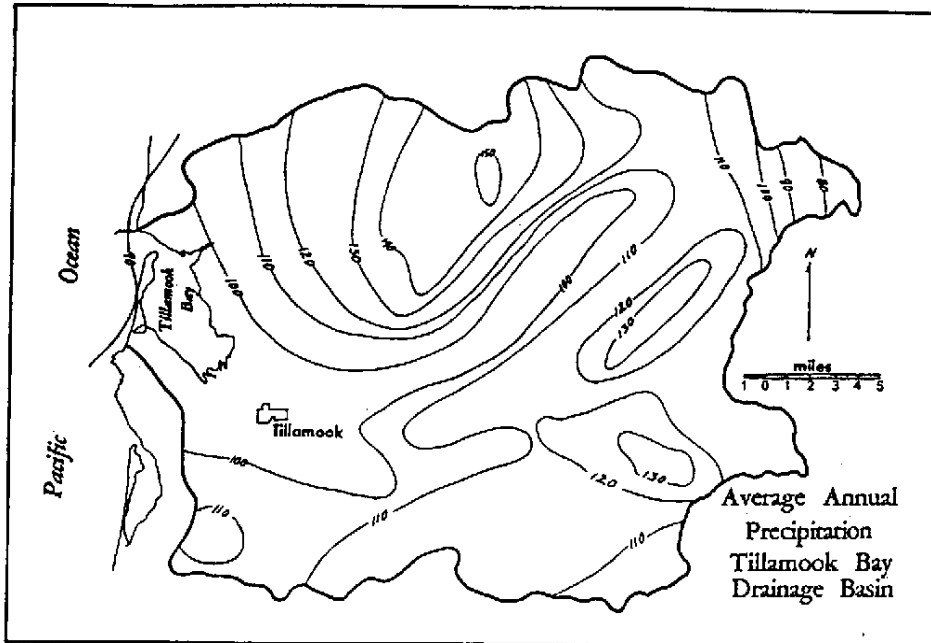


FIGURE 3: Contours of the average annual precipitation in inches over the total drainage basin into Tillamook Bay. [Source: Oregon State Water Resources Board]

TABLE 1: Characteristics of the five significant rivers that flow into Tillamook Bay, with the data derived from the review of Percy et al. (1974).

	River Tidal Reach (km)	Length (km)	Drainage (km ²)	Ave. Annual Water Yield ^a (m ³)
Miami	21.9	93		0.6
Kilchis	22.2 ^b	174		2.1
Wilson	53.4 ^c	500	1.32 x 10 ⁹	2.4
Trask	29.3 ^d	456	1.04 x 10 ⁹	4.2
Tillamook	29.6	158	3.61 x 10 ⁸	7.0

^aEstimated for 1933 to 1958.

^bTo the confluence of the North and South Forks.

^cTo the confluence of Devil's Lake Fork and South Fork.

^dTo the confluence of the North and South Forks.

The watersheds of the rivers have been greatly affected by human activities, with the largest alterations having occurred in the drainages of the three principal rivers that enter the Bay at its southeast corner (Figures 1 and 2). The urban area of Tillamook, with its homes, streets, and shopping centers, has been constructed within the drainages of the Tillamook and Wilson Rivers. The draining of marshes and construction of dikes and levees were undertaken to provide grazing pasturage for the dairy industry. The forest lands within the watersheds of the rivers have been harvested for Douglas fir, hemlock and spruce. A significant impact has been the occurrence of major forest fires, in particular the Tillamook Burns of 1933, 1939, 1945 and 1951 that combined to burn some 1,200 km² (300,000 acres) of forest. It is likely that these various human-induced factors within the river watersheds during the past 200 years have resulted in increased river discharges and rates of sediment delivery to Tillamook Bay.

The mean tidal range in Tillamook Bay is 1.7 m (5.7 ft), with a diurnal range of 2.3 m (7.5 ft) and an extreme tidal range of 4.1 m (13.5 ft). Tidal effects extend up the rivers to various distances from their mouths, ranging from 0.6 km for the Miami River to 11 km for the Tillamook River (Table 1). Important to an estuary or bay is its tidal prism, representing the total volume of water entering due to the tides, essentially being the product of the tidal range and affected area of the estuary. For Tillamook Bay the tidal prism for the mean range of tides has been estimated as 4.63 x 10⁷ m³ (1.63 x 10⁹ cubic feet), with a diurnal range of 6.09 x 10⁷ m³ (2.15 x 10⁹ cubic feet) (Percy et al., 1974). These values are large compared with other estuaries on the Oregon coast, due to the substantially larger area of Tillamook Bay.

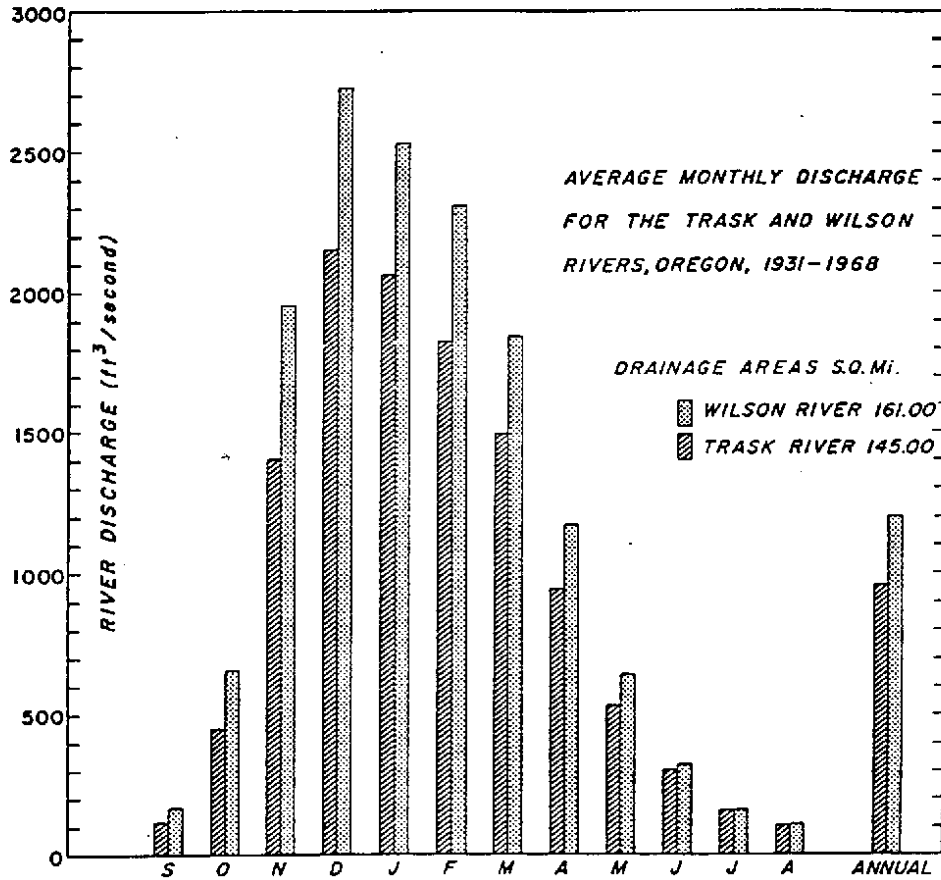


FIGURE 4: Average monthly discharges of the Trask and Wilson Rivers, the two largest rivers that flow into Tillamook Bay. [Source: Oregon State Water Resources Board]

With an opening to the sea and fresh water entering from a river, the main processes within an estuary relate to water circulation and mixing. As one proceeds up-estuary from the inlet, the salinity generally decreases progressively from pure sea water to brackish water, and finally to the fresh water of the river. Pritchard (1955) was the first to classify estuaries into the sequence diagrammed in Figure 5, based on the nature of the circulation and on the degree of mixing of the salt and fresh water. The type of estuarine circulation depends primarily on the river discharge, the strength of tidal currents as governed by the tidal prism, and on the width and depth of the estuary. In most estuaries it is the turbulence generated by the tidal currents that mixes the salt and fresh water. Without those tidal currents the fresh water does not mix appreciably with the salt water, but instead flows out over the surface of the denser sea water which intrudes beneath as a salt-water wedge. The result is a *well-stratified system*, illustrated in Figure 5A, characterized by a strong vertical layering and a narrow zone of sharp salinity change. The well-stratified circulation is best developed in estuaries of low tidal flow and large river discharge. The successive circulation types in Figure 5 demonstrate the increasing effectiveness of mixing between the salt water and fresh water within the estuary, produced by an increase in the tidal current or a decrease in the river discharge. In the intermediate *partly-mixed estuary*, Figure 5B, more salt water is mixed into the outward flowing fresh water in the upper layer. This turbulent mixing not only transfers salt water upward into the fresh surface layer, but also mixes

the fresh water downward. More sea water is added to the surface layer than in a well-stratified estuary, and as a result, the outward flow of the surface layer may be considerably greater than the original river discharge. There also will be a strong inward compensating flow of sea water near the bottom, stronger than in the well-stratified system. With still greater mixing between the salt water and fresh water, a *well-mixed estuary* is formed with little or no vertical stratification (Figure 5C). With complete mixing, the salinity changes gradually along the length of the estuary from that of pure fresh river water to that of ocean water. The lines of constant salinity are then nearly vertical throughout the length of the estuary, and the net discharge at any water depth is directed toward the ocean.

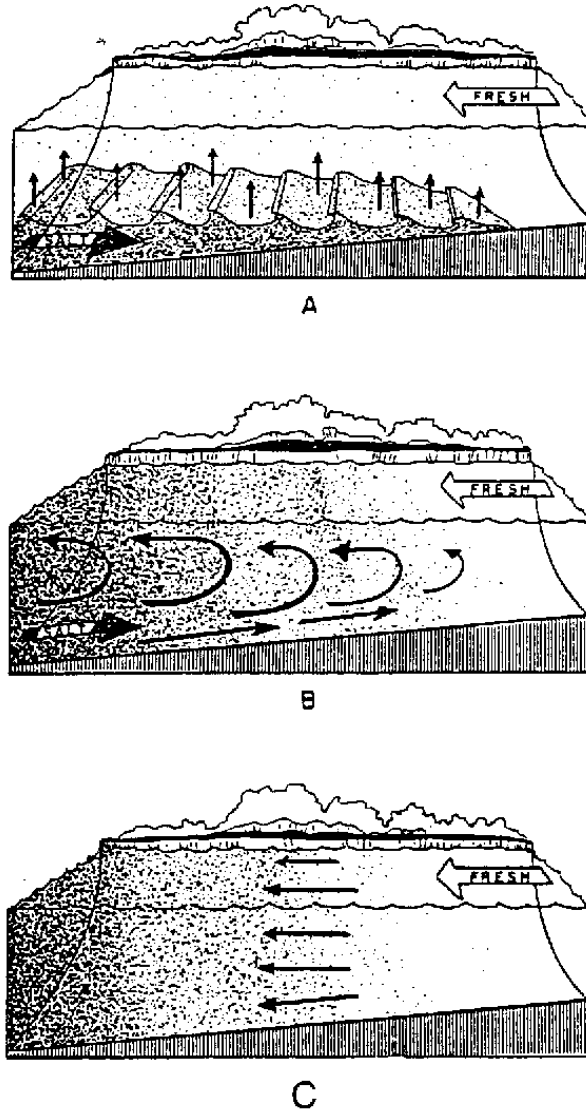


FIGURE 5: Schematic diagram of the three types of water-circulation patterns found in estuaries, according to the classification system of Pritchard (1955). These patterns involve the mixing of salt water from the ocean with the less-dense fresh water of the river.

The type of estuarine circulation, therefore, depends primarily on the strength of the tidal currents and on the discharges of the rivers. It is apparent that for a certain estuary, these factors can vary monthly and seasonally. For this reason, the overall pattern of circulation may change. In the case of Oregon estuaries where there are large increases in river discharges during the winter, there can be a shift in circulation patterns with the estuaries tending to be well-stratified during the winter and changing to a well-mixed circulation during the dry summer months of low river discharge. This appears to be the pattern in Tillamook Bay. In their study of estuaries along the Oregon coast, Burt and McAllister (1959) included measurements of salinities on the Tillamook River, obtained once each month in October 1957 and January, April and July 1958. Maximum salt-water intrusion for these four months occurred on July 23, 1958 when salinity was measured at concentrations of 8.2 ppt on the surface and 8.6 ppt on the bottom (3.6-m depth) at a point 21 km from the ocean. On the basis of those measurements and expected changes in river discharges through the seasons, Burt and McAllister classified Tillamook Bay as a two-layered stratified system during January (winter months) and as a well-mixed system during April and October (summer conditions). Therefore, Tillamook Bay goes through the complete range of estuarine circulation patterns depicted in Figure 5, depending on the season.

The width and depth of an estuary are also important in determining the type of circulation, in that for a given river discharge and tidal range, these dimensions determine the actual water-current strengths and therefore the amount of mixing. Increasing the width or decreasing the depth cause a shift in the estuarine circulation in favor of a decrease in stratification, that is, toward a well-mixed system. An increase in the width of an estuary can also lead to cross-channel variations in currents and salinities. The discussion thus far has centered on two-dimensional estuaries, where the variations in salinity and currents occur along the length of the estuary, and also with depth at any specific position. With a greater width, the estuary is more apt to be three dimensional. In the Northern Hemisphere the Coriolis force due to the Earth's rotation tends to make the river water shift toward the right bank of the estuary when facing down channel. At the same time, tidal currents carrying sea water into the estuary tend to hug the left bank (still looking down channel). The boundary between the upper layer of fresh water and lower layer of salt water is now inclined across the width of the estuary, as well as along its length. In extreme cases the seaward-flowing fresh water and landward-flowing salt water become separated by sand bars into ebb and flood channels. Such three-dimensional patterns of circulation can be expected to be important in Tillamook Bay, but have not been documented by the collection of field data.

Human modifications of the environment can affect circulation patterns within an estuary. It is apparent that damming a river or otherwise diverting the water for industrial, municipal or irrigation purposes, may shift the estuarine circulation toward a more highly-mixed system. In the opposite sense, activities such as deforestation and urbanization may increase river discharges, tending to shift the estuarine circulation toward a more stratified system. Dredging within the estuary, the placement of a landfill, or other activities that modify the configuration and water depths of the estuary can have significant effects on the water circulation and sediment-transport paths. These factors also have not been adequately assessed for human activities in Tillamook Bay.

The inlet to Tillamook Bay, connecting it with the ocean, has been altered by the construction of jetties. Initially only a single north jetty was constructed, completed in 1917 but repaired and extended to a total length of 1,700 m in 1933. As shown in Figure 6 from the study of Komar and Terich (1976), construction of this north jetty resulted in a marked change in the inlet cross section. Prior to jetty construction the inlet channel was wide and depths were reasonably uniform, but jetty construction caused the tidal flows to hug this artificial wall, scouring the sand bottom to considerable depths. The uncontrolled south bank of the inlet, the north tip of Bayocean Spit, expanded into a large shoal. Sand that formed this expanded shoal was derived from the erosion of Bayocean Spit, resulting in the destruction of the resort community that had been developed on the Spit early in the

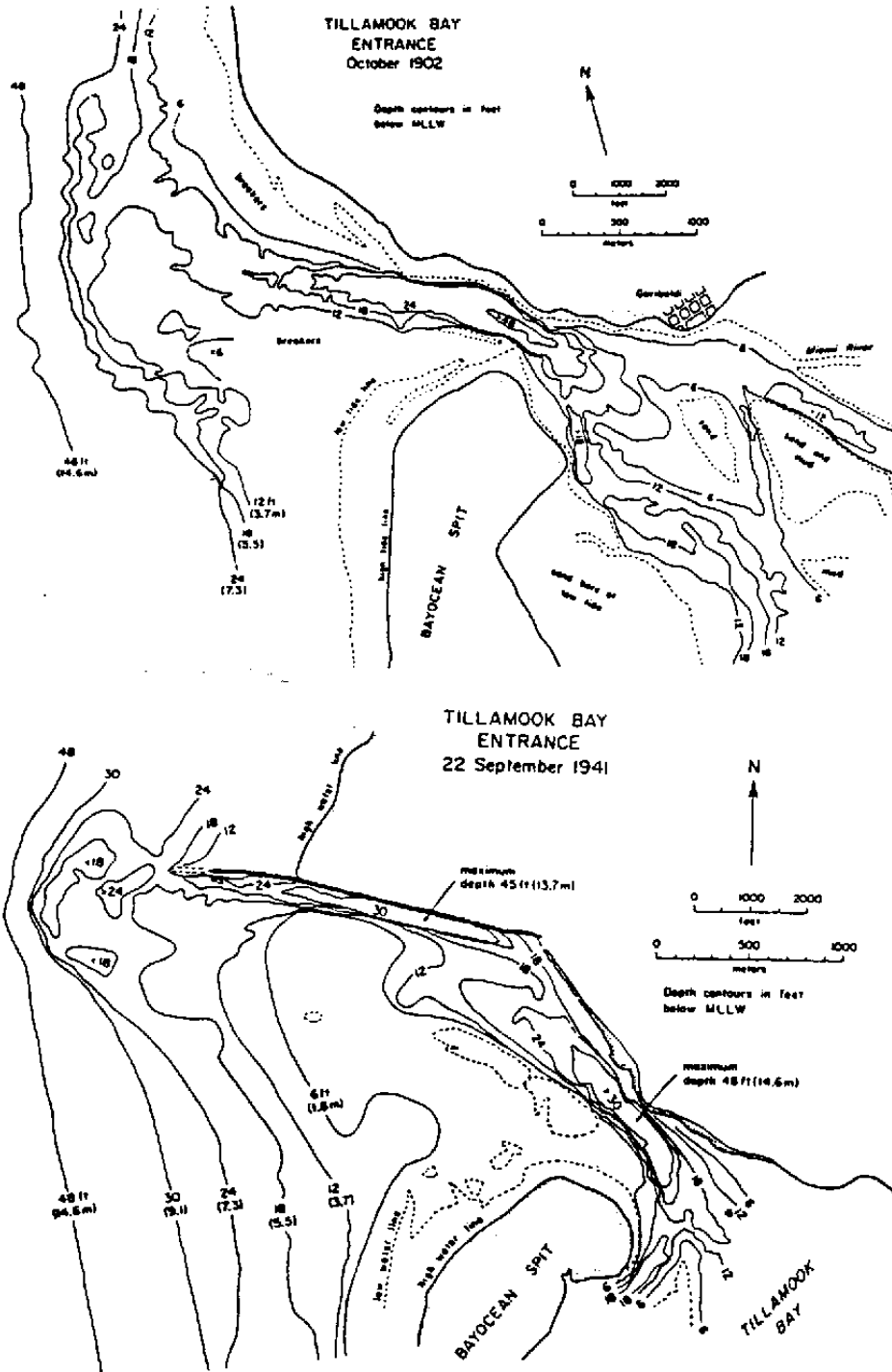


FIGURE 6: Cross sections of the inlet into Tillamook Bay in its natural condition prior to jetty construction, and following the completion of the north jetty in 1917 which resulted in a concentration of the flow adjacent to the jetty and a considerable deepening of the channel, while at the same time shoaling occurred along the uncontrolled bay at the tip of Bayocean Spit. [From Komar and Terich (1976)]

century (Terich, 1973; Terich and Komar, 1973, 1974; Komar, 1997). The presence of the shoal at the entrance to Tillamook Bay likely resulted in increased quantities of beach sand carried into the Bay by the flood-tide currents. Furthermore, erosion of Bayocean Spit led to its breaching in 1952, Figure 7, allowing large volumes of beach sand to be washed into the Bay. In 1956 a dike was built by the U. S. Army Corps of Engineers to close the breach, after which strong tidal flows returned to the natural inlet at the north end of Bayocean Spit (Brown et al., 1958). The continued presence of the large shoal in the inlet with the single jetty represented a hazard to navigation, so in 1969-1975 a south jetty was constructed.

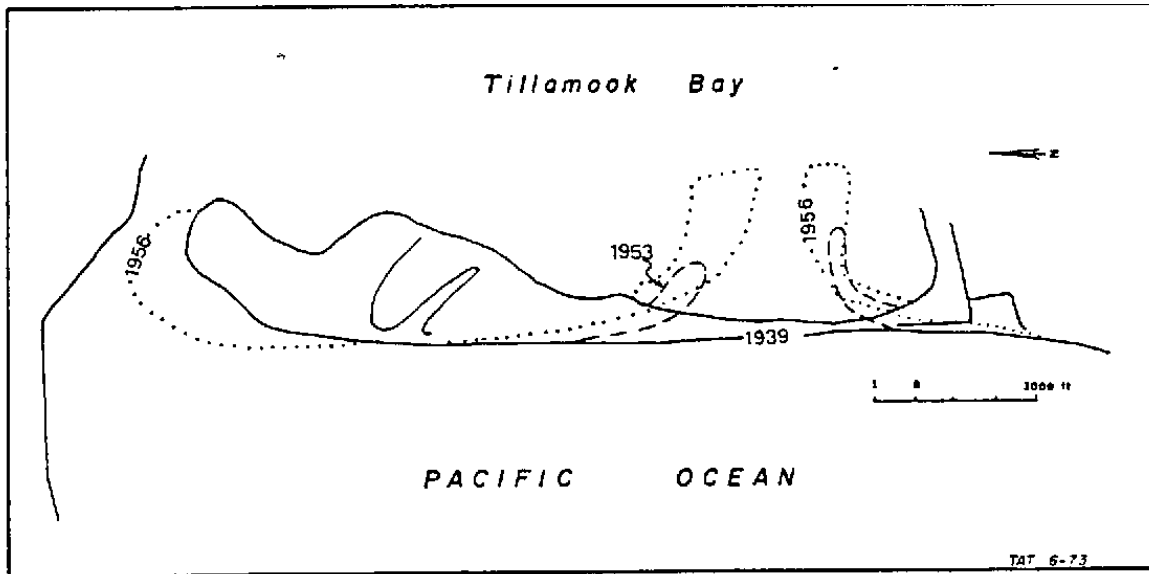


FIGURE 7. Major changes in the shoreline of Bayocean Spit that resulted from its breaching during 1952. Large quantities of beach sand were carried into the Bay. During 1956 a dike was constructed across the breach, and the ocean-beach shoreline returned to near its 1939 position. [From Terich (1973)]

The breach of Bayocean Spit near its south end between 1952-56 resulted in the transport of large quantities of beach sand into the Bay. Komar and Terich (1976) estimated this quantity in their development of a budget of sediments, Figure 8, associated with the construction of the north jetty and subsequent breaching of the Spit. Sand deposition to the north of the jetty amounted to some 6 million m^3 , which was derived from beach erosion further to the north. Comparisons of bathymetric surveys of the shoal within the inlet before and after construction of the north jetty indicated that the volume of the shoal increased by 3.3 million m^3 following construction. This increase was derived from sand eroded along the length of Bayocean Spit, the total of which amounted to some 5.7 million m^3 based on measured beach and dune bluff retreat. Part of this loss of beach and dune sand resulted from its being carried into Tillamook Bay when the Spit breached. This volume was estimated to have been 1.5 million m^3 , a value that was based on the retreat of the spit during the breaching process and shoaling values within the Bay near the breach. The growth of the shoal and quantity of sand entering the Bay through the breach together accounted for 4.8 million m^3 of sand deposition, which is close to the 5.7 million m^3 of estimated erosion from the Spit; the difference suggests that we likely underestimated the amount of sand carried into the Bay. Although the budget of sediments represents only approximate estimates, it confirms that the movement of sand from the beach into Tillamook Bay during the 1952-56 breach was a significant event in the history of Bay filling.

Periodic dredging has been necessary within the inlet to maintain safe water depths for navigation. Dredging is also undertaken to maintain a channel through the Bay to the port at Garibaldi. These dredging activities have been summarized by Percy et al. (1974) and Chesser (1995). According to Percy et al., the Corps of Engineers dredging records from 1959 through 1969 show that the entrance bar and inner channel were dredged annually from 1962 through 1966, prior to construction of the south jetty, with an average of $43,800 \text{ m}^3$ (57,232 cubic yards) of sediment removed. Additional dredging from the small boat basin and approach channel in 1959 resulted in the removal of $8,960 \text{ m}^3$ (11,724 cubic yards) of sediment. According to the abstract summary of Chesser (1995), from 1929 to 1979 approximately 1.2 million m^3 of sediment was dredged from the ocean bar and entrance channel, with the sand having been deposited offshore in the ocean. Only $54,000 \text{ m}^3$ of sediment have been dredged from the Bay since 1979, with none of it removed to ocean disposal sites.

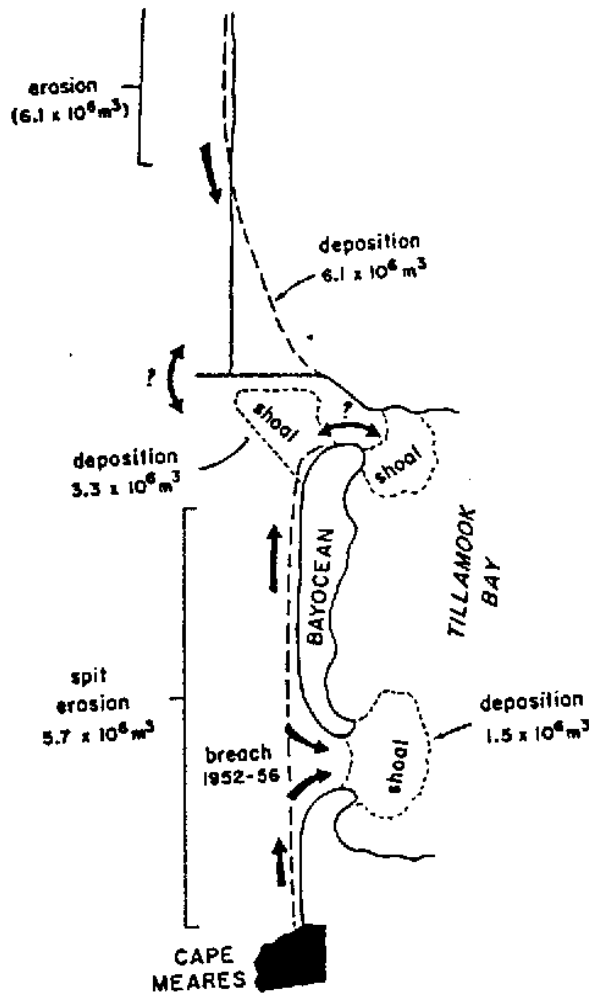


FIGURE 8: The budget of sediments for areas of erosion and accretion following construction of the north Jetty at Tillamook Bay in 1917. [From Komar and Terich (1976)]

PAST RESEARCH OF SEDIMENTS IN TILLAMOOK BAY

Estuaries naturally tend to accumulate sediments. The estuaries along the Oregon coast were formed by the rapid rise in sea level at the end of the Quaternary, a rise that drowned river valleys. Sediment delivery from the rivers could not keep pace, so there was a period during which water depths progressively increased within the submerged estuaries. The rate of sea level rise decreased significantly about 7,000 years BP (before the present), and since that time the main process has involved the accumulation of sediment within estuaries, with much of the river-borne sediment being trapped by the deepened water and the induced circulation that reduces the delivery of at least the coarser grain-size fractions to the ocean. In the case of Tillamook Bay there have been many human activities, particularly within the watersheds of the rivers, that likely increased sediment delivery to the Bay during the last 200 years. An important question is whether these human-induced factors have significantly increased shoaling rates within Tillamook Bay, with an accompanying degradation of habitat.

There has been comparatively little study of the sediments that have accumulated within Tillamook Bay, inadequate to answer questions regarding human-induced factors causing accelerated rates of sediment accumulation. The two principal studies of sediments within Tillamook Bay are those of Avolio (1973) and Glenn (1978), respectively examining distributions of sediment types on the bottom surface and sediments within deep cores obtained in the Bay, documenting the early history of sediment accumulation soon after the estuary was formed. The results of those two studies are reviewed in this section. Also relevant is research by geologists to document the nature of the rocks found within the drainage basins of rivers flowing into Tillamook Bay, since erosion of those rocks constitutes the main source of sediments found within the Bay.

The rivers that flow into Tillamook Bay drain part of the western slope of the northern Coast Range. The rocks of the Coast Range consist of Tertiary volcanics and marine sediments. A list of the geologic rock formations found within the Tillamook Bay drainage basin is given in Table 2, together with a brief description of the lithologies of the rocks. A more detailed review of these rocks is provided in the report by Bostrom and Komar (1997), which also examines differences between the basins of the five principal rivers draining into Tillamook Bay.

Erosion of the volcanics mainly yields gravel and some sand-size sediment, with the particles generally being highly weathered. The mineralogy of the basalts consists of labradorite feldspar, while the heavy minerals are limited to augite and titaniferous magnetite. Erosion of the marine sediments yields sand, together with large quantities of fine-grained silt and clay.

Sediments of the rivers reflect the nature of the rock sources within their drainage basins. Kulm et al. (1968) reported on analyses of the heavy-mineral contents of the sand fractions contained within Oregon coast rivers. In the five rivers that enter Tillamook Bay, the non-opaque heavy minerals are limited almost exclusively to augite and diopside (which are grouped together in heavy-mineral counts). These two minerals account for 92 to 98% of the non-opaque heavy minerals, with titanite making up most of the balance at 0 to 6%, with the Trask River containing the most according to the counts of Kulm et al. Several other heavy minerals were noted, but only in trace amounts. According to the results of Kulm et al., there are essentially no differences in the heavy-mineral contents of the sand delivered to Tillamook Bay by the five rivers, except for the slightly greater titanite content in the Trask River. Their investigation did not analyze the opaque minerals within the river sands, so it is possible that there are differences between the rivers in that mineral component. The only subsequent mineralogical analyses of sands transported by the rivers entering Tillamook Bay are those of Glenn (1978), undertaken as part of their study of Bay sediments. The results are essentially the same as found by Kulm et al. (1968) in terms of contents of non-opaque heavy minerals, although Glenn found the highest content of titanite in the Wilson River (17%), a

smaller amount in the Kilchis River (6%), and none in the other rivers. Glen included "rock fragments" in the heavy-mineral counts, grains that consist of augite/diopside or an opaque heavy mineral, together with feldspar. The percentages of rock fragments were highest in the Miami River (up to 34%), and generally decreased in the series of rivers from north to south, reaching a low of 9 to 12% in the Trask River and 15 to 16% in the Tillamook River.

TABLE 2: Summary of the geologic rock formations found within the drainage basin into Tillamook Bay, and a brief description of the rock lithologies.

Geologic Formation	Geologic Age	Lithologic Description
Siletz River Volcanics	early Eocene	Aphanitic to porphyritic pillow lavas, tuff breccias, massive lava flows and sills of tholeiitic alkalic basalt. The upper sequence contains interbeds of basaltic siltstone, sandstone, tuff and conglomerate.
Yamhill Formation	middle Eocene	Marine siltstone and thin interbedded arkosic and basaltic sandstone. Interbedded lava flows and lapilli tuff.
Cowlitz Formation	upper Eocene	Sandstone and siltstone deposits with minor volcanic flows, breccias and tuffs.
Nestucca Formation	upper Eocene	Interbedded siltstone and calcareous sandstone. The sandstone is feldspathic and basaltic.
Keasey Formation	Eocene to Oligocene	Tuffaceous siltstone, containing occasional ash beds and calcareous concretions. Base of the formation is a pebbly green-gray tuff resting on a silty shale.
Pittsburgh Bluff Fm.	mid Oligocene	Massive quartzose sandstone with local coal beds.
Scappoose Formation	Oligocene to Miocene	Tuffaceous and arkosic sandstone and siltstone. Minor conglomerate layers.
Astoria Formation	mid Miocene	Massive sandstone, shale and siltstone
Columbia River Basalts	mid Miocene	Basaltic lava flows, submarine breccias and pillow lavas.

Large volumes of marine sand have entered Tillamook Bay, through the natural inlet at the north end of Bayocean Spit and through the breach toward south end of the spit that existed between 1952 and 1956 (Terich and Komar, 1974; Komar and Terich, 1977). The input of beach sand into the Bay is best documented by investigations of sand mineralogies, since the beach sand has a distinctive composition compared with the river-derived sand. The most comprehensive investigation of beach-sand mineralogies along the Oregon coast is that undertaken by Clemens and Komar (1988). They demonstrated that there have been three dominant sand sources: (1) the Columbia River at the north, (2) the series of Coast Range rivers that all yield essentially the same minerals, and (3) the metamorphic rocks of the Klamath Mountains that yield a wide range of heavy minerals. Beach sands along the Oregon coast typically contain heavy minerals from all three sources, with the relative contributions depending on distance from the sources. Clemens and Komar further concluded that the observed mineral distributions could only have been achieved during lower stands of sea level, some ten thousand years ago, when mixing of the sand was not prevented as it is now by the many rocky headlands along the coast.

With respect to the ocean beach outside of Tillamook Bay, while most of the heavy minerals in the sand demonstrate that the Coast Range rivers were the dominant source, there also are distinctive minerals derived from the Columbia River and Klamath Mountains, minerals that are not contained within the sand transported into Tillamook Bay by the rivers that flow into the estuary. These heavy minerals distinctive to the marine beach sand can therefore be used to identify its presence within Tillamook Bay, contrasting the contribution from that marine source to the filling of the Bay with contributions by the rivers.

As noted above, there have been two previous studies of sediments within Tillamook Bay, the thesis work of Avolio (1973) and the USGS Open-File Report of Glen (1978). Avolio (1973) collected 35 sediment samples from the Bay, Figure 9, with additional samples obtained from nearby beaches, dunes and rivers entering the Bay. Grain-size distributions were determined by sieving the fraction coarser than 63 microns, while the finer fraction was analyzed using pipette techniques. Environments within the Bay were best differentiated in a plot based on the percentage of sand, silt and clay, Figure 9. Comparatively pure sand is concentrated toward the north end of the Bay in the vicinity of the tidal inlet, and also occupies the beds of the main channels connecting with the rivers to the south. These environments experience the greatest water-flow energies due to tides and river currents, processes that prevent the permanent deposition of silt and clay. Silty sand is found in the southwestern part of the Bay, Figure 9, and clearly represents beach sand carried into the Bay when Bayocean Spit breached in 1952. It is likely that the fraction of silt within this sand was added subsequent to the closure of the breach in 1956. At the center of the breach is an area of sandy silt. This was the deepest portion of the tidal channel when the breach was open, and larger quantities of silt were introduced into this quite depression once the dike was constructed to close the breach. Large areas of the southern Bay contain sandy silt and mud deposits, many of them being shallow areas of eel grass.

Avolio (1973) also analyzed the grain-size distributions in terms of standard statistics — median grain size, sorting and skewness. None of these simple statistics proved to be capable of defining the sedimentary environments within the Bay, beyond noting that there is a tendency for the median grain size to decrease from north to south with distance from the inlet. Such grain-size statistics work best when the sediment is effectively normally (Gaussian) distributed, that is, when there is a single mode of grains present. Avolio noted that the visual appearance of the grain-size distribution curves compelled one to conclude that they consist of mixtures of two or more modes (i.e., they are bimodal or polymodal). Analyses of such complex grain-size distributions require sophisticated computer techniques that separate the individual modes from the mixed sediments (Lewis, 1984), techniques that were not available to Avolio at the time of his study. His results do demonstrate that future investigations of grain-size distributions of sediments in Tillamook Bay will have to rely on those techniques.

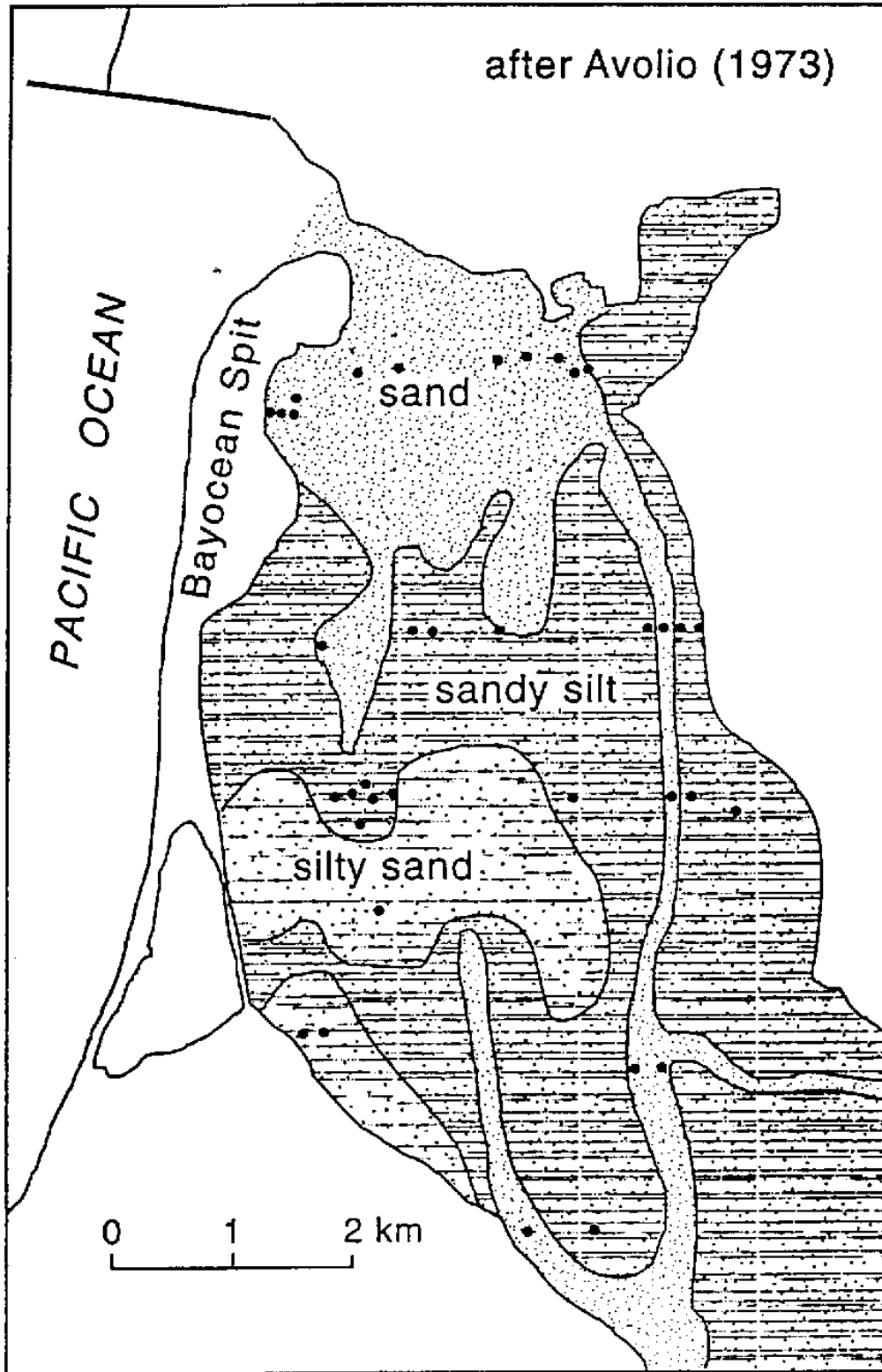


FIGURE 9. Sample locations of surface sediments and distributions of sediment types in Tillamook Bay. [From Avolio (1973)]

Avolio (1973) also separated the heavy minerals from select samples using tetrabromoethane, which has a specific gravity of 2.96. The heavy-mineral separate from a sample was ground in a mortar, and the resulting powder was analyzed by X-ray diffraction techniques. This approach provides a rough "fingerprint" of the heavy-mineral assemblage, a product that is not easily compared with the more standard approach of identifying individual heavy minerals by petrographic microscope techniques [as done by Kulm et al. (1968) and Clemens and Komar (1988)]. Figure 10 shows the X-ray diffraction patterns for a series of samples from the north part of the Bay, arranged in geographic sequence, east at the top and west at the bottom. Included are analyses of sands from the Miami River and from the beach and dunes of Bayocean Spit. Avolio concluded that there is a progressive change from east to west, with the most easterly Bay sample showing a marked similarity to the Miami River sample, while the Bay samples from the west are similar to a composite of the beach and dune sands from Bayocean Spit. The patterns that he saw in Figure 10 are not particularly convincing, and it must be concluded that the X-ray diffraction technique he used cannot be employed to establish quantitative assessments of the proportions of marine (beach) sand versus river sand contained within any sand sample from the Bay. Figure 11 shows X-ray diffraction analyses obtained by Avolio for heavy-mineral fractions of sands from four rivers entering Tillamook Bay. Each river sediment has a somewhat distinctive pattern, which is surprising considering the conclusion of Kulm et al. (1968) that the mineralogies are much the same, a finding based on microscopic counts of mineral frequencies. As noted by Avolio, the difference may be in the opaque heavy minerals, which Kulm et al. did not count. If Avolio's results are correct (which can only be established by further analyses), the X-ray technique may prove to be useful in distinguishing between sands contributed by the several rivers that enter Tillamook Bay, potentially a very useful result.

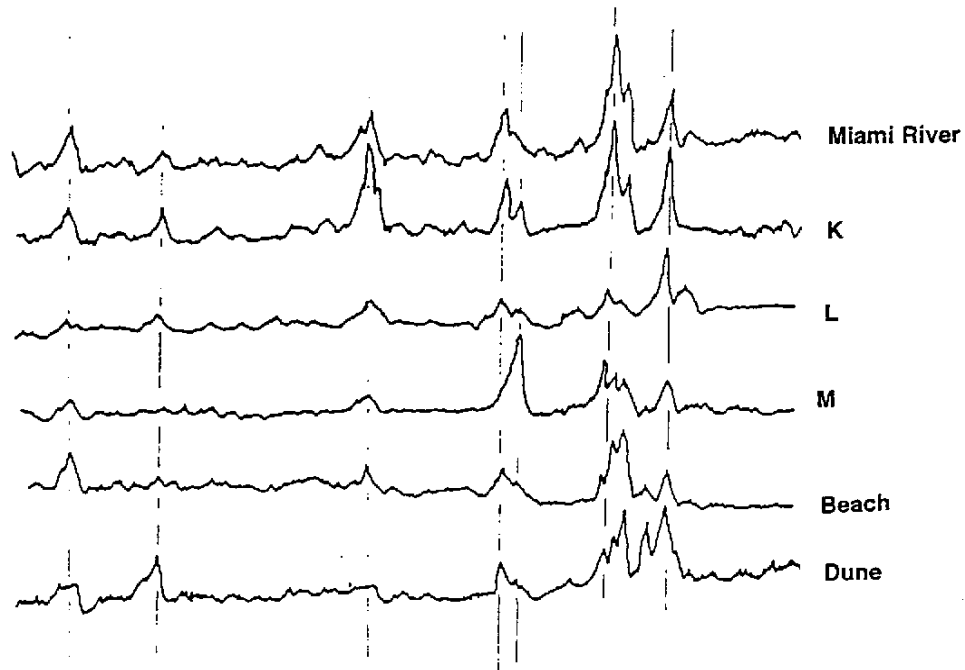


FIGURE 10: The X-ray diffraction patterns of heavy-mineral fractions for a series of samples from the north part of the Bay, arranged in geographic sequence, east at the top and west at the bottom. Included for comparison are analyses of sands from the Miami River and from the beach and dunes of Bayocean Spit. [From Avolio (1973)]

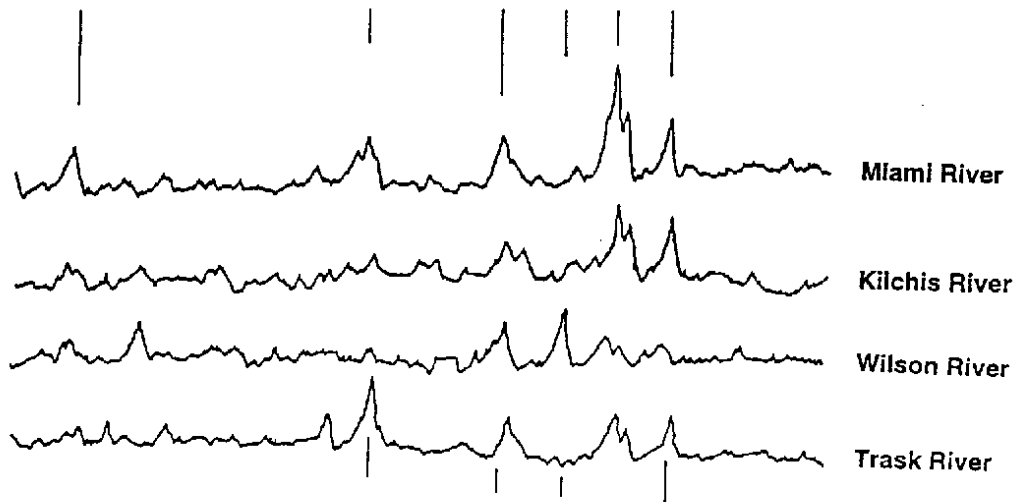


FIGURE 11: X-ray diffraction analyses of heavy-mineral fractions from sands in four of the rivers that flow into Tillamook Bay. [From Avolio (1973)]

The other important study of sediments in Tillamook Bay is that of Glen (1978). While the principal objective was the collection of cores to document the early history of sedimentation within the Bay, Glen also collected 52 surface sediment samples, from the Bay, the ocean beach and dunes, and a large number from the rivers. Only 29 samples actually came from the Bay, and most were from its eastern half; the distribution therefore does not permit conclusions regarding the detailed spatial patterns of surface sediments within Tillamook Bay. The surface samples were analyzed mainly for their heavy-mineral contents in order to establish sources. Glen reaffirmed that there are three sources: (1) the five major rivers entering Tillamook Bay, (2) marine sediments carried into the Bay through the inlet and the 1952-56 breach, and (3) the small streams entering the Bay and direct erosion of the shoreline. Based on microscopic identifications of minerals, Glen concluded that the rivers mainly contribute augite plus diopside, also found by Kulm et al. (1968), with small amounts of hornblende and trace amounts of other heavy minerals. He concluded that the Tillamook River may differ slightly from the other four rivers in the heavy-mineral contents of its sediments. Glen also noted the importance of rock fragments in the river sands, grains that are composed of at least two mineral constituents, usually a feldspar and augite or an opaque mineral. He noted that there is a general tendency for the percentage of rock fragments to increase from south to north in the series of five major rivers that enter Tillamook Bay. Finally, Glen observed that in addition to compositional differences between sands contributed by the rivers versus the marine sands, the degree of grain rounding is also different, with the marine sand being well rounded to subrounded, while the river sands are angular to subangular. Similar differences in grain rounding between beach sand and river sands have been found for Alsea Bay (Peterson et al., 1982) and for the Columbia River (Clemens and Komar, 1988).

Glen (1978) obtained 17 cores, 15 from within Tillamook Bay and 2 on land (Figure 12). Core samples were obtained by augering to the desired sample depth, removing the center plug from the hollow stem of the auger, inserting a split-tube sampler about 46-cm long and 6-cm diameter, and then driving the tube into the sediment below the auger. The cores were examined for stratigraphic variations in sediment color and texture, and also were used to establish inferred sea-level variations from organic material dated by radiocarbon techniques.

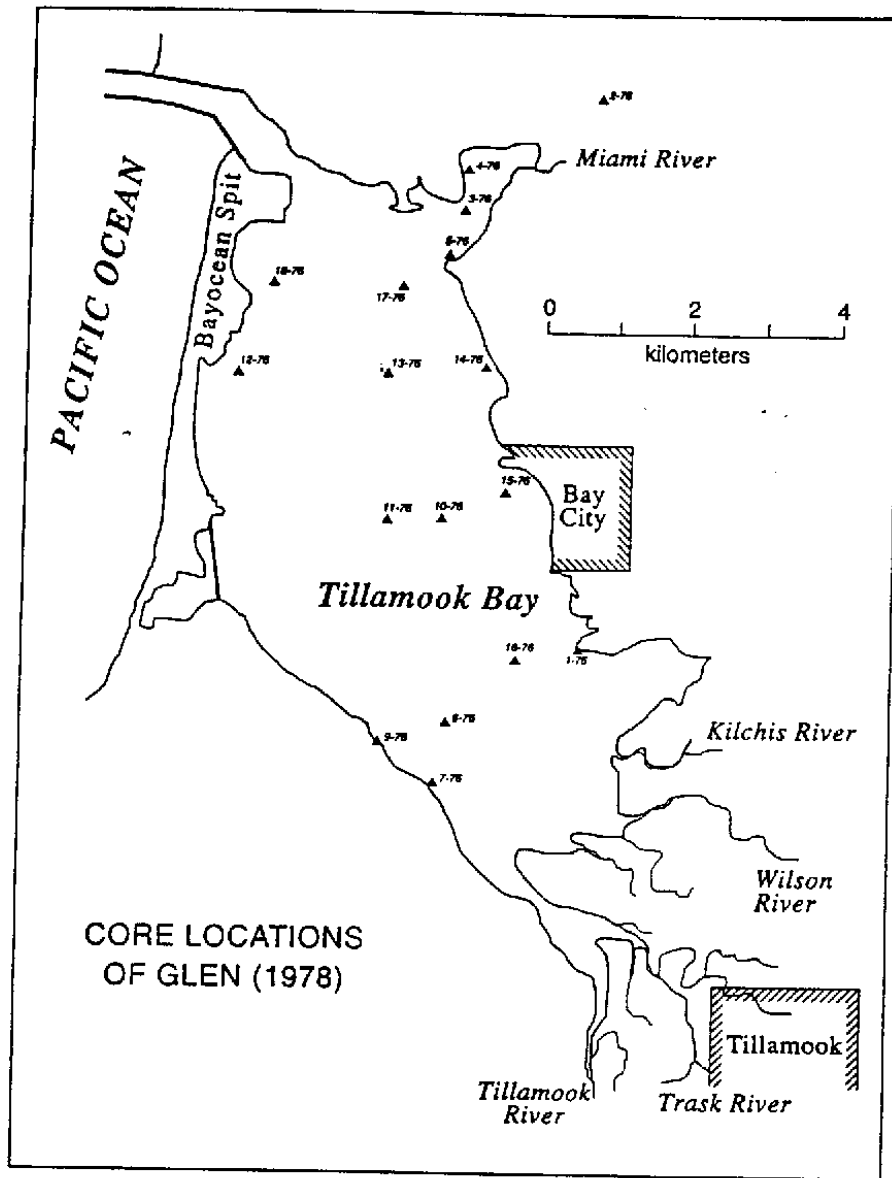


FIGURE 12: Locations of cores obtained by Glen (1978) in Tillamook Bay or from adjacent land areas.

The boundary between the Holocene and pre-Holocene deposits was found in 11 of the 17 cores, and was observed as a sharply defined change in drilling characteristics and/or stratigraphy — the deposits immediately below the boundary were frequently found to be heavily weathered and oxidized. The thickness of the Holocene sediments, those that accumulated since the formation of the estuary, varied from about 1 to greater than 32 m. The Holocene is only 1 to 4 m thick at core sites 1-76, 15-76 and 14-76 (Figure 12) along the eastern margin of the Bay north of Kilchis Point, and 4 to 8 m thick in cores 13-76, 17-76 and 18-76 from the central Bay west and north of Sandstone Point. The greatest Holocene thickness, more than 30 m, occurs in the delta areas of the major rivers (core sites 3-76 and 4-76 in the Miami delta; 7-76, 8-76, and 9-76 in the Tillamook-Trask-Wilson-Kilchis deltas) and toward the western margin of the Bay (cores 11-76 and 12-76). The sediments of the Holocene fill are

generally fine grained; Glen (1978) noted that all analyzed samples average about 60% sand and 40% silt plus clay. In the river deltas, Holocene sediments near the bottoms of the cores contain brown gravel, with the suggestion that cobbles may also be present. In general, the top part of the Holocene is sandier and less-well stratified than the middle part, regardless of core location. The Holocene sediments usually contain abundant quantities of organic matter in the form of isolated small fragments of wood (broken twigs or small branches), or woody to fibrous fine-grained organic layers. In general, these organic materials are more abundant in cores from the delta areas than in cores from sites in the western half of the Bay.

The results from radiocarbon dating of small wood fragments and fibrous to fine woody organic materials contained within the cores are plotted in Figure 13, based on results from core 3-76 in the Miami River delta. The data show that the pre-Holocene deposits underlying the Bay consist of material older than about 38,000 years B.P. (before the present), while the sediment fill within Tillamook Bay has ages that are younger than about 8,400 ± 400 years B.P. Extrapolation of the data in the areas of thickest fill, located in the delta of the combined rivers in the south part of the Bay, suggested that Holocene sediment accumulation may have begun somewhat earlier than 9,000 years B.P. Glen (1978) therefore concluded that sediments in the newly formed estuary began to accumulate in the deeper parts of the river deltas sometime before about 8,000 to 9,000 years B.P.

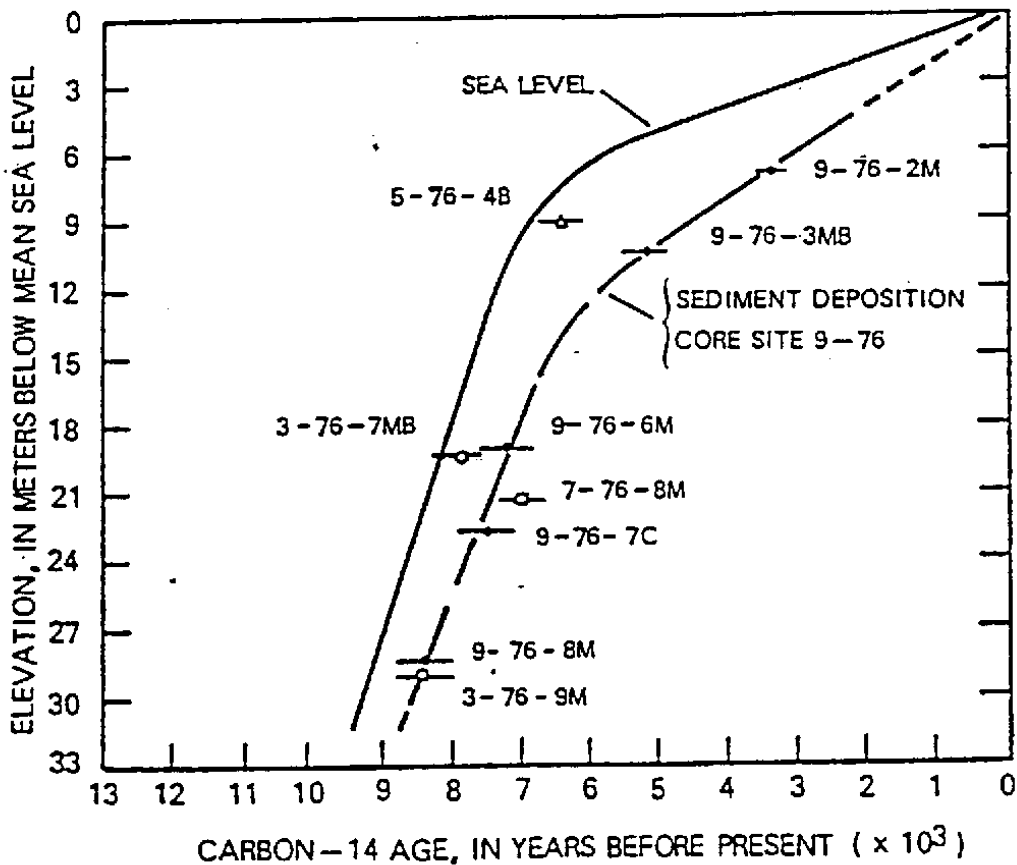


FIGURE 13: Data for the depths of organic material found in cores from Tillamook Bay, with the material dated by radiocarbon techniques. The results document the accumulation of sediments, which is compared with the "global" sea-level curve of Kraft (1971). [From Glen (1978)]

The trend of the data in Figure 13 for dated material in the core documents the progressive filling of sediments in Tillamook Bay, a process that continues. The youngest age of the dated material is $3,300 \pm 200$ years B.P., so the study of Glen (1978) did not document changes in sedimentation rates that may have occurred during the past 3,000 years, including the last 200 years that may have seen the possible effects of human impacts. Also graphed in Figure 13 is a curve for the "global" mean sea level, based on studies elsewhere (Kraft, 1971). The curve drawn through the Tillamook Bay data by Glen generally follows the trends of the global mean sea-level curve, but is displaced downward for a specific age. This displacement is expected in that the Bay sediments and dated material were accumulating in the deeper portions of the Bay; the exact relationship between the dated materials and sediments compared with the local mean sea level cannot be determined. The results do show that there was a rapid rate of sediment accumulation (averaging approximately 1 cm per year) between the initial formation of the estuary and about 6,000 years B.P., with a slower subsequent rate of accumulation (about 0.2 cm per year). Compositional data and stratigraphic observations indicate that during the earlier period of rapid accumulation, the sediments were primarily well-stratified silts and clays, presumably depositing in the deep water of the newly-formed estuary at rates that were sufficiently rapid to prevent appreciable winnowing by currents or disturbance by burrowing organisms. When the rate of global sea-level rise decreased, beginning about 6,000 years B.P., the rate of sediment accumulation also decreased and there was greater opportunity for currents to winnow the sediments, producing generally coarser grain sizes than had accumulated earlier, and organisms were better able to "homogenize" the sediments by their burrowing activities.

SUMMARY AND DISCUSSION

The objective of this report has been to review the past research of sedimentation in Tillamook Bay, and associated processes and environmental factors that play a role in sediment delivery and transport within the Bay. Relatively little research has been undertaken in Tillamook Bay, either of the processes or to document sediment distributions and transport paths. Although it is likely that the estuarine circulation is well mixed during the summer months of low river discharges and highly stratified during the winter when river discharges are greatest, this has been substantiated only by very limited measurements of salinities in the Tillamook River by Burt and McAlister (1958, 1959). That work does not account for the extreme three dimensionality of the Bay, and the fact that fresh water enters from five significant rivers, making it much more complex than the more typical two-dimensional estuary that has only a single major river. Lacking this basic understanding of physical processes in Tillamook Bay, it is not surprising that no attempt has been made to relate those processes to sediment transport and the resulting patterns of sediment accumulation.

There also has been only limited investigations of the sediments in Tillamook Bay. The thesis research of Avolio (1973) provides partial documentation of mineralogical compositions and grain sizes of the surface sediments, while the USGS report of Glen (1978) focuses primarily on the early history of sediment accumulation within the Bay. Those studies did establish that both the rivers and ocean beaches have been important sources of sediment fill for Tillamook Bay. However, because of the poor spatial coverage of their samples across the Bay and due to the lack of detailed analyses of the samples, our understanding of the patterns and processes of sediment accumulation remains poor. It appears that the patterns resemble those found in other Northwest estuaries, where more detailed investigations have been completed:

Yaquina Bay:	Kulm and Byrne (1966)
Grays Harbor:	Scheidegger and Phipps (1976)
Alsea Bay:	Peterson et al. (1983, 1984a)
Siletz Bay:	Peterson et al. (1984b)

Broadly speaking, marine (beach) sand is carried into the estuary through the inlet by reversing tidal currents — and through the 1952-56 breach, in the case of Tillamook Bay — and therefore are most concentrated near the inlet. Much of the estuary is filled by mixed sediments, where the marine sand is blended with river-derived sand in various proportions. In the landward reaches of the estuary, the mixed sediments progressively give way to pure riverine sand. As shown by these other studies, particularly by those of Peterson et al. in Alsea Bay, detailed sediment sampling and analysis can reveal that the patterns of mixing of the marine and river-derived sediments are complex, and differs between the flood-dominated and ebb-dominated channels, and also with the seasons as the river discharges vary and change the nature of the estuarine circulation. These complexities can be expected to be particularly important in Tillamook Bay due to its extreme three dimensionality.

The study of Glenn (1978) obtained core samples from Tillamook Bay to document sediment accumulation during the early history of the estuary, approximately from 9,000 to 3,000 years B.P. The investigation did not examine potential changes in sedimentation rates and patterns that may have occurred in response to human activities and impacts on the environment. In particular, it did not address the important question of whether deforestation and forest fires in the watersheds of the rivers have led to increased rates of sedimentation during this century in Tillamook Bay.

There is the need for additional investigations of sedimentary processes and sediment accumulation in Tillamook Bay. These need to provide a more detailed documentation of the surface sediments, both of their grain-size distributions and mineralogical compositions. Such a documentation should lead to conclusions regarding the relative contributions of sediments by the several rivers and of the marine source. The patterns of grain sizes and compositions of sediments within the Bay may also permit interpretations regarding the sediment-transport paths and dominant processes. Other investigations are required to examine the rates of sediment accumulation during the last several hundred years, to contrast the rates and patterns that have occurred during this past century of greatest human impacts, with those that existed immediately prior to those impacts.

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