Final Report

THE TILLAMOOK BAY
NATIONAL ESTUARY PROJECT
Sedimentation Study

SEDIMENT SOURCES AND THE HISTORY OF ACCUMULATION IN TILLAMOOK BAY, OREGON

James McManus, Paul D. Komar,
Gregory Bostrom, Debbie Colbert
and John J. Marra

August 1998

Final Report

THE TILLAMOOK BAY NATIONAL ESTUARY PROJECT
Sedimentation Study

SEDIMENT SOURCES AND THE HISTORY OF ACCUMULATION IN TILLAMOOK BAY, OREGON

James McManus, Paul D. Komar,
Gregory Bostrom and Debbie Colbert

College of Oceanic & Atmospheric Sciences
Oregon State University
Corvallis, Oregon 97331-5503

John J. Marra

Shoreland Solutions
P.O. Box 153
Newport, Oregon 97365

August 1998

TABLE OF CONTENTS

SUMMARY

Tillamook Bay is a drowned-river estuary that formed initially about 9,000 years ago when the rising level of the sea at the end of the Ice Age inundated the lower reaches of the Trask, Wilson, Tillamook, Kilchis and Miami Rivers. There is now an extensive accumulation of sediment within the Bay, much of it having been deposited by natural processes during the last several thousand years. However, concerns have been raised as to whether human activities, particularly within the watersheds of the five rivers, have significantly increased shoaling rates. The goal of this study has been to examine this possibility through investigations of the sediments found in Tillamook Bay.

Part of this investigation has focused on the surface sediments, and through detailed analyses of 106 samples has attempted to establish the sources of the sediments and their transport paths through the Bay when moved by waves and currents. It was found that the surface sediments are dominantly muddy sand to pure sand, with rare occurrences of gravel. It was concluded that while the rivers supply large quantities of clay and silt, most of this fine-grained sediment is rapidly flushed through the Bay rather than forming permanent deposits. The strength of the water flow permits an accumulation mainly of sand. The surface sediments tend to be coarsest within the deeper channels crossing the Bay, and particularly near the mouths of the rivers and in the tidal inlet connecting the Bay with the ocean.

Detailed analyses have been made of the compositions of the sands collected from the sources (the marine beach and the five rivers), and it was found that the beach sand consists almost entirely of quartz and feldspar sand, while the rivers contribute rock fragments in the sand-size range. Attempts to distinguish between the five river sources based on the heavy minerals contained within their sands was unsuccessful, attributable to the near uniformity of the types of rocks found in their drainage basins. Therefore, we were able to only distinguish between the marine beach source and the combined rivers. All surface sediments collected in the Bay were analyzed for their percentages of quartz and feldspar, rock fragments, and heavy minerals, with the spatial variations across the Bay documenting the relative importance of the marine beach versus the rivers as sources of sediment contributing to the fill of the Bay. As expected, the marine source dominated sediment fill near the active inlet, but also along the entire western half of the Bay. Clearly important was the occurrence of a breach through Bayocean Spit during 1952-56, when large quantities of beach sand were swept into the southwestern part of the Bay. It appears that wind transport of beach sand over the top of the Spit and into the Bay also was important, particularly before the 1930s, by which time the introduction of European beach grass largely halted that process. The eastern half of the Bay is dominated by river derived rock fragments, principally because the combined channels of the Trask, Wilson, Tillamook and Kilchis Rivers, which enter the Bay at its southeastern corner, hug the eastern shore of the Bay as the water flows toward the inlet and into the ocean. Thus, the detailed analyses of the surface sediment samples were successful in establishing transport paths and accumulation patterns of sediments derived from the marine beach and major rivers. The measured sand compositions of the surface sediments were integrated across the extent of the Bay to establish a “budget of sediments”, and it was found that about 60% of the sand within the Bay is derived from the

marine beach, while 40% was contributed by the five rivers. If the fine-grained clays and silt are added to the budget, the contributions made by the rivers would be boosted somewhat, with a proportional decrease in the marine contribution. Roughly, about 50% of the surface sediments are contributed by marine beach sand carried into the Bay by waves, tidal currents and winds, while the remaining 50% is sand, silt and clay contributed by the rivers.

Another aspect of the study has involved making detailed geochemical analyses of the surface sediments in an attempt to better define the sources, and in particular in the hope of finding a distinction between sediments derived from the five rivers. Again, there was a clear distinction between the geochemistry of the marine beach and river sources, particularly in their titanium (Ti) contents which are significantly higher in the river sediments. Unfortunately, analyses of the dominant elements such as Ti, and even of minor elements and trace elements such as the rare earths, were unsuccessful in differentiating between sediments contributed by the five rivers. The geochemical analyses did demonstrate the existence of combinations of elements in the southwest part of the Bay that cannot be explained by a simple mixture of marine and river sediment. This grouping may represent weathered material washed into the Bay from the region south of Bayocean Spit, sediment that is different from the weathered material brought into the estuary by the rivers, or it may be unique material carried through the 1952-56 breach in the Spit.

Analyses of the surface sediments served as the basis for investigations of changes in sediment sources and accumulation patterns with time, based on comparable analyzes of old sediments buried beneath the bottom of the Bay. With this objective, 9 gravity cores were obtained within Tillamook Bay and submitted to detailed analyses. The geochemical analyses revealed marked variations in the aluminum:titanium (Al:Ti) ratio down core, implying that there have been significant changes through time in the proportions of marine beach versus river sediments filling the Bay. In general, there is an increase in Al:Ti down core, implying that back in time there was more sediment contributed by the marine beach compared with the present, relatively less having been contributed by the rivers. One core showed a maximum in Al:Ti at a depth of about 60 cm into the sediment, as well as maxima or minima in other elements, which indicates the occurrence of a large marine sand input in the past, declining up to the present. Another core documented the occurrence of highly episodic inputs of large quantities of marine sand. An interpretation of the cause is uncertain. There may have been major breaches of Bayocean Spit in the past, larger than that which occurred in 1952-56, during which time large quantities of beach sand were swept into the Bay. An alternative, plausible explanation is that the large influx of marine sand occurred during a subduction earthquake and accompanying tsunami, an event that would have caused the abrupt subsidence of the Bay relative to mean sea level and could account for massive transport of beach sand into the Bay. The last major subduction earthquake occurred in the year 1700, and if this maximum in Al:Ti at a depth of 60 cm corresponds to that event, it implies a subsequent average sedimentation rate of approximately 20 cm per century.

Much effort has gone into attempts to determine sedimentation rates in Tillamook Bay, in order to develop a historical perspective on sediment accumulation, to identify areas that have experienced the greatest relative sedimentation, and to establish whether there have been increased rates of sediment accumulation during historic times that might be the result of human activities in the watersheds. Two shell samples found at about 100 cm depth within the cores were dated by their carbon-14 contents, yielding dates of 1460 AD and 1720 AD which correspond to average sedimentation rates of 20 and 43 cm per century. Most of our effort was directed toward the use of lead-210 contents measured in the cores, since complete down-core profiles of this element held the promise of establishing whether rates of sediment accumulation have changed with time. Unfortunately, the results are extremely difficult to interpret, apparently due to active burrowing by organisms which vertically mixes the sediment and affects the down-core distribution of lead-210. If the analysis is limited to measurements below a depth of 50 cm in the sediment, where burrowing activities should be less, the lead-210 profiles yield estimated sedimentation rates between 7 and 138 cm per century for the several cores analyzed. Within this range, the highest rates are found for cores collected in the southern portions of the Bay, likely reflecting the proximity to the river mouths.

The sedimentation rates measured by carbon-14 dating and by the lead-210 down-core profiles are largely substantiated by direct analyses of the bathymetry of Tillamook Bay, surveyed in 1867, 1954 and 1995. The changing depths (below the Mean Lower Low tidal elevation) during the interval 1867-1954 yield an average sedimentation rate of 68 cm per century, while the interval 1954-1995 gives a rate of only 5 cm per century. A more detailed analysis of the changing bathymetry shows that the Bay is mainly filling along its sides, particularly in the delta region in the southeastern part of the Bay. At the same time the deeper parts of the Bay have actually increased in depth. But the filling along the sides of the Bay would be most apparent to people, and this could lead to the perception of excess sedimentation having taken place historically within the Bay.

Processes of sedimentation in estuaries are always complex since this is an environment where the ocean realm collides with the land, and sea water interacts with the fresh water of rivers. By their nature, most estuaries are “out of equilibrium” in a geological time scale, since they were formed only a few thousand years ago when the rapid rise in sea level flooded the drainages of coastal rivers. The history of most estuaries has been their gradual filling by accumulating sediment, trapping silt and sand supplied by the rivers and also carried into the estuary from the ocean by tidal currents. The results of our study demonstrate that Tillamook Bay is similarly complex in its sedimentation processes, but in some respects is more complex than usual because it has five significant rivers supplying sediment and affecting the Bay circulation, and because of the tectonic setting of the Oregon coast. It is now well established that subduction earthquakes and giant tsunami have struck the coast repeatedly during the past several thousand years, with the most recent having occurred on 26 January 1700. The effects of such an event on Tillamook Bay would have been profound. The release by the earthquake of the accumulated subduction strain likely produced an abrupt subsidence of the land by 1 to 2 meters, increasing water depths in the Bay. Within minutes after the earthquake a giant tsunami would have swept across the Bay, carrying beach sand into the deepened water. For decades thereafter, normal storms would have been able to wash over Bayocean Spit, carrying additional sand into the Bay. With time and the progressive filling of the Bay with sediment, the marine influx would have decreased and contributions of sediments from the rivers would have become relatively more important. Although this scenario remains somewhat speculative, it is based on the known occurrence of a subduction earthquake in 1700 and expected processes resulting from that extreme event, and agrees with the down-core measurements obtained in this study of changing compositions of sediments accumulating in the Bay during the past 300 years, and also with the measured declining rates of sediment accumulation.

With such profound natural changes having occurred in Tillamook Bay during the past 300 years, it should not be surprising that it is difficult to establish what impacts humans might have had on sedimentation within the Bay during the last 100 years. Certainly most or all of our activities in the watersheds of the five major rivers would be expected to have increased sediment yields, leading to more rapid rates of sediment accumulation in the Bay. Foremost of these activities in the watersheds is deforestation due to logging and forest fires such as the Tillamook Burns, but also by the diking of the river channels in their lower reaches. In addition, the construction of a jetty at the inlet to Tillamook Bay in 1917 led to the breaching of Bayocean Spit in 1952-56, a period when large quantities of beach sand were swept into the Bay. Some of these human impacts can be seen in the compositions of the surface sediments, particularly the influx of beach sand through the 1952-56 breach. Unfortunately, we have been unable to document any potential increase in sedimentation rates that might have resulted from human activities, because this increase would have been recorded in the upper 50 cm of sediments and this is the zone that is highly mixed by the burrowing activities of organisms. The bathymetric surveys going back to 1867 indicate that if excess sedimentation has occurred due to human activities, it has been confined to the margins and shallow regions of the Bay. Deforestation of the river watersheds can be expected to have resulted in increased quantities of fine-grained clays and silt entering Tillamook Bay from the rivers. While much of this fine sediment is flushed through the Bay to the ocean, a portion of it has accumulated in the marshes along the edges of the Bay and in shallow tidal flats, so the outward growth of the shoreline and expansion of tidal flats during historic times might be the result of human impacts in the watersheds.

INTRODUCTION

Background and Need

Tillamook Bay is located on the northern Oregon coast, about 80 km south of the Columbia River (Figure 1). It 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. Since its initial formation, the Bay has been trapping and accumulating sediment transported by these five rivers, as well as sediment carried into the Bay by waves and tidal currents from the ocean beaches and shallow offshore. There is now an extensive accumulation of sediment within Tillamook Bay, to the extent that its average depth is roughly 2 meters and intertidal flats comprise some 50 to 60% of its surface area.

Although much of this sediment fill in Tillamook Bay is the product of natural processes that have occurred since formation of the Bay, human-induced factors during the past 200 years may have resulted in increased rates of sediment accumulation. These factors include logging of the river watersheds and the occurrence of major forest fires, in particular the Tillamook Burns of 1933, 1939, 1945 and 1951. Also affecting delivery of riverine sediments to the Bay has been the development of an extensive system of dikes, levees and riprap throughout the lower watershed. At the same time, sediment has entered the Bay through the inlet at the north end of Bayocean Spit, Figure 1, and large volumes of beach sand were washed into the Bay during 1952-56 when a breach occurred near the south end of the Spit.

An important question is whether human-induced factors have significantly increased shoaling rates in Tillamook Bay, with an accompanying degradation of habitat, and whether the impacts are reversible. In order to respond to such issues, the goal of this study has been to characterize the types and sources of sediments entering Tillamook Bay, and to develop a chronology of sedimentation volumes and rates of accumulation.

Study Objectives and Tasks

The tasks listed below are those proposed to the Tillamook Bay NEP-Sedimentation Study, to be completed by this investigation in order to meet the objective of understanding the factors affecting sediment accumulation in Tillamook Bay. The scope of the tasks remains the same as originally proposed, but the specifics have changed somewhat in response to the actual findings of this investigation. In addition, longer term objectives related to detailed investigations of human impacts in the watersheds are the focus of an ongoing three-year study supported by EPA/NSF. Completion of that research will provide a more comprehensive understanding of sedimentation and human impacts in Tillamook Bay and its watersheds.

As outlined below, the tasks of this study have included reviews of previous sedimentological research undertaken in Tillamook Bay, and specific tasks related directly to our investigations of surface sediments in the Bay and longer-term accumulation rates determined from core samples. The final task involves a synthesis of the results of our investigation into a comprehensive understanding of sedimentation in Tillamook Bay and discussions of the management implications.

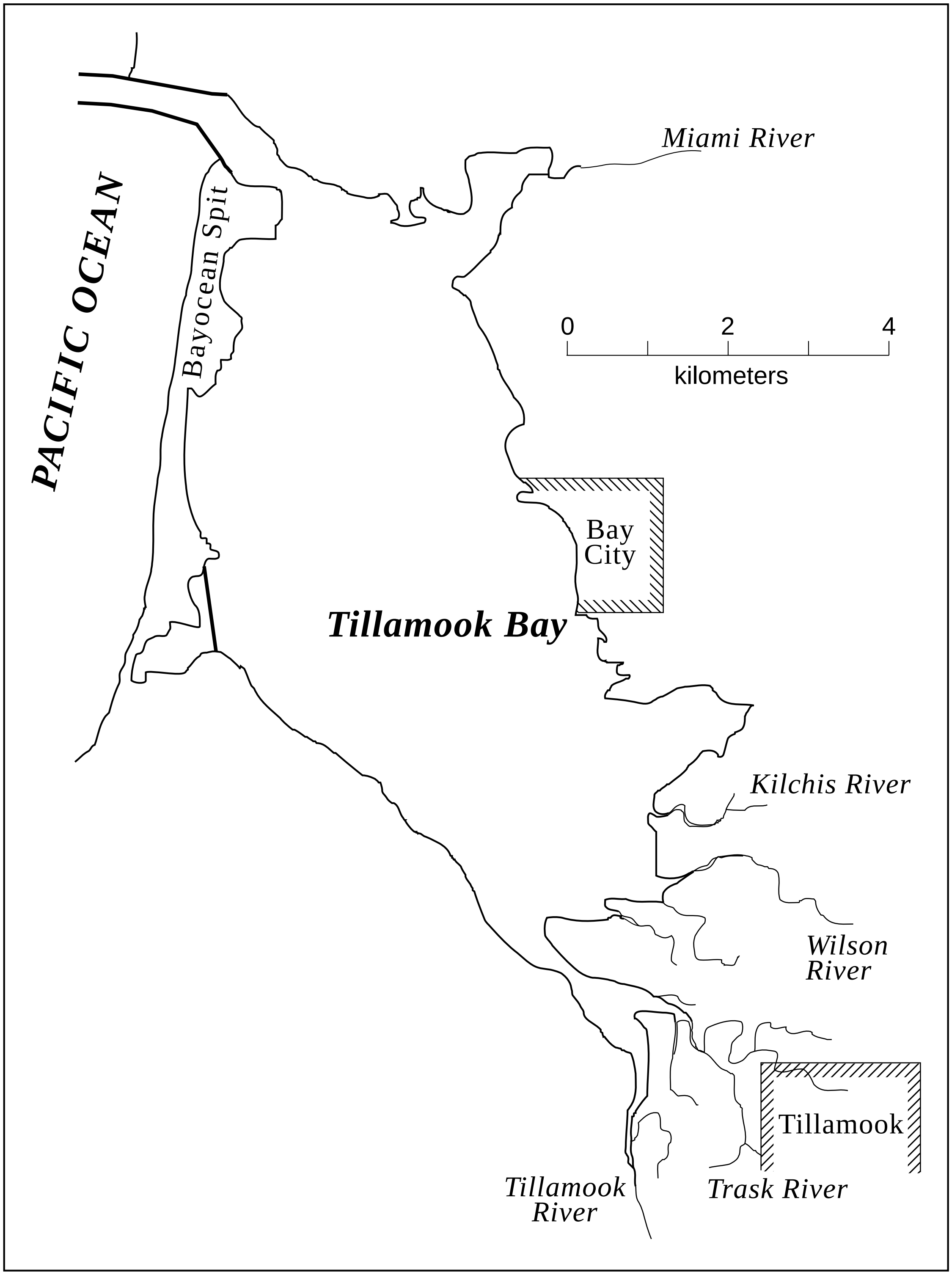


Figure 1. Tillamook Bay, with five significant rivers forming its watershed.

Task 1: Reviews and Coordination of Study

(a) Review previous publications, reports and TBNEP research dealing with circulation, tides, wave climate, precipitation, river discharge, eustatic sea level, sedimentation and bathymetric changes within Tillamook Bay.
(b) Coordinate with TBNEP Scientific/Technical advisory committee in regard to current studies underway.
(c) Write a review report that summarizes information related to processes of sedimentation in Tillamook Bay.

Task 2: Surface Sediment Characteristics and Transport Paths

(a) Review previous studies of sediments within Tillamook Bay, and design a program to collect additional surface sediment samples to establish sources and transport paths.
(b) Undertake field work to obtain surface sediment samples from the Bay and from potential sources (rivers and beaches).
(c) Undertake laboratory analyses of the sediment samples to determine their grain-size distributions and compositions.
(d) Interpret the results from the laboratory analyses to establish sources of sediments in Tillamook Bay and transport paths once the sediments have reached the Bay.
(e) Complete a report dealing with the surface sediments in Tillamook Bay and inferred transport paths and processes.

Task 3: Long-Term Sedimentation Rates

(a) Identify priority regions for sediment core collection, through reviews of current literature and on-going TBNEP studies.
(b) Obtain sediment cores at the selected sites.
(c) Develop a chronology of sedimentation rates over the last 100 years by detailed laboratory analyses of sediments within the cores.
(d) Characterize the types and sources of sediments within the cores, including the development of chemical "signaturing" that would be indicative of the various sedimentary sources (e.g., different river watersheds and agricultural inputs).
(e) Identify areas that have experienced the greatest relative sediment accumulation over the past 100 years, and potentially identify processes that have caused those changes.
(f) Develop a historical perspective of sedimentation in Tillamook Bay to examine how sediment accumulation may have changed through time or in response to particular land-use practices or natural events.

Task 4: Synthesis of the Results and Recommendations

(a) Synthesize the results of the investigations of surface sediment samples and of long-term sedimentation rates as determined from the sediment cores into a comprehensive interpretation of sedimentary processes and sediment accumulation in Tillamook Bay.
(b) Recommend monitoring needs for the improved understanding of the factors affecting

sedimentation in the Bay.

(c) Based on the synthesis, offer suggestions for the improved management of resources within Tillamook Bay and its watersheds.

(d) Outline research needs to improve our understanding of sediment accumulation in Tillamook Bay and of the natural processes and human induced factors that affect the accumulation.

The principal products resulting from Task 1 have been the completion of two reports based on reviews of past research:

Rocks of the Tillamook Bay Drainage Basin, the Coast Range of Oregon — Sources of Sediment Accumulation in the Bay
Gregory Bostrom and Paul D. Komar
Report for the Tillamook Bay National Estuary Project
March 1997, 6 pp.

Sediment Accumulation in Tillamook Bay, Oregon, A Large Drowned-River Estuary
Paul D. Komar
Report for the Tillamook Bay National Estuary Project
May 1997, 23 pp.

The products of Tasks 2 and 3 are contained within this report. The findings of the study of the surface sediments are presented first, followed by a presentation of the investigations of longer term sedimentation determined from the cores. This report concludes with a discussion that integrates the results of these respective investigations, and summarizes the ramifications to the sedimentation history of Tillamook Bay and the management of its resources, the objectives of Task 4 as outlined above.

SURFACE SEDIMENTS — A DETERMINATION OF SOURCES AND TRANSPORT PATHS

Collection of Surface Sediments

A comprehensive program was required to obtain a large number of surface sediment samples in order to provide good spatial coverage over the entire expanse of Tillamook Bay and to obtain sediment samples from potential sources (all rivers and from the marine beaches). This was the objective of our field program undertaken between 30 September and 3 October 1996.

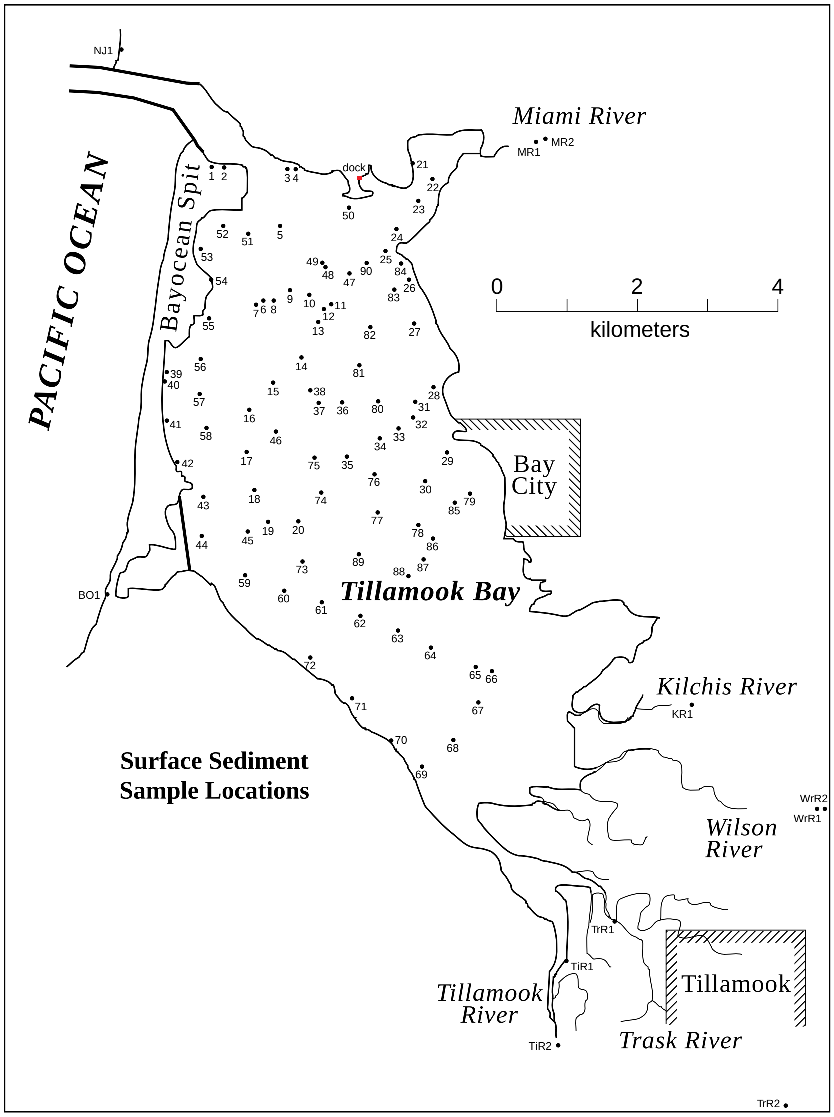


Figure 2. Sample locations for surface sediments collected in Tillamook Bay and from potential sediment sources. The circles represent the main set of surface samples analyzed in this part of the study, while the square symbols are coring locations and where additional surface samples were obtained.

A total of 106 surface sediment samples were collected from the locations identified in Figure 2. Of these, 94 are from the Bay, 3 from the ocean beaches to the north and south of the inlet, and 9 are from the five principal rivers entering Tillamook Bay.

Sediment samples from Tillamook Bay were collected from a Zodiac-type boat having a small draft so that we were able to access all parts of the Bay. Nearly all of the Bay samples were collected with a Forest Peterson-type “grab” sampler, with the samples immediately transferred to 1-liter plastic sample containers and sealed with tape. Samples were collected at approximately 500-meter intervals along a series of transects spanning the Bay, and this grid sampling was supplemented by higher-density sampling in areas of special interest such as channels. Positions of individual sample sites were established accurately through the use of a Garmin 45xl GPS Receiver and Garmin GBR 21 DGPS Beacon Receiver. The Differential Global Positions System (DGPS) uses land-based correction data transmitted by the U.S. Coast Guard to improve the accuracy of the GPS satellite-based position information. Accuracy of position fixes using this technique is reported as 5 to 10 meters RMS. A complete list of surface-sediment samples, their locations in latitude/longitude, WGS1984 UTM, and NAD1927 Conus UTM coordinate systems, and the results of the grain size and composition analyses described below are provided in a separate data report (Komar et al., 1998).

Analysis Procedures

The sediment samples collected from Tillamook Bay and from potential sources were returned to Oregon State University for analyses in the Sediments Laboratory of the College of Oceanic & Atmospheric Sciences. An outline of the analysis procedures is given in Table 1. An objective of Steps #1 through #4 was to remove salt from the sediment, since its retention would adversely affect subsequent analyses, particularly the sieving of the sand fractions to determine the details of the grain-size distributions and compositions. The other objective of these initial steps in the sample analysis was to separate the fine-grained “mud” component from the coarser sediment, the silt and sand, and in a few cases gravel. This was accomplished by wet sieving the entire sample through a 4ϕ (0.0625 mm) sieve, following standard procedures (Lewis, 1984). The separated fine and coarse fractions were individually weighed so that ultimately we could fully characterized the spatial distributions of these fractions within Tillamook Bay.

The separation at 4ϕ yields the coarser fraction — silt, sand and gravel — that is amenable to detailed grain-size determinations by sieving. Furthermore, this coarser fraction is expected to be most informative as to sources of sediment fill in Tillamook Bay, with differences existing between river and marine (beach) sources in their respective grain-size distributions and compositions.

The separated coarse fractions from all samples were subjected to sieving analyses, again following standard procedures (Lewis, 1984). This first involved drying the coarse fraction (Step #6), and then splitting it down to yield a 100-200 gram sub-fraction needed for sieving (larger weights tend to clog the sieves). Sieving procedures for all samples employed an array of sieves ranging from -2ϕ (4 mm) down to 4ϕ (0.0625 mm) at 0.25ϕ intervals. Such an extensive array of sieves was needed to yield grain-size distributions having the desired high level of detail, making possible the separation of individual grain-size modes which potentially could reflect different sources and transport paths. Each sieve fraction was weighed to 0.001 gram accuracy (Step #8), and was then retained in a separate vial.

The last procedure (Step #10) in the laboratory analyses of the surface sediment samples involved determinations of the compositions of all sieve fractions for each sample. This was accomplished by inspection of the sediment grains under a binocular microscope, and classifying 300 individual grains by their compositions (this large number is required to provide meaningful statistical results). Three components were distinguished in the counts: rock fragments, quartz and feldspar grains, and heavy minerals. These three components effectively represent the entire compositions of the samples, to the near exclusion of other components; the only additional component involved small amounts of shell fragments, mainly in the coarsest grain-size fractions. Moreover, an inspection of the samples from the rivers and beaches established that the rock fragments are derived primarily from the rivers, while the beach sand consists almost entirely of clean quartz and feldspar grains. Therefore, identifications of these respective components within the Bay samples provided a direct indication of the relative significance of contributions by rivers versus

Table 1. Procedures for Analyses of Surface Sediment Samples

1. Transfer sample to a large beaker or flask, add water and thoroughly mix. Remove any large organic matter (seaweed, etc.).

2. Let the sediment settle within the container, and siphon off as much of the clear water as possible.

3. Wet sieve the sample through a 4ϕ sieve (0.0625 mm) to separate the sand and coarser sediment (retained on the sieve) from the silt and clay. Capture the fine fraction in a large beaker or flask.

4. Let the fine fraction settle, and siphon off excess water. Dry and weigh. Transfer this fraction to a labeled bottle and archived.

5. Rinse the coarse fraction on the sieve with distilled water, pick out any debris, and transfer to a flat dish (labeled) for drying.

6. After the coarse fraction has dried, weigh the entire sample to 0.001 gram accuracy.

7. If necessary, split the coarse sample down to a fraction having a weight of about 100 to 200 grams to be analyzed by sieving (if the sample contains gravel, use a split that contains 100-200 grams of sand). Return any extra sand and gravel to the original container (that has been cleaned and dried).

8. Weigh the split sand fraction, and sieve with an array extending from -2ϕ to 4ϕ, using 0.25ϕ sieve intervals. Sieve for 20 minutes. Weigh the size fractions to an accuracy of 0.001 gram. Retain the size fractions in separate vials for analyses of compositions.

9. Add the “pan” fraction (size < 4ϕ) to the separated fine-grained sample.

10. For each sieve fraction, determine by microscopic analysis the proportions of rock fragments, quartz/feldspar grains, and heavy minerals. Count 300 grains.

the marine (beach) source. No attempt was made to distinguish between grains of quartz and feldspars, since this is difficult unless staining techniques are employed; more important, since both are derived principally from the marine (beach) source, little could have been learned by having distinguished the quartz from the feldspar grains.

The heavy minerals in the Bay sediments are mostly derived from the ocean beach, but a portion come from the rivers entering Tillamook Bay. Originally, a proposed task of this study involved undertaking detailed analyses of the different minerals contained within the heavy mineral assemblages of the Bay sands. Such analyses could have distinguished between the marine (beach) and combined river sources, but this already had been accomplished more effectively and easily by counting the quartz and feldspar versus the rock fragments, derived from those respective sources. At the beginning of this study the hope was that detailed analyses of the heavy minerals could distinguish between sediments derived from the five rivers entering the Bay, even though earlier studies were unable to make such distinctions (Avolio, 1973; Glen, 1978). This inability is due to the drainage basins of the five rivers containing effectively the same geological rock formations (Bostrom and Komar, 1997). We analyzed the heavy mineral contents of sand samples obtained from the five rivers, and unfortunately confirmed the conclusions of the earlier studies that sediment contributions from the different rivers cannot be distinguished by their heavy mineral contents. Therefore, there was no scientific justification for undertaking detailed analyses of the heavy mineral contents of the Bay sands as originally proposed.

Counts of the three principal compositional components — rock fragments, quartz and feldspar, and total heavy minerals — contained within the sieve fractions of the Bay samples, fortunately allows us to establish the relative contributions of the rivers versus the marine (beach) as sediment sources important to the filling of Tillamook Bay, that is, at least within the coarse sediments (silt and coarser).

Results of Analyses

The first product from the analyses of the surface sediment samples, following the procedures given in Table 1, is a determination of the relative proportions of mud (sediment less than 0.0625 mm diameter — silt and clay), sand (0.0625 to 2 mm), and gravel (grains coarser than 2 mm). While present in several samples, gravel made up a significant portion of only two samples obtained within Tillamook Bay, one collected near the mouth of the Miami River and a sample from the inlet into the Bay, obtained just offshore from the gravel beach that has formed at the landward end of the south jetty. Therefore, representation of the texture for nearly all Bay samples is provided by the relative proportions of mud and sand. These proportions are graphed in Figure 3 where the sediments are classified as:

mud	> 90% silt and clay
sandy mud	50 to 90% silt and clay
muddy sand	50 to 90% sand
sand	> 90% sand

It is apparent in the figure that the surface sediments are dominantly muddy sand to pure sand. One area of mud accumulation is in the former 1952-56 breach area of Bayocean Spit, where the water is still locally deep within the Bay due to tidal currents having scoured a channel when the breach was open. Mud is now being trapped within the quiet water of this deep part of the Bay. Undoubtedly mud is being contributed in significant quantities by the five rivers entering Tillamook Bay, but its relatively small portion in the Bay sediments compared with sand demonstrates that much of the mud must be flushed through the Bay and reach the ocean, rather than being permanently deposited in the Bay. In contrast, sand contributed by the rivers must not be effectively moved through the Bay to the ocean, and therefore dominates sediment accumulation within Tillamook Bay.

Due to the importance of sand accumulation in Tillamook Bay, most of the subsequent analyses have focused on this fraction. The first step in its analysis (Table 1) was to determine the grain-size distribution by sieving. Figure 4 shows the patterns of the median grain sizes of the samples (the median grain size is the diameter at which half of the sample is finer in terms of weight, half is coarser). The median grain sizes are classified as:

range	ϕ units	millimeters
very fine sand	4 to 3	0.0625 to 0.125
fine sand	3 to 2	0.125 to 0.25
medium sand	2 to 1	0.25 to 0.50
coarse sand	1 to 0	0.50 to 1
very coarse sand	0 to -1	1 to 2
gravel	coarser than -1	coarser than 2 mm

This terminology and limits to the grain-size ranges follows that normally employed by sedimentologists (Lewis, 1984). It is seen in Figure 4 that most surface sediments have median grain sizes in the fine and medium size ranges. The occasional coarse to very-coarse grained sand is found within the channels crossing the Bay, particularly close to the river mouths and tidal inlet where water currents are strong. This includes the southern most part of the Bay, at the collective mouths of the Wilson, Trask and Tillamook Rivers. While these rivers supply mud through gravel to the Bay, the strength of the water flow permits an accumulation of only the very coarse sand and gravel, with the finer sediment being carried farthest before deposition or flushed entirely through the Bay to the ocean. A similar situation is found near the mouth of the Miami River where it enters the northeast corner of the Bay. Although the median grain sizes of these samples fall in the very coarse range as defined above, the samples can actually range from coarse sand through gravel, so often represent the rare sites within the Bay where gravel is found.

Following the sieving analysis of a sample, each sieve fraction was examined under a microscope to determine the percentages of rock fragments (RF), quartz and feldspar (Q/F), and heavy minerals (HM). Figure 5 shows the results of such an analysis for a sample from the middle of the Bay where each of these components is found. The upper graph gives a histogram of the entire grain size distribution, the first product of the sieving analysis. In this example the dominant mode of grain sizes is centered at about 2.125ϕ (0.23 mm), but the tail of the distribution extends down to -0.875ϕ (1.8 mm), so there is a small portion of coarse to very coarse grains within this otherwise medium grained sand.

The middle graph in Figure 5 is the result of the composition determinations for the individual sieve fractions, obtained by grain counts using a microscope. The coarsest grains found in the sample are rock fragments (RF), while Q/F dominates the medium size fractions. The proportions of HM increase in the finer sieve fractions, with it being most important in the finest fraction. This result is typical of heavy minerals in sediments, generally tending to be the smallest but densest grains. This compositional graph is somewhat misleading since it must always add up to 100% for each sieve fraction. Thus, while RF form 100% of the coarsest fractions in the sample, the histogram in the upper graph shows that these coarse fractions form only a small portion of the entire sediment sample. The lower graph in Figure 5 is obtained by multiplying the upper graph by the compositional proportions of the middle graph, yielding the grain size distributions of the three compositional fractions. It is seen that modal sizes of RF and Q/F are essentially the same, shifted to a slightly finer grain size (larger ϕ) compared with the histogram for the entire sample. The modal size of the HM is marginally finer. This lower graph in Figure 5 best shows that while RFs do account for the coarsest grains in the sample, most of the RFs are in the medium sand range, just as is the case for the Q/F fraction.

Having completed detailed analyses of the grain sizes and compositions found within the sample, it is simple to add up the proportions in the series of sieve fractions to determine the total percentages of RF, Q/F and HM in the entire sample. The patterns for the RF and Q/F percentages within Tillamook Bay are shown respectively in Figures 6 and 7; one pattern is nearly the inverse of the other, since these are the two dominant compositional components in the sand, with the heavy minerals generally representing only a minor percentage. RFs form essentially 100% of all river samples (there is a small fraction of coarse grained Q/F in the river sediments), so the occurrence of high RF percentages in the Bay generally reflects the dominance of the river source. This result is apparent in the pattern seen in Figure 6 where the highest RF contents are found near the river mouths, and more generally this compositional fraction dominates the eastern half of the Bay. There is one outlier sample with a high RF value in the southwestern part of the Bay; this is near the 1952-56 breach, and it may be either beach gravel carried into the Bay during the breach, or it may be that the sample is contaminated by RFs derived from the riprap dike built by the Corps of Engineers to close the breach. Otherwise, RF forms less than 25% of the sand found in the western half of the Bay, where the Q/F otherwise dominates (Figure 7). The samples of sand collected directly from the ocean beaches consist almost entirely of Q/F, with only small proportions of HM and minor contents of RF. Thus, the Q/F contents of the Bay samples reflect the significance of processes that transport the Q/F sand into the Bay from the ocean beaches. As expected, this contribution is very high near the inlet at the north end of Bayocean Spit, but the importance of Q/F in the Bay sand extends to the south along the full length of the spit. It may be that beach sand has been blown into dunes covering the spit, and then blown further into the Bay; this likely has been an important source of sediment fill in the Bay, especially prior to the 1930s before the introduction of European beach grass that now thickly covers the dunes on Bayocean Spit. Q/F dominates the Bay sediments in the area of the

1952-56 breach at the south end of the Spit; it is know that large quantities of sand were washed into the Bay through the breach (Terich and Komar, 1974; Komar and Terich, 1977), so this result was expected.

As demonstrated in Figure 5, separate grain size distributions have been determined for the RF, Q/F and HM components in each sample. Therefore, we can examine whether the grain sizes of these components vary within the sediments accumulating throughout the aerial extent of the Bay. The median grain sizes of the RF components of the samples are graphed in Figure 8. The

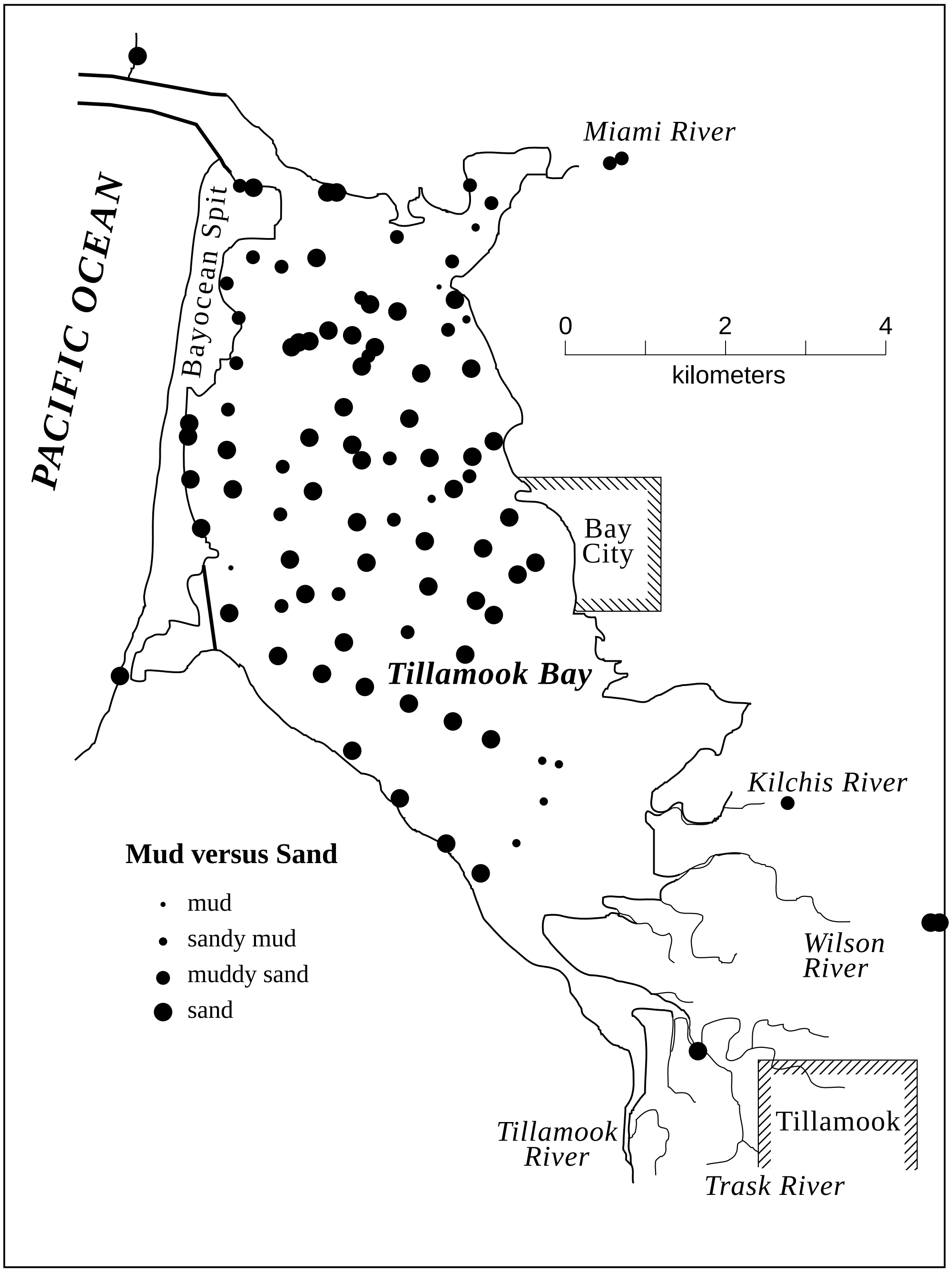


Figure 3. The proportions of mud versus sand in surface sediments.

RFs consist of gravel in the shallow part of the Bay offshore from Hobsonville Point, a promontory composed of basalt extending into the Bay, so this gravel may be of local origin. Very coarse median diameters of the RF component are found near the river mouths, while in the channels the medians are mainly coarse sand. This is true also of the RF component in samples near the 1952-56 breach. Otherwise, throughout the middle of the Bay the RF fraction is dominantly medium to fine sand. This is also true of the Q/F component (Figure 9), but in this case the grain size is controlled mainly by the source, specifically the fact that the beach sand falls predominantly in the medium to fine sand ranges. The few examples of a coarse grained Q/F fraction can be attributed to the very small amounts contributed by the rivers, and it is seen in Figure 9 that these occurrences are near river mouths where the sediment is otherwise coarse grained RFs.

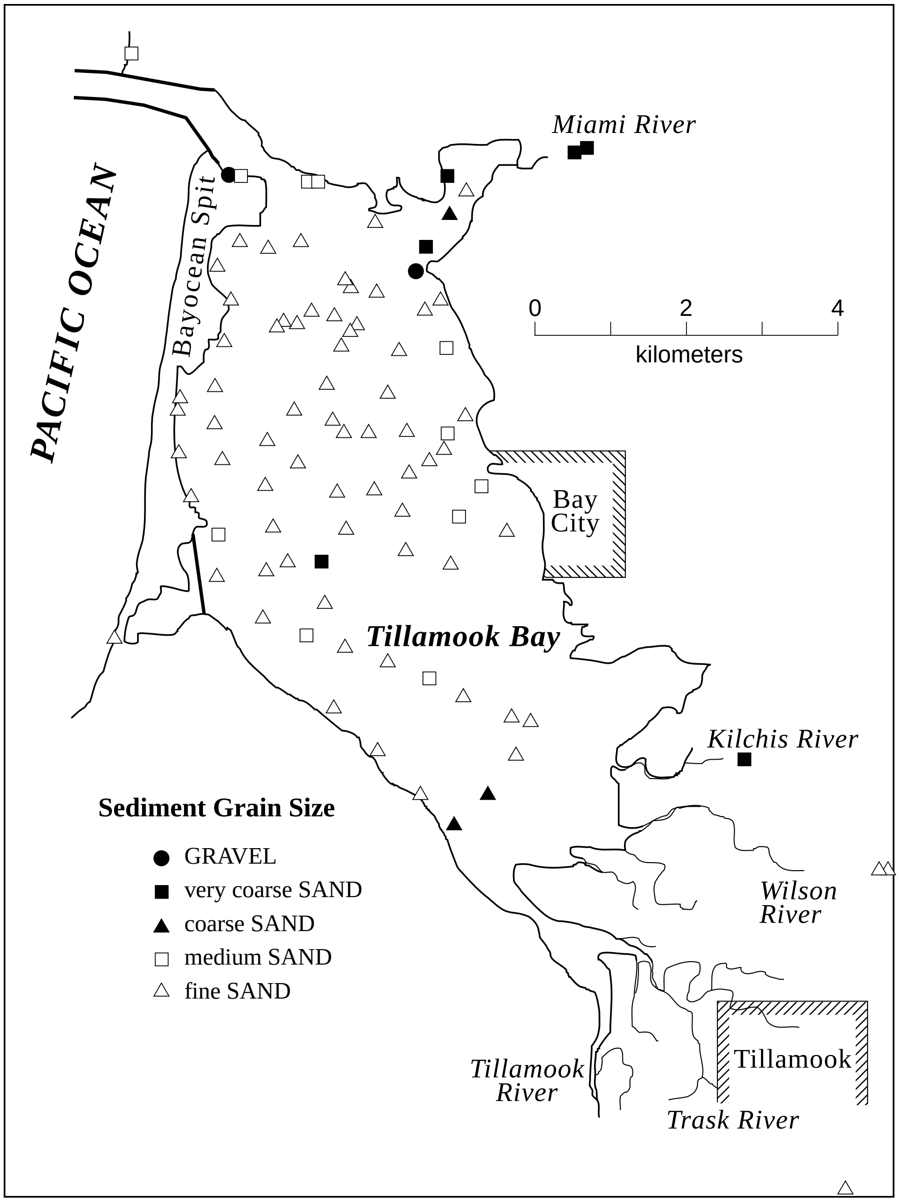
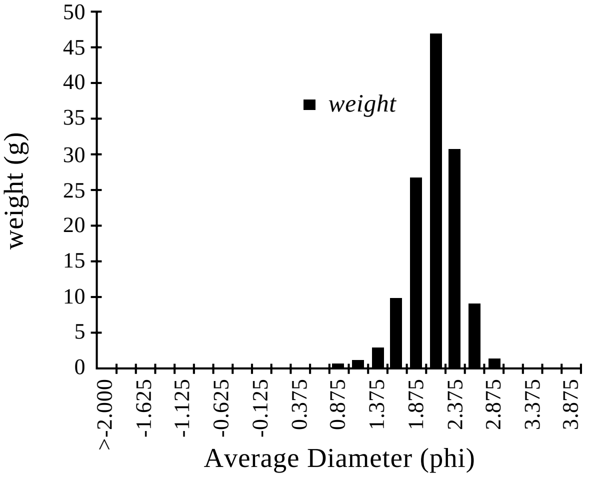
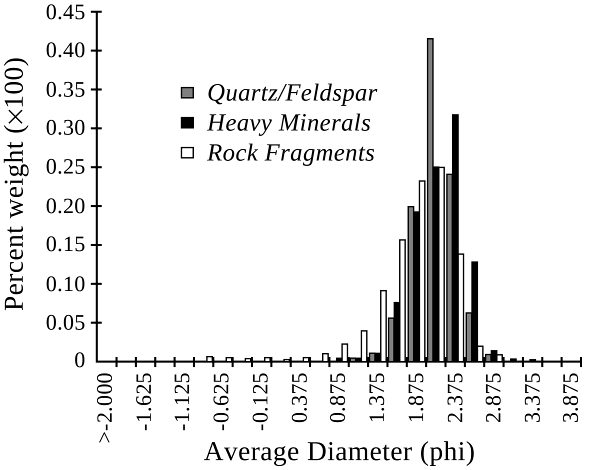


Figure 4. Mean grain sizes of the non-mud fractions of surface sediments, determined by sieving. Size ranges are defined in the text.

a) Sample grain size distribution



b) Percent distribution



c) Compositional distribution

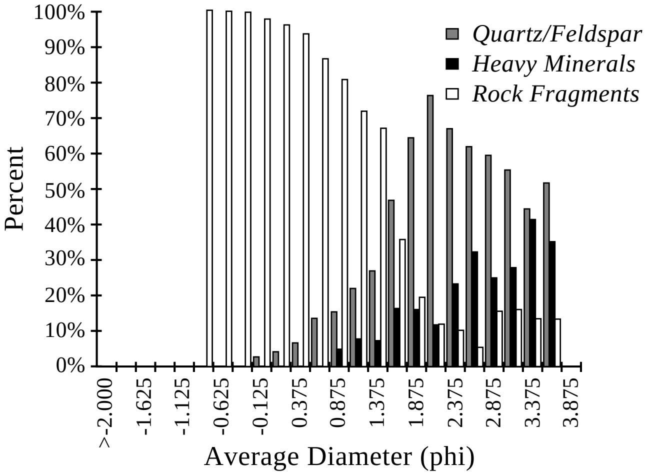


Figure 5. Example analysis of the grain size distribution of a sediment sample (upper), the compositional contents of the sieve fractions (middle), and the grain size distributions of the compositional components (lower).

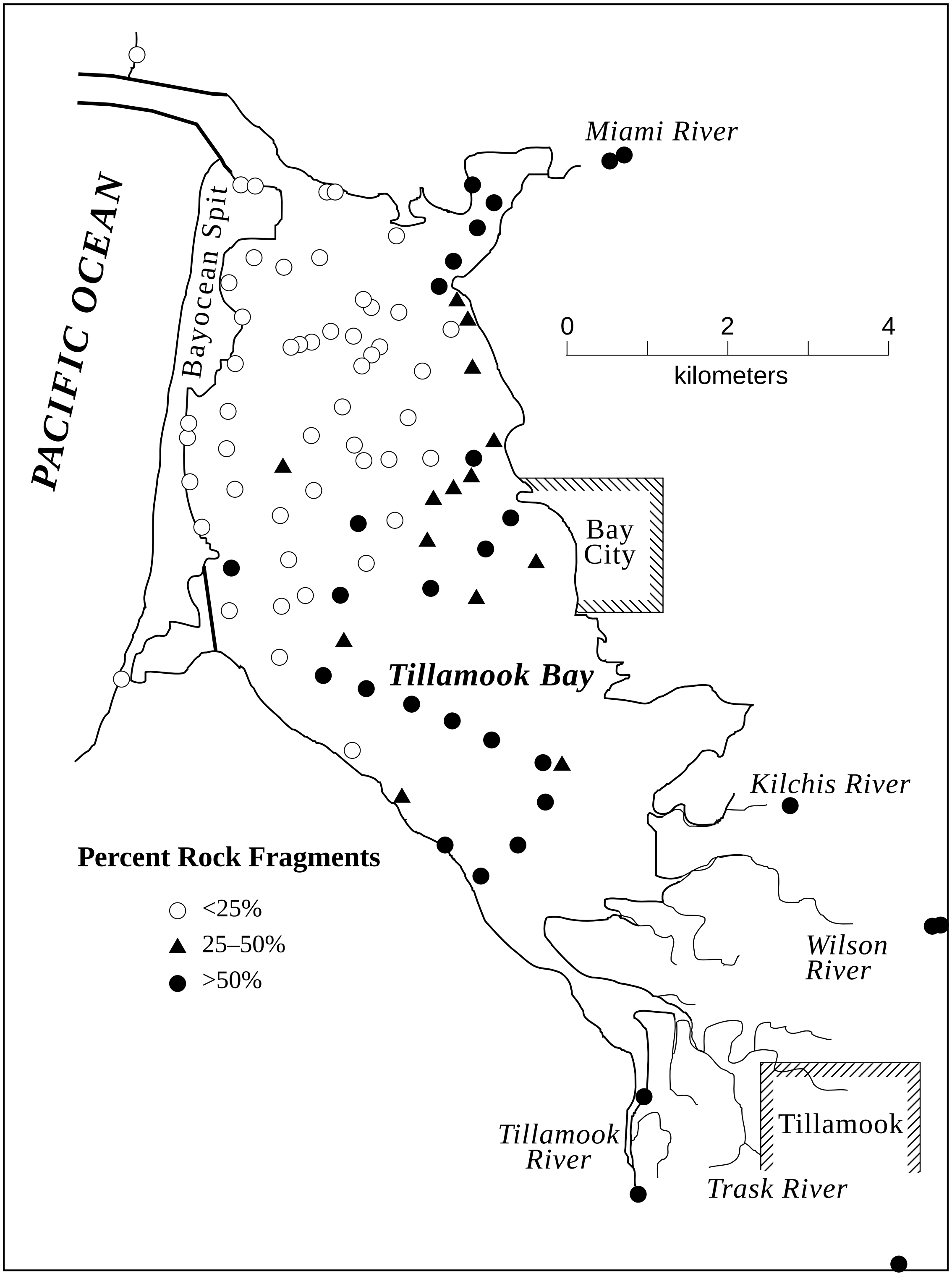


Figure 6. Percentages of rock fragments (RF) in the surface sediments.

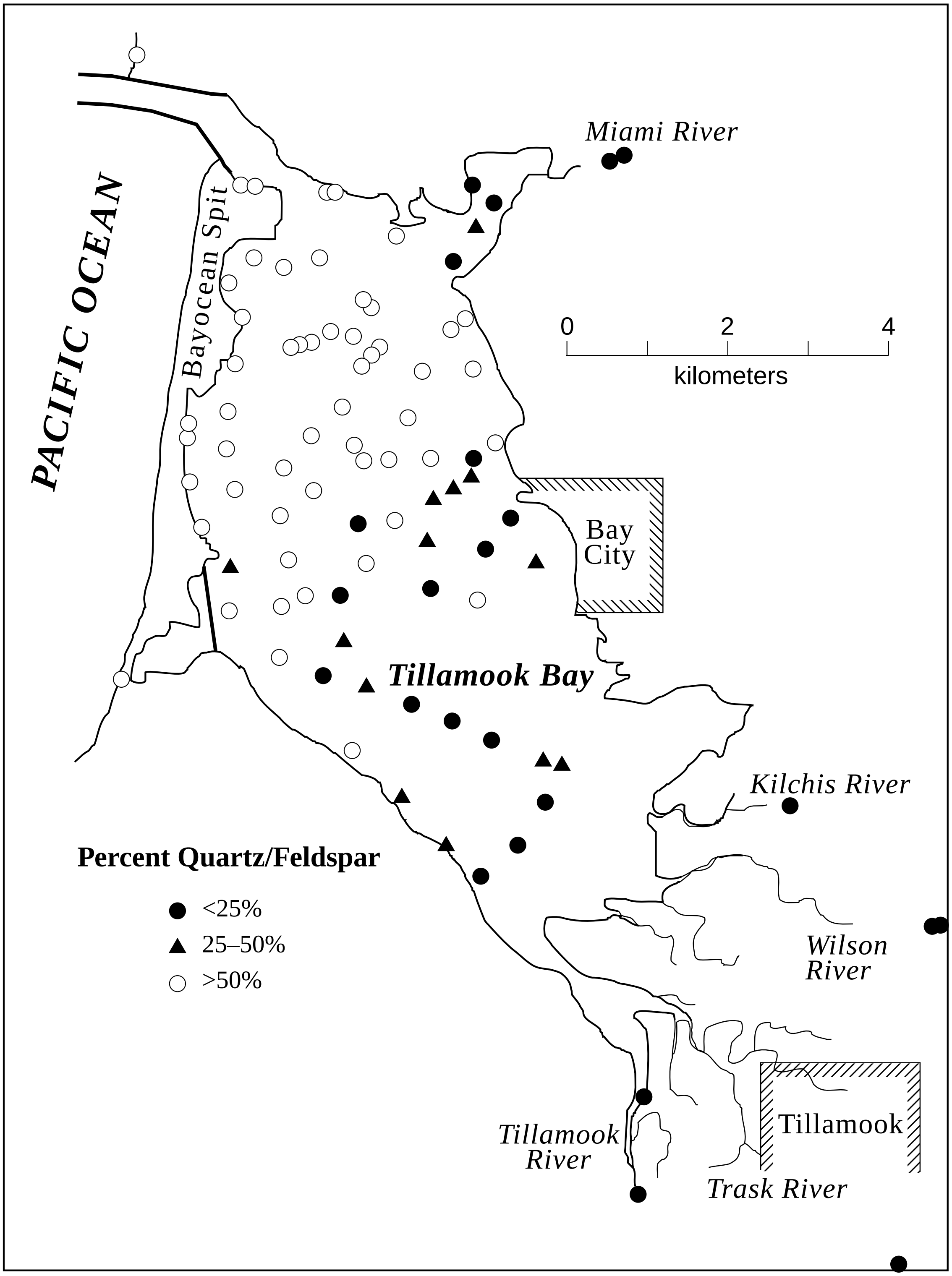


Figure 7. Percentages of quartz and feldspar (Q/F) in the surface sediments.

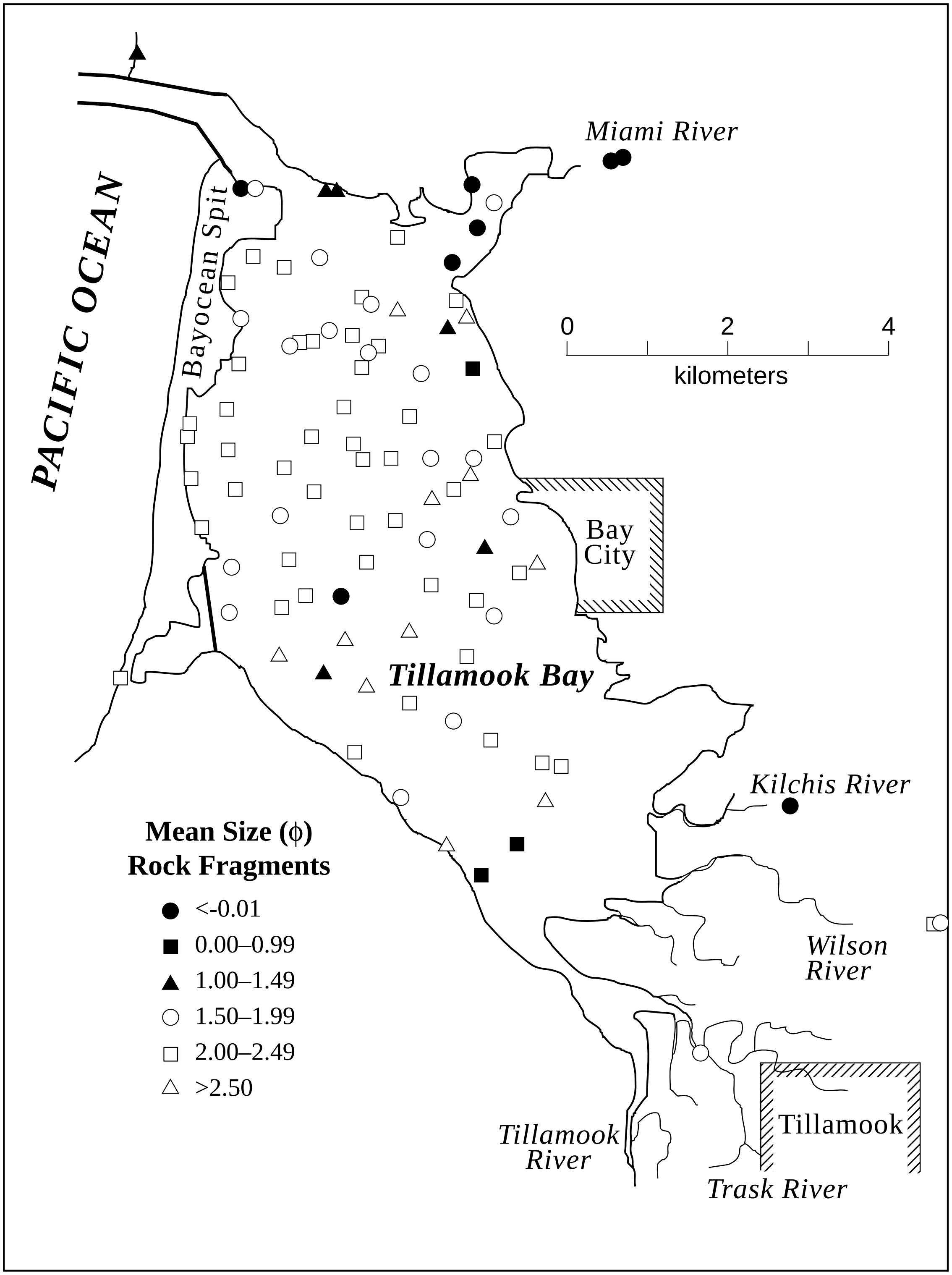


Figure 8. Mean grain sizes of the rock fragments (RF) within the surface sediments.

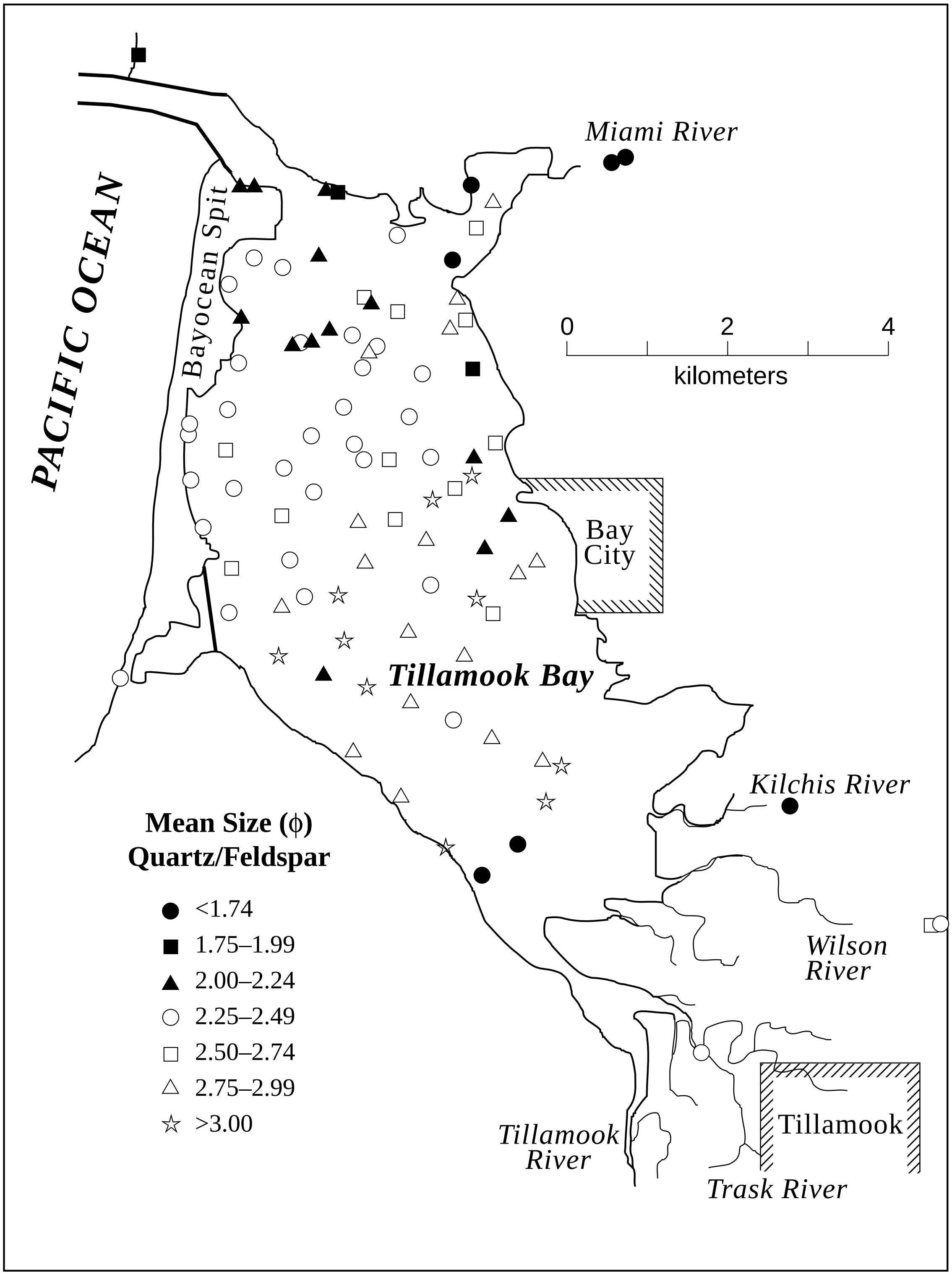


Figure 9. Mean grain sizes of the quartz and feldspar (Q/F).

Interpretation of Results

The dominant sources of sediment entering Tillamook Bay are the five rivers that drain into the Bay, and waves and tidal currents that flow through the inlet and transport beach sand into the Bay. The five rivers collectively contribute large quantities of sediment ranging from mud (clay and silt), through sand, and some coarse gravel. Analyses of the surface sediments in the Bay demonstrate that they are dominantly sand, with only minor amounts of mud. This observation leads to the conclusion that the fine-grained mud is largely flushed through the estuary without residing for an extended period within the Bay. In contrast, gravel contributed by the rivers is likely all trapped in the Bay, and probably nearly all of the river sand is trapped as well. At the same time, sand is carried from the ocean beach into the Bay by waves and tidal currents flowing through the inlet (and during 1952-56, through the temporary breach at the south end of Bayocean Spit). Therefore, it is concluded that the sand and gravel derived from the sources is of primary importance to sediment accumulation in Tillamook Bay.

The analyses undertaken as part of this study have demonstrated that it is possible to distinguish the contributions made by the rivers and beach to the accumulation of sand and gravel in the Bay. Direct analyses of sediment samples from the rivers demonstrate that the sand and gravel consists almost entirely of rock fragments (RF). In contrast, the beach sand is almost entirely quartz and feldspar (Q/F), restricted in grain sizes to medium and fine sand. There is some compositional overlap in the two sources. The rivers also contribute small amounts of Q/F, but much of this is in the coarse to very coarse size ranges. The beach sand contains a small percentage of RF; its contribution of RF to the Bay may have been more important during the 1952-56 breach, due to the intensity of this event and the fact that the south end of the beach near the breach is rich in basalt gravel. Both the rivers and beach sediments contain some heavy minerals (HM). Unfortunately, sediment contributions from the five principal rivers could not be distinguished based on differences in their heavy mineral contents, due to effectively the same geological rock formations being found in their drainage basins.

Rock fragments together with quartz and feldspar dominate the sediments accumulating in Tillamook Bay, so their proportions can be used to infer the relative contributions made by the rivers versus the ocean beach, and also to analyze transport paths as these sediments are carried into the Bay. It has been found (Figures 6 and 7) that, as expected, RF from the rivers dominates the Bay sediments near the river mouths. Four of these rivers enter the Bay in its southeast corner, while the Miami River enters from the northeast. Due to their combined contributions, Bay sediments consist primarily of RFs along the eastern half of the Bay. This pattern is likely reinforced by water circulation in the Bay, with the fresh water from the rivers tending to hug the eastern shore of the Bay as it otherwise flows toward the inlet. There is a well defined channel along the length of the Bay, extending from the river mouths northward to the inlet. This is the main path of the river flow, and of the sediments carried into the Bay by the rivers. The Q/F component of the Bay sediments, derived principally from the ocean beach, predominates along the western half of the Bay (Figure 7). When flood-tide currents enter the Bay through the inlet, they flow southward along the back side of the Spit. There is a well defined flood channel there, though not as markedly developed as the channel to the east dominated by the river flow. Much of the beach sand carried into the Bay by the flood-tide currents will therefore preferentially be transported into the western half of the Bay. The 1952-56 breach of Bayocean Spit at its south end also contributed large quantities of beach sand to the western half of the Bay. Finally, Bayocean Spit is covered with sand dunes, and winds likely have been important in blowing beach sand into the western Bay.

While river sand dominates the eastern half of the Bay, and beach sand the western half, most of the accumulating sediment represents mixtures of sand from the two sources. The spatial patterns of their respective percentages in samples from throughout the Bay can serve as tracers of sediment movement from the river mouths and tidal inlet, as the sand is carried in and accumulates. An interpretation of transport paths is also aided by an understanding of the patterns of water circulation in the Bay, as this largely is the controlling process. Figure 10 provides such an interpretation based on analyses of the surface sediments and the above discussions. It must be recognized that the inferred transport paths are based on analyses of surface sediment samples and on the present day bathymetry and circulation of the Bay. It is certain that while the rivers and ocean beach contributed similar types of sediment in the past, the proportions may have been different and the patterns of accumulation in the Bay would not necessarily have been the same as that found today and documented in our analyses of the surface sediments.

Finally, results from analyses of the surface sediments can be incorporated into something of a “budget of sediments” (Komar, 1996) for Tillamook Bay. This is accomplished by spatially integrating the percentages of rock fragments (Figure 6) across the extent of the Bay, and the percentages of quartz and feldspar (Figure 7). The integrated quantities respectively reflect the relative contributions made by the rivers and marine beaches to the filling of Tillamook Bay. If the small quantities of heavy minerals found in the Bay sands are equally allotted to these two sources, the resulting sediment budget indicates that about 60% of the sediment fill is derived from the marine beaches, while the 40% balance was contributed by the five rivers draining into the Bay. These are the proportions of the coarser grain sizes, very fine sand up through gravel. It is likely that the finer sediments (clays and silt) found in the Bay are derived from the rivers, and its inclusion would somewhat boost the contribution made by that source and proportionally decrease the percentage derived from the ocean beaches. Accordingly, roughly 50% of the surface sediments found in Tillamook Bay were derived from the marine beaches, 50% from the rivers. Again, these results are based on analyses of the surface sediments, and undoubtedly would have been different in the distant past.

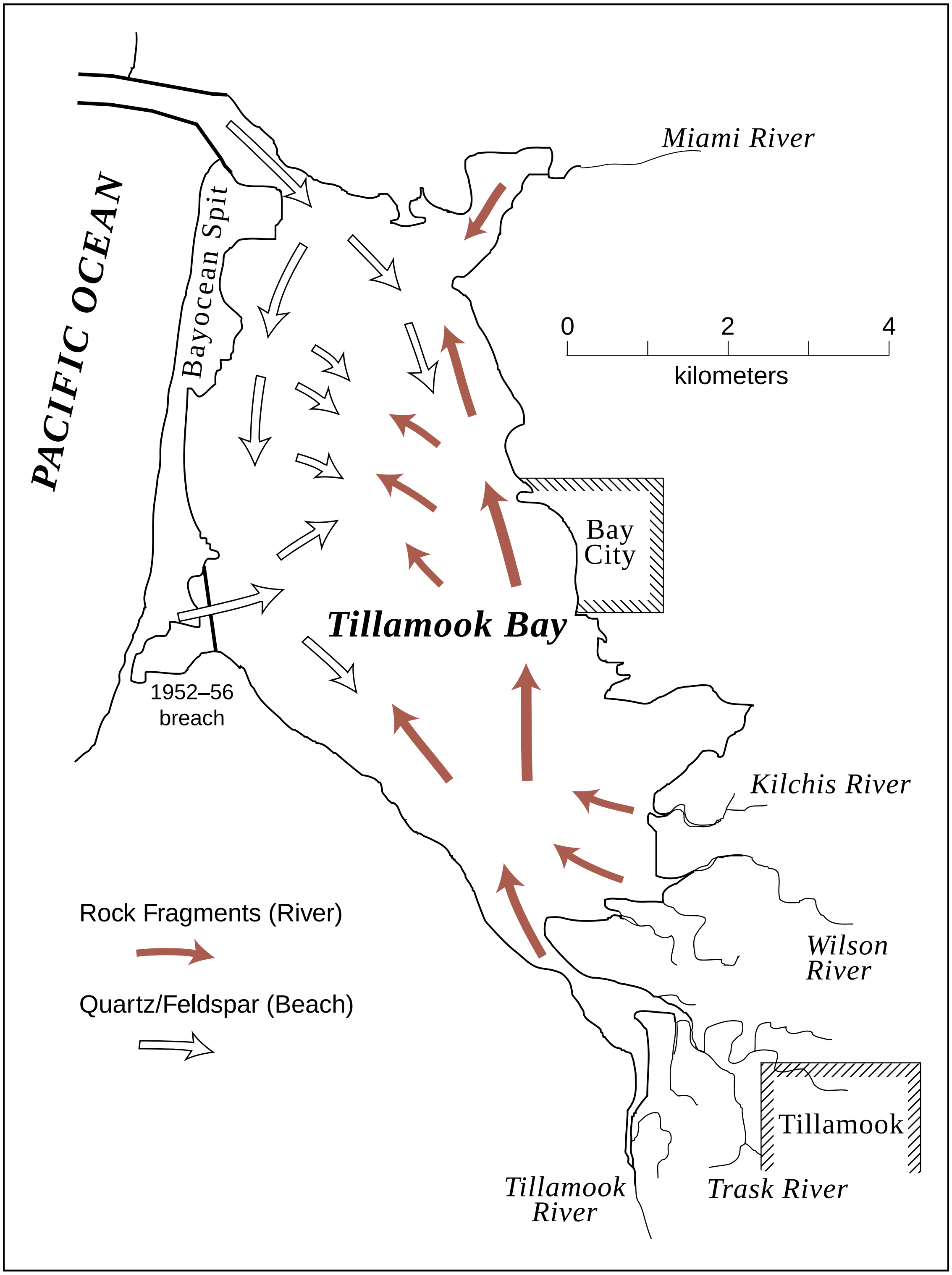


Figure 10. Inferred paths of sediment transport in Tillamook Bay of the sand and gravel derived from the five rivers and from the ocean beach.

SURFACE SEDIMENTS — GEOCHEMICAL INVESTIGATIONS

Background

In addition to the analyses of grain-size distributions and mineralogies of the surface sediments, we also have undertaken a series of geochemical analyses. As seen in the preceding section, while there are substantial differences in grain sizes and mineralogies of the marine beach sand versus sand contributed by the rivers, distinctions could not be made between the five individual rivers based on those gross sediment properties. One objective in undertaking the geochemical analyses was to determine whether there might be more subtle differences that would make distinctions between the rivers possible, so we could establish their respective transport paths and relative contributions to sediment fill in Tillamook Bay. This would be possible if there are measurable differences in the chemistries of the rocks found within the watersheds of the five rivers, as such differences would likely be reflected in the sediments eroded from those rocks.

Unfortunately, as will be described in this section, even with measuring minor chemical elements within the sediments we have been unable to positively distinguish between sediments contributed by the five principal rivers. However, there are marked geochemical differences between the marine beach sand and river sands, not surprising in that we already have seen that they have contrasting mineralogies. Still, this is an extremely useful result in that geochemical analysis can clearly differentiate between marine beach and river sands, and can provide more accurate assessments of these sources than the more laborious technique of counting grain mineral compositions as undertaken in the preceding section. The geochemical distinctions made in this section, based on analyses of surface sediments, will serve as the basis for the down-core analyses of sediments in the following section of this report, undertaken to examine changes in sources back through time.

Sediment Sampling and Analytical Procedures

Surface samples for geochemical analyses were collected in Tillamook Bay and from the rivers using the same sampling techniques described earlier in obtaining samples for analyses of grain-size distributions and mineralogies. However, due to the different types of analyses undertaken and the destructive nature of the geochemical analyses, separate sets of samples were collected. The locations of the samples for the geochemical studies are shown in Figure 11.

The procedures for processing the sediment samples in the geochemical analyses are summarized in Table 2. This description includes procedures for dissolving (“digesting”) the sediment samples. Elemental analyses were then performed on the digested samples using a Liberty 150 Emission Spectrometer (Al, Ba, Ca, Fe, Mn, and Ti) and a VG PlasmaQuad 2 ICP-MS (other trace elements). Carbon (C) and nitrogen (N) contents of the sediment samples were determined using a Carlo-Erba CNS analyzer. Internal rock and sediment standards were employed; based on comparisons with these standards, the absolute accuracy of the procedure is better than 10% for all of the major elements.

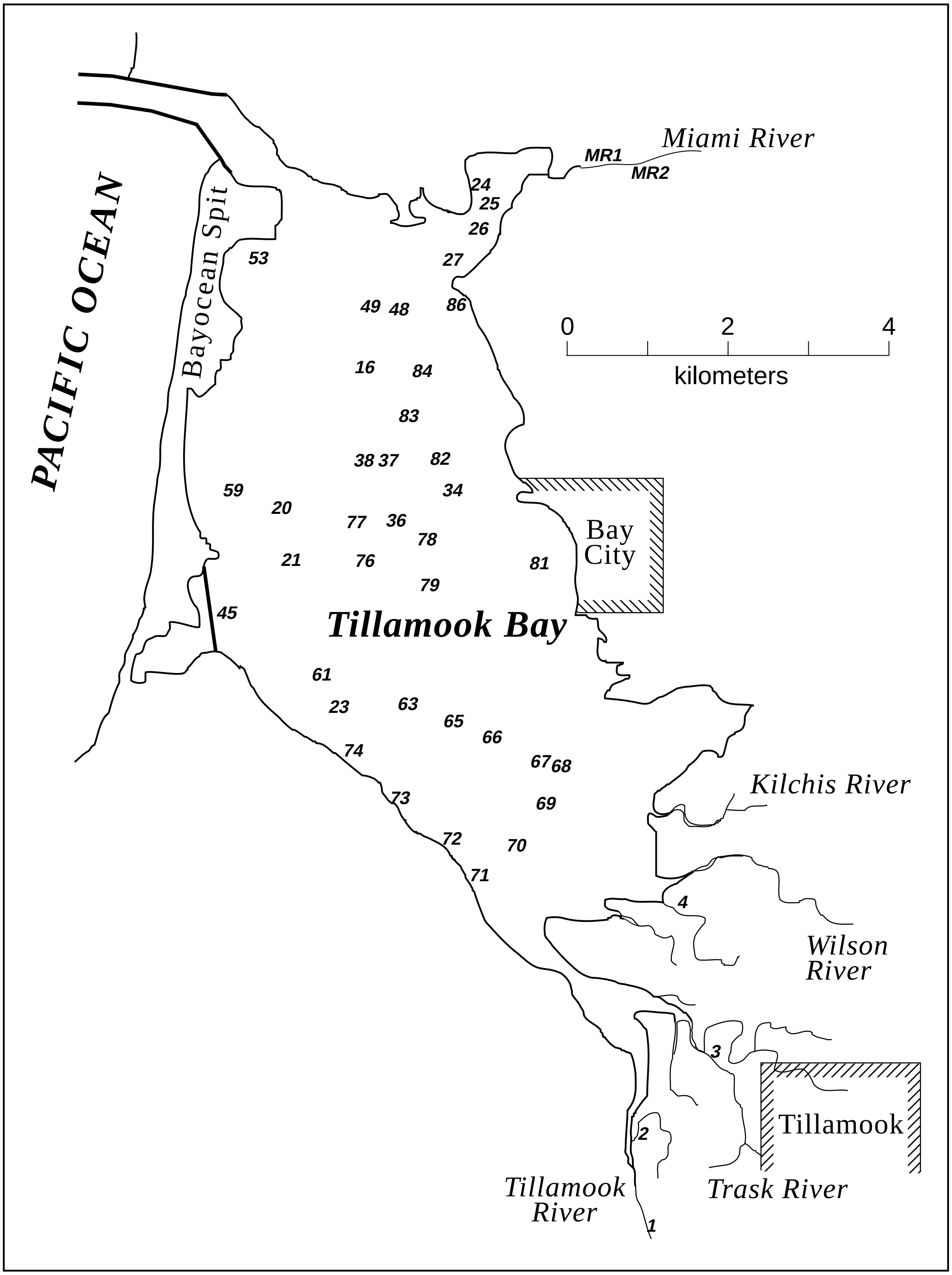


Figure 11: Map showing the locations of surface sediment samples collected for geochemical analyses.

Table 2. Procedures for digesting sediment samples.

1. If estuarine samples, rid salt by successive centrifuging and rinsing with DW or by successive candle filtering.
2. Freeze sample and freeze-dry 1 to 3 days—depending on sample size.
3. If necessary, hand grind with ceramic mortar and pestle.
4. Wiggle-bug 5 minutes in plastic vial with plastic ball pestle.
5. Weigh out approximately 0.1 gram into a small vial and place sample in constant humidity chamber overnight.
6. Weigh numbered Sevillex Teflon vial.
7. Weigh out 0.025 grams nominal of dried sediment.
8. Add 1 ml. of concentrated double-distilled HF to Sevillex vial and add dried sediment.
9. Add 1 ml. of 16N double-distilled HNO_3.
10. Put in 80-85° C oven overnight.
11. Let cool to room temperature.
12. Rinse lid into vial with 0.25 ml. 6N double-distilled HCl - 2 times.
13. Put on hot plate in laminar flow bench and heat to just below boiling with lid off.
14. Evaporate the sample to about 0.5 ml.
15. Move hot plate to $HClO_4$ fume hood and add 0.5 ml conc. double-distilled $HClO_4$ - evaporate sample down to small bead - 2 times.
16. Take sample back to laminar flow bench and add 0.5 ml. 16N double-distilled HNO_3 and evaporate sample to a small bead.
17. Add 0.5 ml. 8N double-distilled HNO_3 and evaporate down to small bead.
18. Add 5.0 ml. 2N double-distilled HNO_3 and with the lid on, let sit overnight ONLY!
19. Weigh and transfer to storage vial.

Analysis Results

Detailed results from all of the geochemical analyses of the surface samples in Figure 11 are presented in the data report (Komar et al., 1998). We will not discuss the measurements in detail because many of the elements analyzed show the same or similar patterns; thus, any discussion on an element by element basis would be redundant.

Titanium (Ti) is generally a major element in rock material (for the Coast Range, TiO_2 contents are typically between 1 and 3% (Globerman, 1980). Ti distributions throughout Tillamook Bay should generally reflect contributions of rock material and sand from the upland regions of the river watersheds. A map of the distribution of this element, Figure 12, supports the conclusion that the primary source of material in Tillamook Bay is weathered volcanic debris from the uplands and that rivers dominate the input of this element into the Bay. The marine beach sedimentary component provides a source of low titanium sand. Clearly the data in Figure 12 support the conclusion based on measurements of mineral grain sizes and compositions that the northwest portion of the Bay is dominated by the input of marine sand, whereas the southern and eastern Bay are dominated by riverine material.

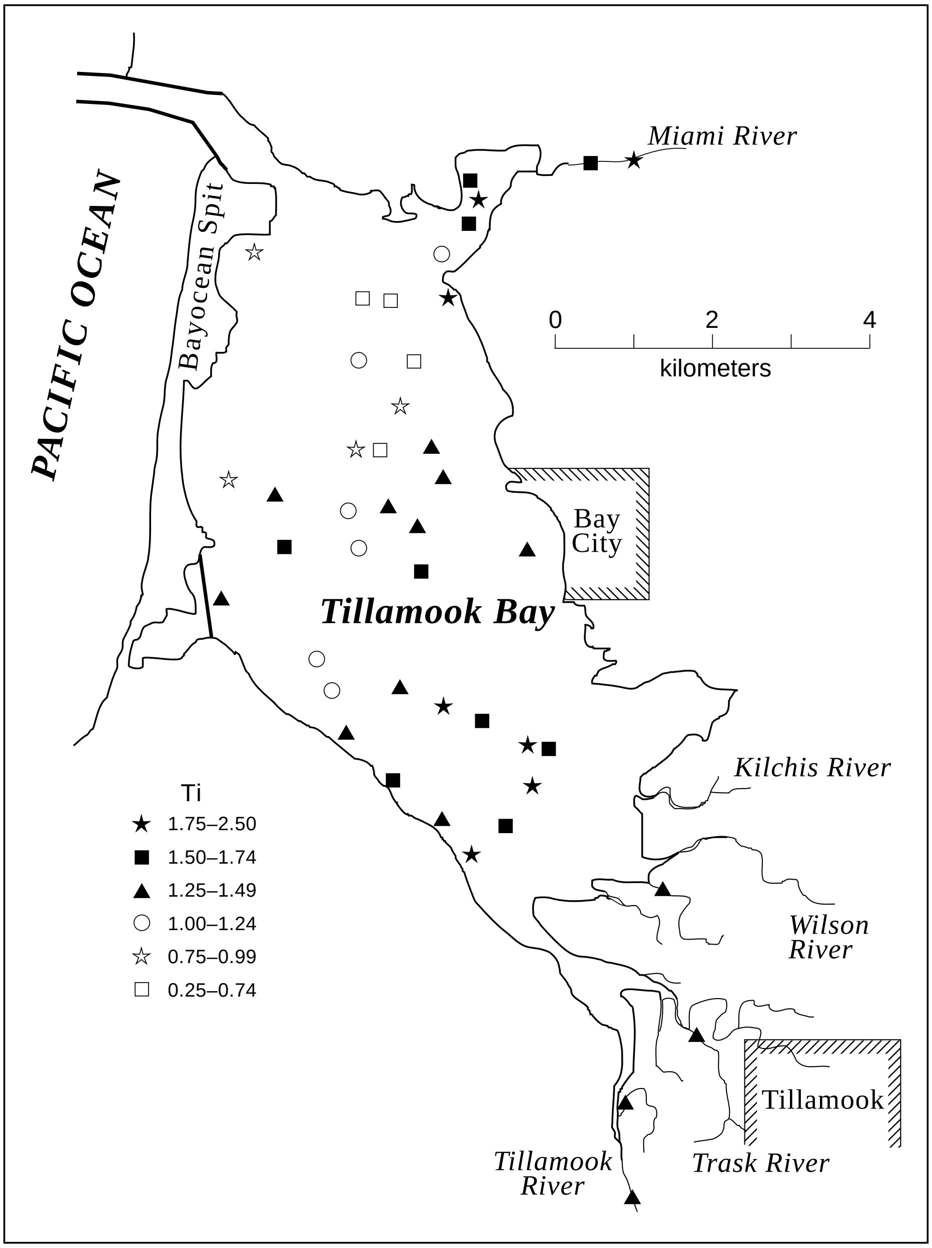


Figure 12: Distribution of titanium (Ti) concentrations in the surface sediments.

A standard procedure in analyses of geochemical data is to examine variations in ratios of elements, rather than inspecting absolute concentrations as done in Figure 12 for titanium. By forming ratios of titanium with other elements, it may be possible to distinguish additional differences in source materials. Aluminum contents in crustal materials are relatively constant (~8%), whereas the Ti contents tend to be more variable in volcanic rocks. Thus, the Al:Ti ratio could provide a means to distinguishing between different sources of Bay sediments. The map of the Al:Ti ratio, Figure 13, again clearly supports a difference between the riverine and the marine sources of sediment; however, the ratios near the river sources are all relatively constant, thus the use of this particular ratio does not provide a tool for differentiating between the five different river sources.

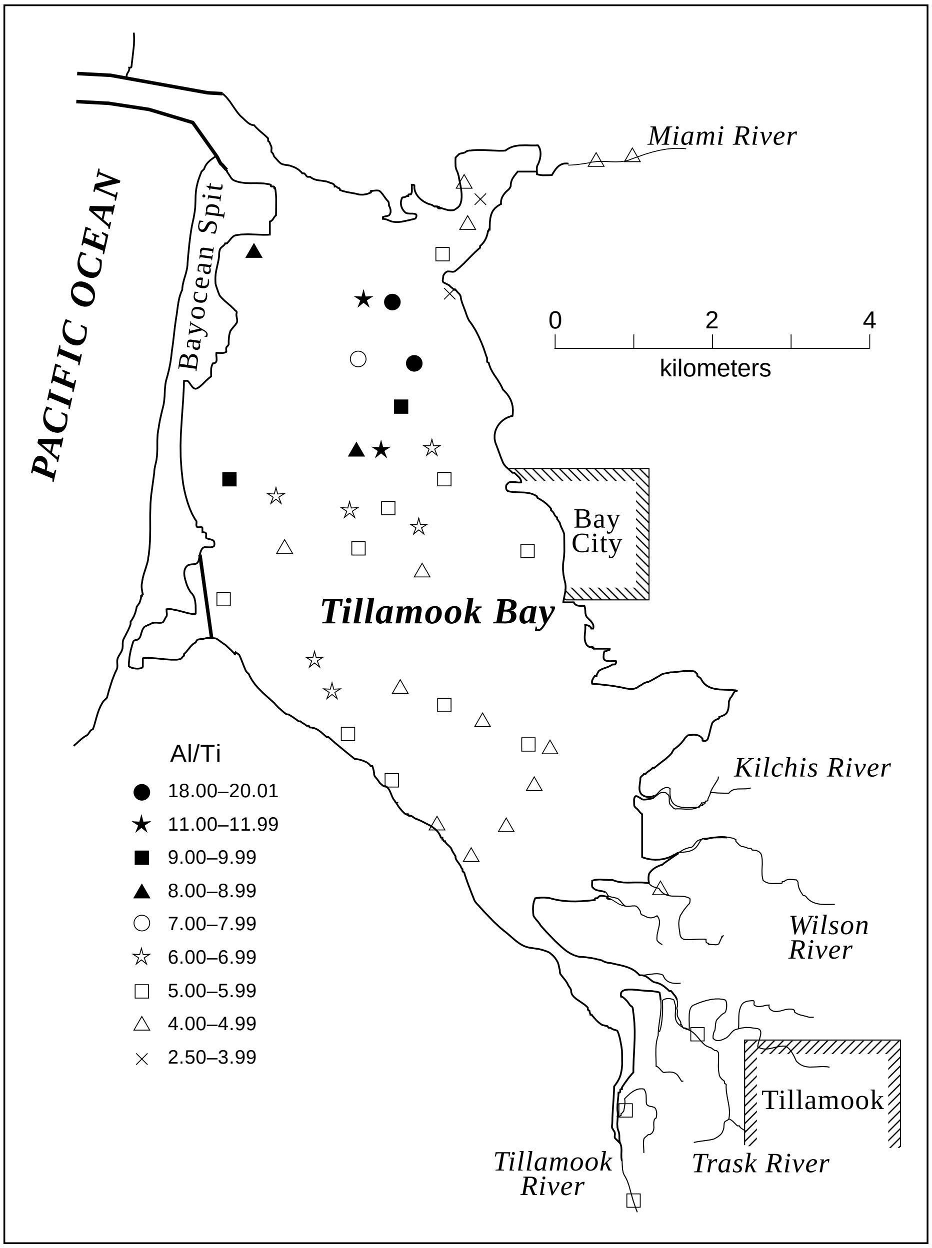


Figure 13: Distribution of Al:Ti ratios in the surface sediments.

We also measured the concentrations of a number of minor or trace constituents in the surface sediment samples. These trace constituents potentially provided our greatest hope in using geochemical analyses to differentiate between sediments derived from the five individual rivers, but would only be successful if there are significant differences in trace elements between the rock types found in the five watersheds. As an example of the analysis results, the Ba:Ti measured ratios plotted in Figure 14 exhibit a pattern across the extent of Tillamook Bay that is consistent with there being only two sediment sources — the rivers and the marine environment. Unfortunately, again no significant distinctions could be made between the five rivers in the minor and trace element constituents.

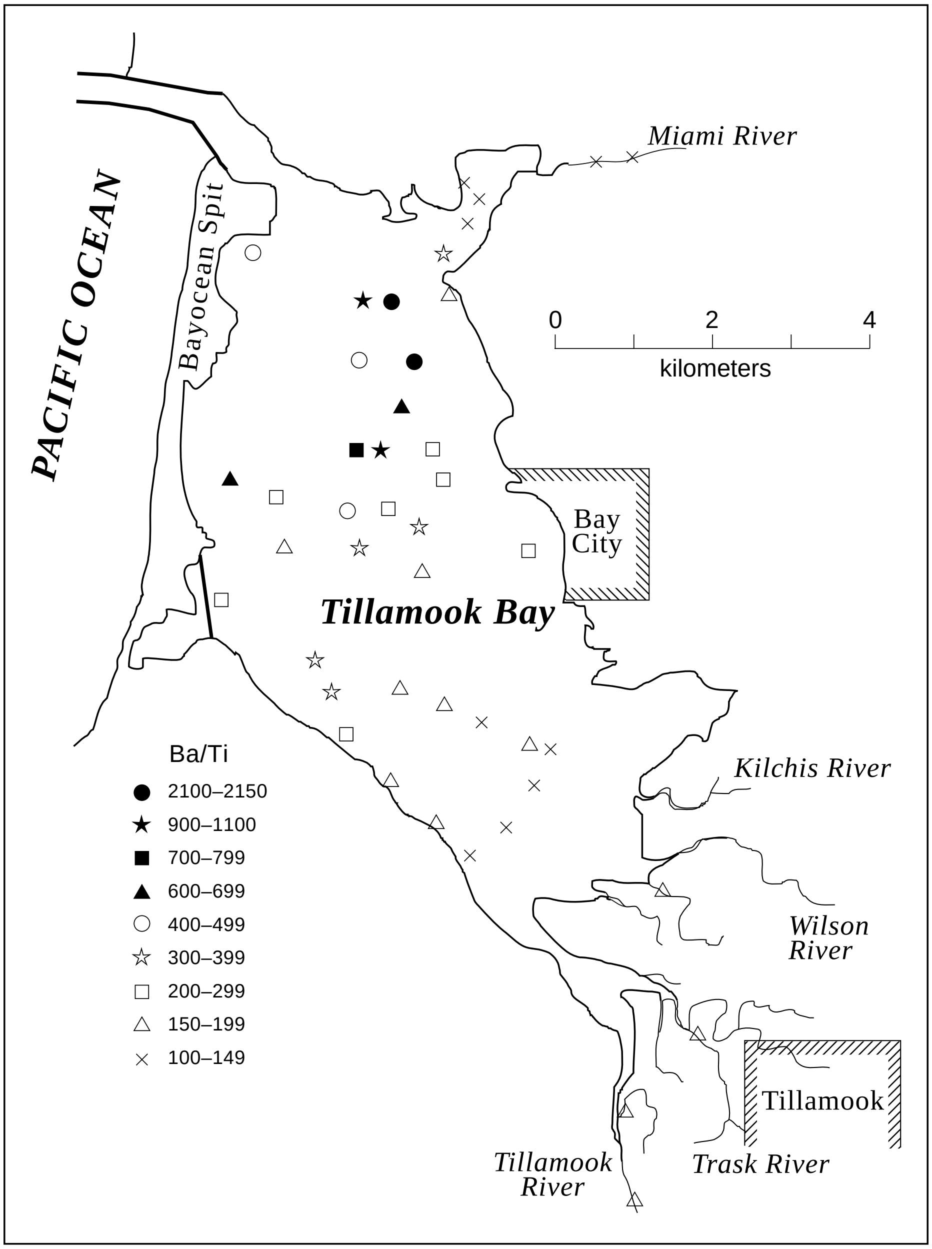


Figure 14: Distribution of Ba:Ti ratios in the surface sediments.

Overall, as seen in Figures 12, 13 and 14, the distributions of major crustal elements and minor trace elements all indicate a mixed riverine source of sediment entering the Bay and dominating the sediment distribution throughout the southern and eastern portions of the Bay. The dominant pathway of riverine sediment transport is clearly along the eastern channel. The dominance of marine sand near the site of the 1952-56 breach on the western side of the Bay suggests that this is not a significant route of riverine sediment transport. Thus, the results from the geochemical analyses reconfirm the interpretations of sediment transport paths presented in Figure 10, based on analyses of grain-size distributions and grain mineralogies.

While the preponderance of data generally divide the sediments into two sources, there are subtleties within the geochemical measurements that may suggest the existence of additional sediment sources. As discussed above, the Ba:Ti ratio clearly suggests a two-source system. When plotted in Figure 15 as the Ba concentration versus the Ti concentration, the nearly linear trend of the data is evidence that most of the variation is explainable as the mixing between two end-members (a high Ba:Ti end-member, and a low Ba:Ti end-member). Despite this nearly linear indication that there are only two components, the data in Figure 15 suggest that there may actually be a third component — there are samples within the system having relatively invariant Ba concentrations, but with changing Ti concentrations. This implies that the Ba:Ti ratio may not be sufficiently sensitive to detect small changes in sedimentary sources. Thus, we further pursued our investigation by examining the distributions of other trace constituents. These constituents will have their own unique chemical behaviors during rock formation and subsequent weathering. Therefore, certain sedimentary sources may have fairly unique trace element chemistries, yet may have similar major element chemistries.

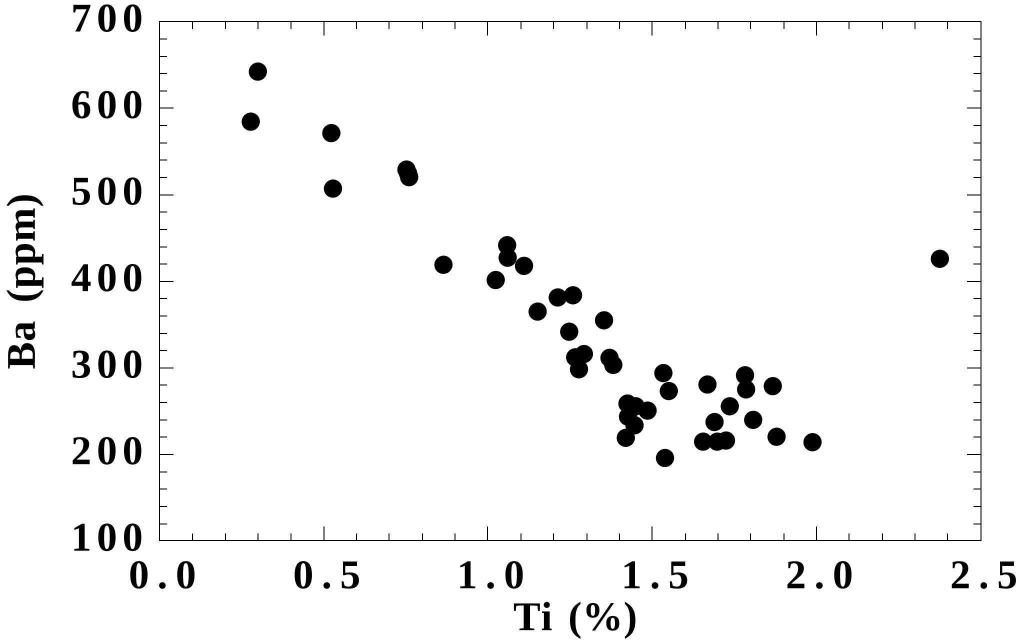


Figure 15: Barium (Ba) versus titanium (Ti) concentrations in the surface sediments.

Several other trace elements suggest that there are three sedimentary components within the Tillamook Bay system. For example, both phosphorus (P) and samarium (Sm) demonstrate what appears to be a three component system (Fig. 16). Note that P is a minor element in the sediments, with concentrations in the parts-per-million (ppm) range, whereas Sm is a trace element in the parts-per-billion (ppb) range. Sm is one of a group of elements called the rare earth elements, 15 elements having atomic numbers from 57 to 71. The rare earths are a particularly useful group in geological studies because they are geochemically very similar. Except for Eu and Ce, the rare earths are trivalent under most geological conditions having a regular change in the ionic radii for the trivalent rare earths from 1.03 to 0.861 angstroms (e.g.,

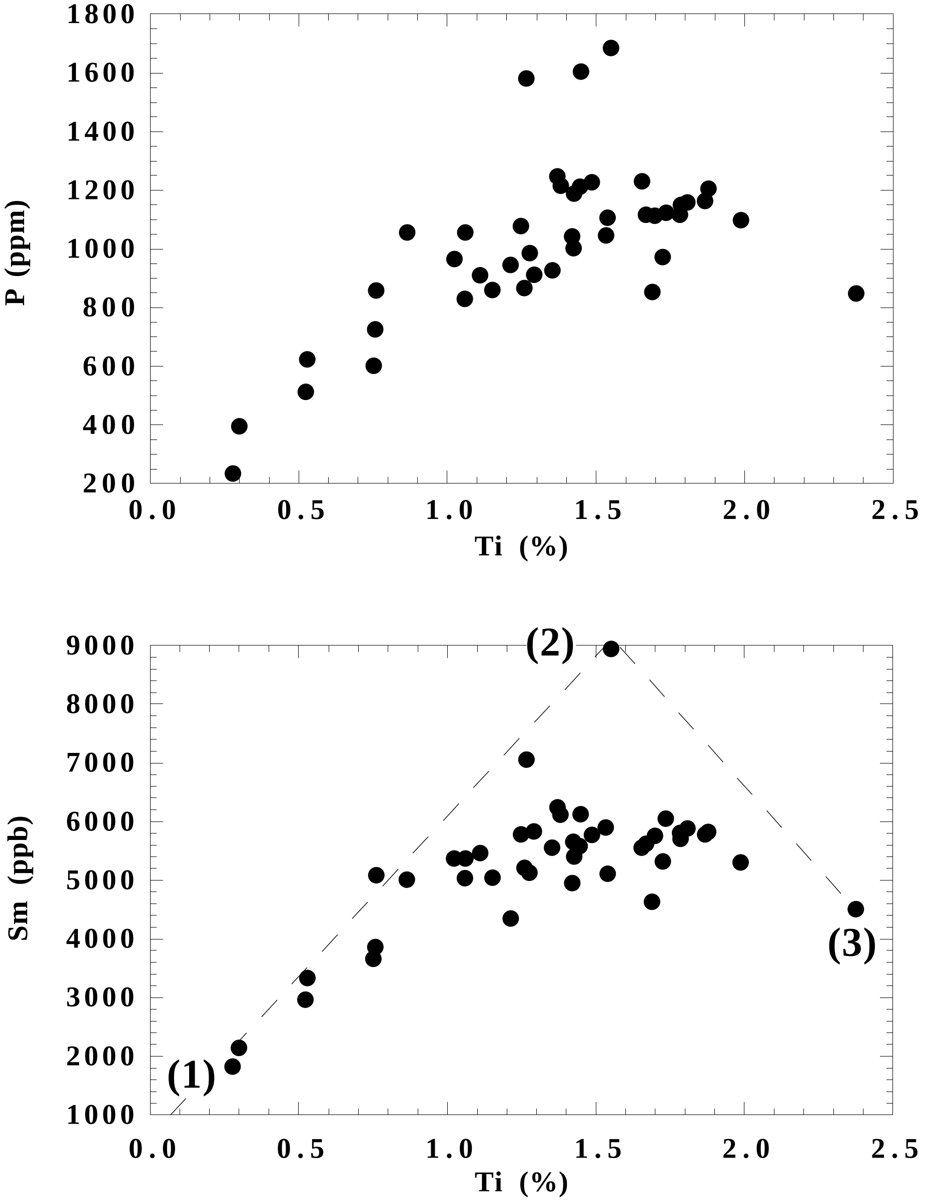


Figure 16: Phosphorous (P) and samarium (Sm) concentrations versus the titanium (Ti) concentrations in the surface sediments.

see review in Hanson, 1980). The rare earths are abundant in minerals with sites preferring an element with a cation radius of about 0.9 to 1.0 angstroms — for example, hornblend. In minerals without such a site (e.g., olivine or plagioclase), the rare earths will have low abundances (Hanson, 1980). The rare earths thus behave similarly from element to element; however, there are systematic differences between the lighter rare earths and the heavier rare earths. We thus examined the ratio of a light rare earth element (neodymium, Nd, atomic number 60) to a heavy rare earth element (Ytterbium, Yb, atomic number 70) to further examine the geochemical characteristics of the surface sediment samples.

Unfortunately, the three components identified in Figure 16 are **not** composed of two riverine and one marine end-member, rather there is a single collective riverine component, a marine component, and either an additional beach component or a component that comes from weathered material from the south of Bayocean Spit. This tentative conclusion is based on the observation that in the northwest part of the Bay there are two distinctly different components, and that the sediments from this region are mixtures between these two non-riverine components. Figure 16 demonstrates the chemical differences between these two non-riverine sources in that samples which fall along the line between (1) and (2) are mixtures of these two chemically distinct components. The end-member samples identified as (1) and (2) in Figure 16 are designated as samples 48 & 84 for component (1) and samples 20 & 21 for component (2); component 3 is the Miami River sample — see Figure 11 for sample locations. Samples 48 and 84 are in a region of the Bay to the west of the dominant channel. These samples contain the lowest Ti concentrations of all samples, and therefore represent an end-member. One possible way to explain these results is that hydraulic sorting in this region may have left behind only the high Al:Ti material (likely to be predominantly feldspar). Consistent with this idea is the fact that the samples from this region were taken from a large sandy area out of the main channel. Samples 20, 21, and 61 have low Al:Ti ratios, but have other elemental ratios much like the marine component that was characterized by the high Al:Ti ratios. For example, both sets of samples have high Nd:Yb ratios, whereas the rivers tend to exhibit lower Nd:Yb ratios. It is possible that this second grouping of samples (labeled 2 in Figure 16) represents weathered material from the region south of Bayocean Spit that is distinctly different from the weathered material brought into the Bay by the five major rivers. Much of this material could have been delivered to the Bay when it was breached in 1952-56, or may simply be part of the natural weathering process. Consistent with the idea of a weathering process contributing additional material to this region is the fact that our sediment grain size and composition studies suggest a substantial gravel component in this area. The presence of the gravel suggests that local rock material may be contributing to sedimentation. It is important to further note that the beaches in this region have a significant gravel component. Another possible explanation for the observed pattern of sedimentation in the northwest region of the Bay is that there is a single “marine” component and sediment sorting has preferentially concentrated a specific component on the western side of the Bay, leaving the central portion of the Bay depleted in that component. Further work will be needed to elucidate the sources of these components.

The riverine components all appear quite similar in composition, with the Miami being the one river having the most extreme composition — i.e., end-member (3) in Figure 16 is derived from the Miami region. All of the other riverine or near-riverine sources have similar Ti concentrations and the ratios of other elements to Ti also reflect a common source. Thus, we must conclude that each of the rivers delivers very similar material from the same types of rocks in their upland watersheds. This conclusion is not subtle; all of our data corroborate this finding.

Summary of Results and Interpretations

The initial objective in undertaking the geochemical analyses of surface sediment samples collected in Tillamook Bay and from the five rivers was to determine whether there might be subtle chemical differences that would help us to distinguish between sediments from the multiple sources. Unfortunately, even at this level of sophisticated chemical analysis we cannot positively distinguish between sediments contributed by the five individual rivers. Only the Miami River appears to be distinctive, and this required the measurement of trace elements as well as major elements. The near uniformity of the geochemistry of the sediments derived from the five rivers is attributable to the essentially identical rocks found within their watersheds, and similar weathering processes.

Sediments within Tillamook Bay derived from the marine beach and from the rivers are geochemically much different. For the most part analyses of both major and trace elements demonstrate a first order linear mixing between sediments from these two environmental sources, although the details of the analyses suggest that there may be a third source that is interpreted to be weathered material entering the Bay from south Bayocean Spit.

The geochemical distinctions made in this section, based on analyses of surface sediments, can serve as the basis for the down-core analyses of sediments, and this will be the focus of the following section of this report. It is easier and more accurate to measure the down-core variations in chemical elements than it is to measure grain-size distributions and mineral compositions at intervals down core. As demonstrated in the surface sediments, the geochemical analyses of down-core samples would provide measurements of relative contributions of riverine versus marine sediment inputs into the Bay, undertaken to examine changes in sources back through time.

THE HISTORY OF SEDIMENT ACCUMULATION IN TILLAMOOK BAY — A STUDY OF CORE SAMPLES

Background

Questions concerning the long-term accumulation of sediments in Tillamook Bay require analyses of ancient deposits buried beneath the floor of the Bay, sediments that were deposited hundreds to thousands of years in the past. Investigations of those deposits are needed in an attempt to establish a chronology of sediment accumulation and to determine whether there have been changes in river versus marine source inputs through time. For this purpose, gravity cores were collected and subjected to a variety of analyses. Attempts to measure sediment accumulation rates are based on carbon-14 dating of shells found at depth within the cores and measurements of lead-210 profiles down core. Interpretations of the results are made difficult by the activities of organisms that burrow into the sediments, but the evaluated sediment accumulation rates are found to be largely consistent with historic changes in bathymetric depths within the Bay determined by surveys. Changes in river versus marine source inputs through time are established using the geochemical distinctions made in the preceding section, based on analyses of surface sediments. In this section the same types of analyses of major and minor elements are extended from the sediment surface down core to similarly evaluate sources of the ancient sediments.

Core Collection and Analysis

Sediment cores were collected from 9 different sites within Tillamook Bay, shown in Figure 17. Note that core ID numbers have been abbreviated in the figure—i.e., core SAC9610-006GC is abbreviated as SAC006, having eliminated the 9610 and GC from the name. Core locations were accurately established by using a ship-board GPS system. Core collection was accomplished by using a standard gravity corer and a Benthos gravity corer deployed from the Oregon State University ship *RV Sacajawea*. Site selection focused on areas that could be reached by boat during high tide, and were sufficiently deep to permit deployment of the gravity corers. Eight of the 9 collected cores were in the length range 1.5 ± 0.25 meters, while the ninth core was about 0.5 meters in length. The eight longer cores were first processed for color reflectance, visually described, and then photographed for archiving. Shell material that could be used for carbon-14 dating was extracted from the cores. The cores were then sampled at intervals along their lengths and subjected to lead-210 activity measurements and to the same geochemical analyses described in the preceding section and outlined in Table 2.

Color variations can often be seen in freshly collected cores, changes that may relate to different materials or sediment grain sizes having been deposited in the past. Of specific interest in Tillamook Bay is whether distinct dark layers might be visible in the cores, layers associated with the “Tillamook Burns”. Reflectance measurements were made to test this possibility, employing an *Automated reflectance spectroscopy logger* that is far more sensitive than the human eye in detecting color changes. This split-core logger measures diffuse reflectance spectra in ultraviolet, visible, and near-infrared bands. The reflectance instrument consists of four subsystems: (1) a core transport mechanism to slowly move the sediment past the sensors, (2) illumination and sensing optics, (3) a spectrograph and detector, and (4) computer control and data processing. Split sediment cores move under the sensing optics on a computer-controlled conveyor system. A regulated light source illuminates the sediment surface via a glass fiber-optic cable. The sensing head, which moves vertically to maintain a constant distance from the sediment surface, collects the reflected light. A second fiber-optic cable delivers the reflected

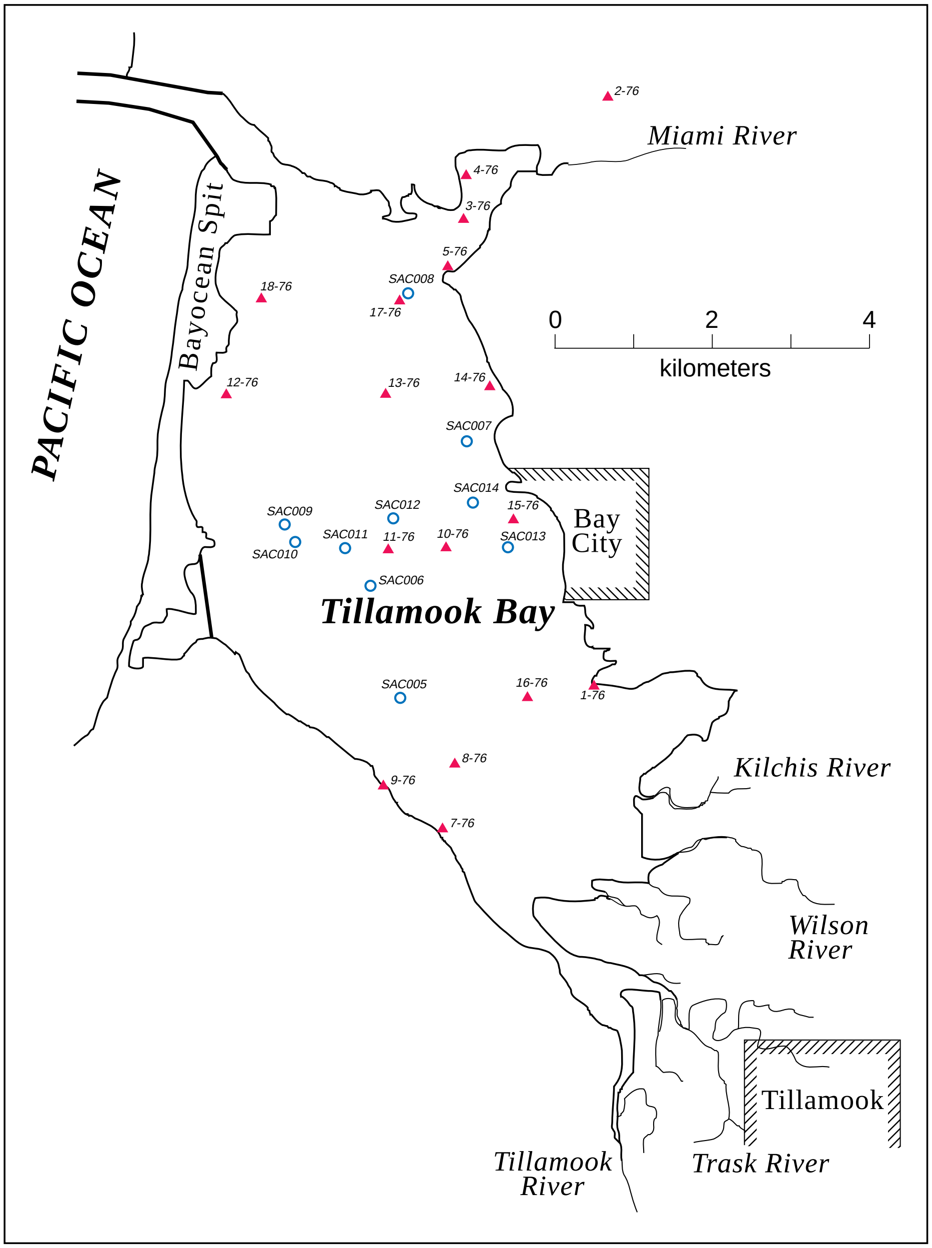


Figure 17: Coring sites for this study [open circles] and for those collected by Glenn (1978) [filled triangles].

light to the spectrograph, where it is split into its spectrum with a diffraction grating and detected in a 511-channel diode array. The measurement system is controlled by a 386-PC computer, but raw data are written directly to a more powerful Sun UNIX workstation. This computer converts the data to reflectance spectra and makes them available for immediate analysis (Mix et al, 1992).

Reflectance Measurements

Reflectance measurements were made at 1 to 2 cm intervals along the lengths of the cores collected in Tillamook Bay. The results for the red and blue components of visible light are plotted in Figure 18. As can be seen, there is a near uniformity in sediment color along the lengths of the cores, and this is found as well for the other light components measured. While there is the occasional “spike” in color change (e.g. Core SAC007), there are no distinct color signatures common to all cores that might be attributable to material associated with the Tillamook Burns.

In the 1970s the U.S. Geological Survey collected a number of sediment cores from Tillamook Bay (see Figure 17 for locations), and similarly were unable to detect any noticeable dark layers that might have resulted from forest fires (J. Glenn, personal communication). Based on our

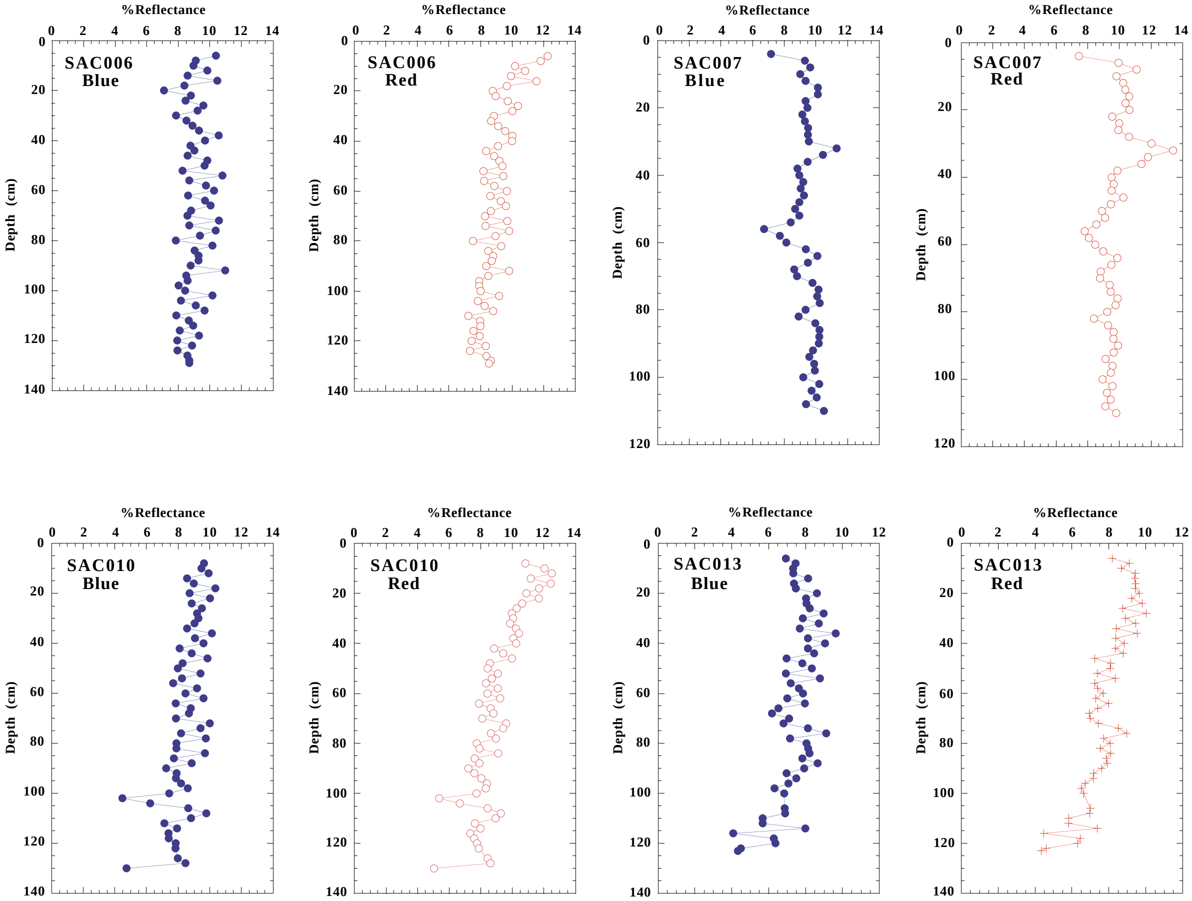


Figure 18: Reflectance measurements along sediment cores collected in Tillamook Bay.

combined results from cores over much of the extent of Tillamook Bay, it can be concluded that there are no well defined layers in the Bay that might be attributed to material resulting from the Tillamook Burns. This absence of direct evidence does not preclude the possibility that there actually was a period of increased sedimentation as a result of the fires. Charred wood from the fire would float and therefore would have been quickly flushed through the estuary. Our hope was that some had become water logged and settled to the bottom, forming a dark layer that could be detected by the reflectance measurements. However, even if some charred material did initially accumulate on the bottom following the fires, the dark layer would likely have been dispersed by the burrowing activities of organisms. Their burrowing largely homogenizes the upper 1 meter of sediment in the Bay, and this factor more than any other probably accounts for the uniformity of color reflectance seen in the measurements in Figure 18, and the lack of distinct sediment layers that can be attributed to the Tillamook Burns.

Changes in Sediment Sources with Time

The investigations of the surface sediments discussed in the preceding section were successful in distinguishing between sediments contributed to Tillamook Bay by the major rivers and sediments carried into the Bay from the marine beach. Initially the distinction was based on detailed analyses of grain-size distributions and mineral compositions, but subsequent analyses established that the distinction could be more easily made by differences in geochemical measurements of major and minor elements. Those investigations of surface sediments and their sources can serve as the basis for an examination of changes with time in the source inputs to the Bay, based on the same types of geochemical analyses of sediments found at depth within the sediment cores.

Figure 19 shows the results for the geochemical analyses of sediments in Cores 5, 6, 7, and 10, whose locations are given in Figure 17. Changes in the Al:Ti ratio down core imply variations with time in the relative contributions of marine versus riverine sediment, with the higher Al:Ti ratios corresponding to an increase in the marine source relative to the rivers. In Figure 19 (a) it is seen that Core 7 clearly shows a large increase in the Al:Ti ratios at depth within the sediment. At the earliest stage in the sediment record, the marine beach was a significantly more important source of sediment to Bay filling than now, but with time up to the present there has been a progression in the sedimentary regime from predominantly marine to predominantly river supplied sand at the site of this core. Core 7 came from the eastern half of the Bay, Figure 17, from the edge of the main channel along which water and sediment from the rivers now moves toward the ocean inlet. This is a location that should have been particularly sensitive to changes in relative sediment contributions from the marine and river sources back through time. Cores 5 and 6 from the south part of the Bay have lower Al:Ti ratios than Core 7, Figure 19 (a), demonstrating that in the past this area has been dominated by river sediments. In Core 5 there is a subtle increase in Al:Ti at about the 60-cm depth, which matches the more dramatic increase in Core 7.

The Al:Ti profile in Core 6 is irregular, Figure 19 (a), suggesting that at this core site there has been some fluctuation in the relative contributions between the marine and river sources. Core 10, to the immediate west of Core 6 and closer to Bayocean Spit (Fig. 17), shows much stronger

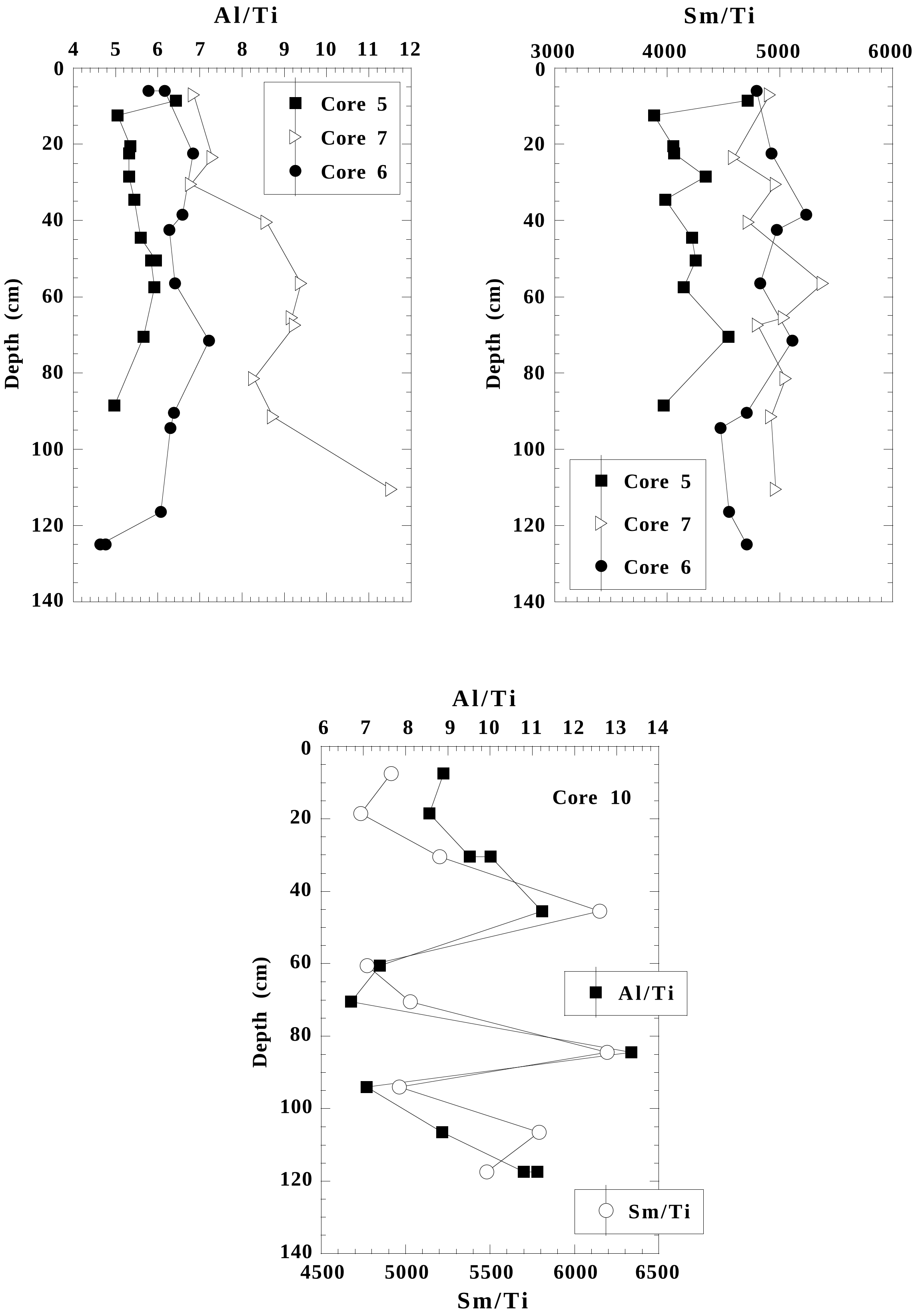


Figure 19: Variations in Al:Ti and Sm:Ti ratios at depth within core samples.

variations in Al:Ti ratios, Figure 19 (c), with a strong dominance of marine sediment at the 42- and 82-cm levels in the core. The down-core variations in Al:Ti in Cores 6 and 10 are suggestive of past episodes of breaching or overwash of Bayocean Spit, at the south end of the Spit where it is narrowest and where the 1952-56 breach occurred.

An increase in the marine component in the past might have resulted from either the occurrence of a former breach in Bayocean Spit, perhaps larger than occurred in 1952-56, or it might be the result of a subduction earthquake and tsunami, the last occurrence having been in January 1700. Complicating any interpretation is the fact that, as seen in analyses of the surface sediments, there are two low Al:Ti sources. Therefore, the lower ratios found in the sediment cores could be caused by the input of either the component delivered from the Bayocean Spit area or a riverine component. The interpretation of the high Al:Ti ratios is, however, less ambiguous. The high Al:Ti ratios clearly come from the marine source and are indicative of feldspars. For the lower Al:Ti ratios, to differentiate between the riverine and the spit components, we can use the ratio Sm:Ti in conjunction with Al:Ti. As seen in Figure 19 (b), the Sm:Ti ratio is high for both components in the northwest region of the Bay, whereas it is low for the riverine material. These differences offer an additional tool for interpreting the record of sedimentation within the Bay. For Core 7 the Sm:Ti ratio is fairly constant, exhibiting a maximum at about 60 cm depth in the core. This maximum corresponds to the maximum at 60 cm for the Al:Ti ratio, and is consistent with our interpretation of a predominantly marine source. The similarities in the down-core Sm:Ti ratios contrast with those for the Al:Ti ratios. The invariance in the Sm:Ti ratios suggests that some of the variability in the Al:Ti may actually be driven by significant inputs of the spit component. This interpretation is somewhat tenuous, given the relative insensitivity of the Sm:Ti ratio as compared to the Al:Ti ratio. That being said, when we compare the chemistry of the core samples with the surface sediment samples, the chemistry of the core samples are similar to the surface sediment mixtures found in the northwest region of the Bay. In summary, the distinct elevation in the Al:Ti ratio (and in the Sm:Ti ratio) at about 60 cm depth is clearly from a large input of a marine sediment, whereas other variations in the Al:Ti ratio are at least partly influenced by changes in the relative contributions of the two non-riverine sources through time.

Measurements of Sediment Accumulation Rates

A primary objective of our study has been to determine rates of sediment accumulation in Tillamook Bay, and to assess whether those rates have increased during historic times due to human induced factors. More specifically, with respect to sedimentation issues we have had three primary objectives: (1) To develop a chronology of sedimentation rates; (2) to develop an historical perspective of sedimentation in the Bay; and (3) to identify areas that have experienced the greatest relative sediment deposition during the last 100 years and potentially identify processes producing those changes. In an attempt to achieve these goals, we have obtained carbon-14 dates of shells found at depth within the sediment cores, and measured lead-210 profiles from 5 cores. As will be discussed, there are unfortunate characteristics of sedimentation within Tillamook Bay that have made achieving these goals to the level intended impossible. However, we can still provide some accounting for each of the above stated goals, and by comparing the measured sedimentation rates with surveyed bathymetry changes during the past century, make inferences regarding historic changes in sediment accumulation. The essence of our findings to date is that sedimentation has decreased during the last 50 years.

One approach to determine average sedimentation rates was to find organic material at depth within the cores that could be dated using carbon-14 techniques. Two shell samples were obtained at approximately 1 meter depths in 2 cores, and these were analyzed for carbon-14 contents to provide dated ages that might be employed to assess long-term average sedimentation rates; the results are given in Table 3. Unfortunately, the uncertainties in carbon-14 dating techniques are substantial. The largest of the uncertainties is the correct calendar age of the sample. In Table 3 we have presented the data in two different ways; (1) without a reservoir correction, and (2) with a reservoir correction of 390 radiocarbon years. Pacific Ocean water off the coast of Oregon does not have a 0 radiocarbon age (its “age” could be as great as 700 years; A. Mix, pers. comm.). This considerable age of the ocean water results because upwelling returns old water from the deep Pacific to the surface, and this old water has a radiocarbon age of approximately 1000 years — i.e., it takes about 1000 years for deep water to come from the Atlantic to the Pacific, and then return to the surface. Thus, once the water upwells it will produce a much older surface “age” than would otherwise be expected. River water , in contrast, should supply a 0 age reservoir of carbon. If the organisms that formed the shells found in the cores were predominantly exposed to river water, then we would need no reservoir correction (this is unlikely). The accumulation rates calculated from shells having no reservoir correction (Table 3) should be considered to be minimum estimates. The correction for 390 radiocarbon years is reasonable if the shells are exposed to a mixture of 0 age river water and sea water that is approximately 700 radiocarbon years in age.

Table 3. Historic sedimentation rates in Tillamook Bay

Sample	**Depth**	**Age**[1]	**Age**[2]	**Rates (cm $100y^{-1}$)**
SAC9610-06GC	100 cm	1170 AD	1460 AD	13[1], 20[2]
SAC9610-13GC	99 cm	1420 AD	1720 AD	19[1], 43[2]

[1] Ages and rates that are not reservoir corrected. [2] Ages and rates that are reservoir corrected.

Since the ages of the dated shells are only a few hundred years, the reservoir correction is a significant factor. Both uncorrected ages and those corrected for the 390 years reservoir age are listed in Table 3. Even the corrected ages indicate that the shells are old, some 300 to over 500 years, although found only at 1 meter depth buried within the sediments of Tillamook Bay. The last column in Table 3 gives the corresponding calculated sedimentation rates. Here it is seen that the lower ages of the corrected dates yield sedimentation rates that are approximately twice as rapid as rates based on uncorrected ages. Of the two possible sedimentation rates, the estimates based on the corrected dates are more consistent with what we think the rates should be for the later Holocene, as well as being consistent with the bathymetry survey data that will be examined below. Thus, despite difficulties in interpreting the carbon-14 dates, and also in analyzing the bathymetric surveys, it is significant that these independent approaches yield largely consistent results.

A commonly used technique for determining a “chronology” of sedimentation rates is the use of lead-210 (^{210}Pb) activities measured within core sediments. Lead-210 is derived from the decay of radioactive radon (^{222}Ra) in the atmosphere. Radon is a gas derived from the decay of uranium isotopes in rocks, and can be expected to maintain relatively constant concentrations in the atmosphere spanning geologic time. Its decay thus provides a relatively constant source of lead-210, a solid that “rains out” and accumulates in the sediment. The fundamental assumptions in using lead-210 as a tracer for sedimentation can introduce significant uncertainty when interpreting the data. The primary assumptions are that: (1) the input of unsupported lead-210 into the system has remained constant through time, (2) the distribution of radon is constant with depth in the sediment, and (3) sediment mixing is negligible. This final assumption is critical, and as already discussed in connection with the reflectance measurements, this assumption is invalid in Tillamook Bay due to the burrowing activities of organism. The occurrence of sediment mixing again represents an obstacle in assessing sedimentation rates in Tillamook Bay, this time using lead-210 measurements.

In a well-behaved system, lead-210 activities should decrease with depth in the sediments, eventually reaching a constant value supported by the decay of radon. The lead-210 activity above that supported by the radon is termed “excess lead-210”. It is the distribution of this excess lead-210 down core that provides information on physical processes (i.e., the net sedimentation rate and rate of vertical mixing due to bioturbation). Most of the lead-210 profiles taken from Tillamook Bay show simple distributions where lead-210 activities decrease exponentially with depth, Figure 20, approaching a constant value. Deviations from this pattern are the result of either non-uniform sediment mixing with depth, or non-uniform sediment accumulation through time. For Tillamook Bay, the dominant factor controlling the distribution of lead-210 in the sediments is likely to be mixing by burrowing shrimp and by redistribution of sediment throughout the system — i.e., sediment may come into the Bay and reside at a single location for a period of time, and then be transported elsewhere within the Bay during a major storm or flood event. In Tillamook Bay, neither the sediment mixing rate nor the accumulation rate can be uniquely determined from the distribution of lead-210 alone. For example, if sedimentation of excess lead-210 is at a steady state and if transport of lead-210 down-core can only happen through physical means (i.e., organism mixing), then the distribution of excess lead-210 can be analyzed mathematically to yield relationships for the depth variation of excess lead-210 as a function of the sedimentation rate and the sediment mixing rate (see the Appendix for the mathematical relationships). The difficulty in interpreting the lead-210 measurements in the cores is that the distribution of excess lead-210 can be governed by mixing, sediment accumulation, or a combination of the two processes. It was our hope that sediment mixing would be confined to approximately the top 50 cm of the sediment column, and that measurements from deeper within the cores would represent accumulation below that mixed zone. However, mixing probably penetrates below this 50-cm depth in Tillamook Bay, due to the depth of burrowing by ghost shrimp. We can fit the profiles of excess lead-210 to the equations given in the Appendix to generate “best fits” for values of sediment mixing and accumulation. It is possible to produce meaningful results by assuming that either the sedimentation rate or mixing are negligible, and this has been done to yield the results in Table 4. Depending on the choice of depth interval and on whether or not mixing is included in the model, sedimentation rates derived from these fits range from 7 to 240 cm per century. If we only use data below the 50 cm depths in the cores, this range is reduced significantly to between 7 and 138 cm per century. Limiting the analysis still further by using only measurements below a depth of 75 cm reduces the evaluated sedimentation rates to between 7 and 30 cm per century, results that are most consistent with the carbon-14 dating and with the bathymetric surveys.

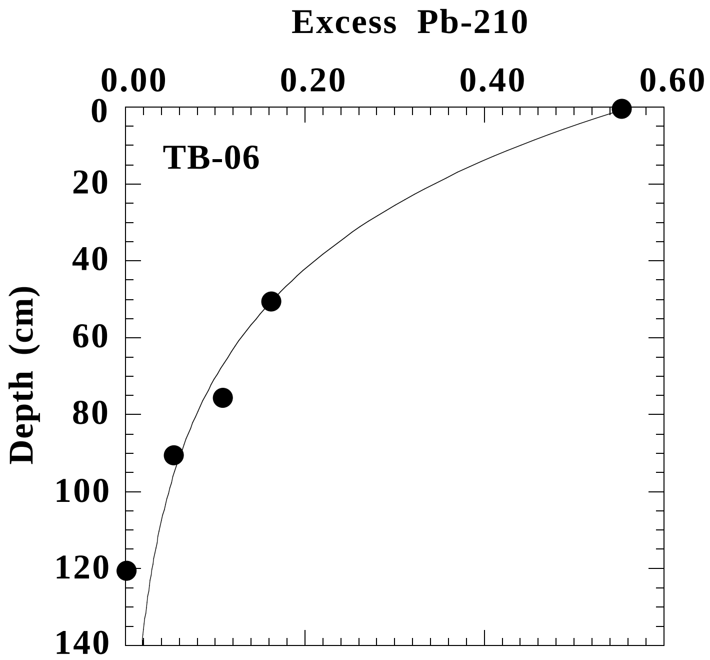


Figure 20: Lead-210 as a function of depth for one of the sediment cores.

Table 4. Summary of lead-210 (^{210}Pb) profile measurements.
D_b = vertical rate of sediment mixing (cm^2/year)
S = sediment accumulation rate (cm/year)

Core	**D_b[1]**	**S[1]**	**D_b[2]**	**S[2]**	**S (no D_b)**	**D_b (no S)**
SAC9610-05GC	44	0.60	3.5	0.70	—	—
SAC9610-06GC	36	1.03	62	0.94	1.49	92
SAC9610-07GC	103	1.06		0.07[3]	2.40	185
SAC9610-10GC	50	0.97	12	1.38	1.64	106
SAC9610-11GC	—	—	—	—	0.20-0.30[4]	—

[1] Model results using equation (1) in Appendix and all the excess Pb-210 data.
[2] Model results using only deeper data (>50 cm).
[3] Model results using data between 85 and 95 cm.
[4] Model results using data between 75 and 90 cm.

Despite the fact that the lead-210 data appear to be consistent with the other sedimentation data, at least when obtained at depth within the cores where mixing by organisms would be reduced or eliminated, the inherent assumptions and modeling uncertainties make further interpretation of this data difficult without additional constraints in employing the equations in the Appendix. What we can say from this data is that Tillamook Bay sediments do not exhibit a simple pattern whereby there is a continuous (and non-mixed) accumulation of sediment at a given rate, followed by a change in sedimentation rate. To express this another way, lead-210 profiles in Tillamook Bay cannot be used to develop an accurate chronology of sedimentation rates. This problem is especially true for the upper 50 cm of sediment. However, if we assume that the data below 50 cm depth in fact represent accurate sedimentation rates, then the rates for cores SAC9610-07GC and SAC9610-11GC are consistent with the long term average sedimentation rate for the Bay (see below). In contrast, cores SAC9610-05GC, SAC9610-06GC, and SAC9610-10GC, which are all in the southern and western portions of the Bay, exhibit extremely high sedimentation rates (70 - 138 cm per century). If accurate, these high rates are likely to be a product of sedimentation processes during the first half of this century, and the contemporary rates for these cores are not definable because of intense sediment mixing in the top 50 cm of sediment.

Bathymetric Surveys and Sedimentation Rates

Probably the best assessments of sedimentation rates during the last 100 years are derived from repeated bathymetric surveys that have been undertaken in the Bay (Bernert and Sullivan, 1998). The bathymetric surveys show that the Bay volume has decreased from 31,051,168 m^3 in 1867 to 23,464,061 m^3 in 1954, followed by an increase to 24,828,008 m^3 in 1995. There are a host of caveats connected with the interpretation of this data (see discussion by Bernert and Sullivan); however, there is simply no other source of data that allows one to ascertain whole-bay net sedimentation rates.

To calculate the net change in Bay volume due to the accumulation of sediment, we need to remove the portion due to the long-term rise in sea level, since that rise could have contributed to the change in Bay volume. To remove this effect we have assumed that the local rate of change in sea level relative to the land in the Tillamook area is 1.5 mm per year, a rate deduced from resurveys of geodetic bench marks (Komar, 1997). By subtracting the volume changes and dividing by the surface area of the Bay at the Mean Lower Low tidal elevation, we can estimate the net rate of sediment accumulation; the results are given in Table 5.

Table 5. Chronology of sedimentation rates

Years	Rates (cm $100y^{-1}$)
1867-1954	68
1954-1995	5
net 1867-1995	48

If we accept that these changes in Bay volumes revealed by the surveys are reasonably accurate, then it appears that during the first half of this century Bay sedimentation was a factor of 2 to 4 times larger than typical of late Holocene rates, and that during the second half of this century rates have decreased substantially. It is difficult to accurately ascertain sedimentation rates from this data, and we emphasize that these are net rates below Mean Lower Low tide. Furthermore, because the U.S. Army Corps of Engineers has dredged the Bay repeatedly throughout this century, these rates should be considered as minimums. In addition, as shown below, the Bay is accreting along its sides and the areas above Mean Lower Low tide are accumulating sediment at a higher rate than those below Mean Lower Low tide, and this pattern also means that the rates given in Table 5 are minimums if one is considering the entire Bay. Despite these caveats, the rates in Table 5 based on the bathymetric surveys are consistent with the carbon-14 and lead-210 sedimentation rates.

Issues regarding sedimentation within Tillamook Bay are clearly complex. The area that has experienced the greatest relative sediment deposition during the last 100 years appears to be the southern delta region of the Bay. The bathymetric surveys are supportive of the idea that the Bay is accreting along its sides. The results in Table 6 are based on the surveys, and give percentages of the Bay bottom area between different depths (elevations). For example, the fraction of the Bay that is between +2 to +1 meters in elevation relative to Mean Lower Low tide has increased from less than 1% in 1957 to greater than 16% of the total Bay bottom in 1995. This apparent shoaling has come at the expense of the 0 to -2 meter depth interval, which has decreased from about 90% of the bottom area to 70% over the same time interval. Essentially, the data would seem to suggest that the shallowest areas of the Bay have increased substantially during the last 40 years. The dynamics of sediment movement through Tillamook Bay have produced a situation where the area dominated by the shallowest regions have increased at the expense of the next shallowest region. The change in the distribution of sediment, without significantly altering the net accumulation of sediment within the Bay as a whole, could lead to the perception of the occurrence of excessive sedimentation, especially since the 1950s.

Table 6. Percentage of Bay bottom within each elevation (depth) interval. (data provided by R. Garano)

Interval (m)	Interval (ft)	1867	1957	1995
+ 2 to +1	+7 to +3	1.10	0.09	16.06
0 to -2	+2 to -7	80.45	91.15	70.70
-3 to -5	-8 to -16	16.08	7.10	10.08
-6 to -8	-17 to -26	1.69	1.20	1.69
-9 to -11	-27 to -36	0.55	0.33	0.96
-12 to -14	-37 to -45	0.13	0.11	0.38
-15 to -18	-46 to -59	0.01	0.03	0.13

Sedimentation in Tillamook Bay during its Early History

As discussed in the Introduction, Tillamook Bay initially formed roughly 9,000 years ago, when the rising sea level at the end of the Ice Age flooded the drainages of the rivers. It can be expected that sedimentation rates in the Bay would have been high at that time, a period during which river sediments would have been trapped in the deep Bay and tidal currents would have actively transported marine sediments into the Bay.

Sedimentation in Tillamook Bay during this early stage of its formation and history was the focus of an investigation undertaken by the U.S. Geological Survey during the 1970s, with the results published in the report by Glenn (1978). To reach those sediments deposited thousands of years ago, now buried deep within the Bay, the USGS drilled long cores reaching depths of about 30 meters. Locations of their cores are given in Figure 17. Details of the field operations, sample analyses and results can be found in the report by Glenn (1978).

Carbon-14 dates were obtained at intervals along the full lengths of the cores. The dates are derived from extracted organic carbon rather than from shells as used in our study. The reservoir correction for organic material is completely different from that of the shells. In the case of organic material we have to assume that it had a 0 age at the time of its deposition — an unlikely assumption. However, this correction is somewhat less important than before given the considerable ages of the materials being dated. A compilation of carbon-14 ages found in their study is given in Table 7, with the cores grouped by region within Tillamook Bay. Different cores from each region have yielded dates spanning various time intervals, with sedimentation rates inferred for the intervals. Thus, an understanding of the changing rates of sedimentation comes from a compilation of carbon-14 dates obtained in several cores, with the results pieced together.

From the carbon-14 ages listed in Table 7, ranging from 3,300 to 8,400 years BP (before the present), it is apparent that the long cores obtained by the USGS (Glenn, 1978) have recovered samples of sediment that were deposited in Tillamook Bay during the early stages of its history. The time period is obviously much older than has been the focus of our study, which has centered on sediment accumulation during the last few centuries. However, a comparison of sedimentation rates is of interest as it leads to a better understanding of the entire history of sedimentation in Tillamook Bay.

According to the results of Glenn (1978) as summarized in Table 7, the general pattern is one of decreasing rates of sedimentation since the initial formation of the Bay; see also Figure 21, where the measurements from the South Bay and Miami River delta are graphed as age versus depth in the sediment. Sedimentation rates between about 7,000 and 8,000 years BP were on the order of 200 cm per century, but more recent than about 7,000 years BP the rates had dropped to roughly 20 to 40 cm per century, effectively an order-of-magnitude reduction. This declining trend in sedimentation rates is further illustrated in Figure 22 where the calculated sedimentation rates in Table 7 from the South Bay have been plotted. In the South Bay, rates were once as high as 209 cm per century, and then subsequently decreased to approximately 20 cm per century.

In the North-Central Bay (core 13-76 in Figure 17), the USGS dated material at depths of greater than 6 meters in the sediments as having ages greater than 40,000 years BP (Table 7). This simply means that the carbon material and sediment was too old to date using carbon-14 techniques. In view of the fact that the present estuary came into existence only during the last 9,000 years, it is apparent that these ancient sediments recovered by the USGS must pre-date the modern Tillamook Bay. The deposits, identified as marine sands (Glenn, 1978), might actually represent a much earlier estuary formed during a previous high stand in sea level. The >40,000 dates have no direct relevance to sedimentation rates in the modern Tillamook Bay, but the thinness of the modern sediment, less than 6 meters, implies that there has been only limited sedimentation in the North-Central Bay during the last 9,000 years.

In summary, according to the study of Glenn (1978) based on carbon-14 dated material derived from long sediment cores, following the initial formation of the Bay by the rising sea level at the end of the Ice Age, many areas of the Bay trapped large quantities of sediment such that rates of accumulation were on the order of 200 cm per century. However, as the rate in rise of sea level decreased and sediment had begun to fill the initially deep Bay, accumulation rates declined to about 20 to 40 cm per century. As a backdrop for the present study, those values can be viewed as the "natural" rates of sediment accumulation in Tillamook Bay. Of significance, those rates for thousands of years in the past are approximately the same as we have obtained through carbon-14 dating and lead-210 profiles of sediments that have accumulated in the Bay during the last few hundred years.

Table 7. Historical sedimentation rates in Tillamook Bay.
Date from Glen (1978)

Location	Time (years before pres.)	Depth (m)	Rate (cm per century)
Miami River Delta			
Core 5-76	6,360-present	8.1	13
Core 3-76	7,850-present	18.5	24
Core 3-76	8,310-7,850	27.9	204
Core 5-76	>40,000-6,360	20.3	—
South Bay			
Core 9-76	3,300-present	6.6	20
Core 9-76	5,190-3,300	11.1	24
Core 7-76	6,970-present	20.3	29
Core 9-76	7,230-5,190	18.7	37
Core 9-76	7,450-7,230	23.3	209
Core 9-76	8,400-7,450	27.9	48
North-Central Bay			
Core 13-76	>40,000-present	6.1	—
Core 13-76	>40,000-present	11.2	—
Core 13-76	>40,000-present	14.8	—

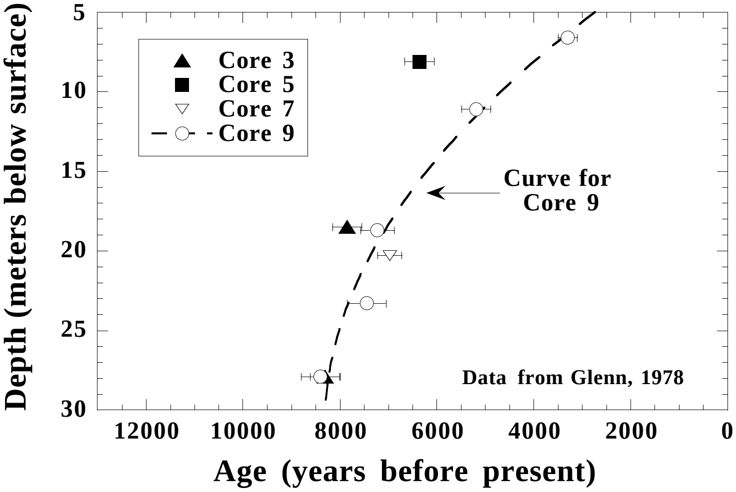


Figure 21: Down-core ages of sediments in the South Bay and Miami River delta regions, the values given in Table 7 from the USGS study.

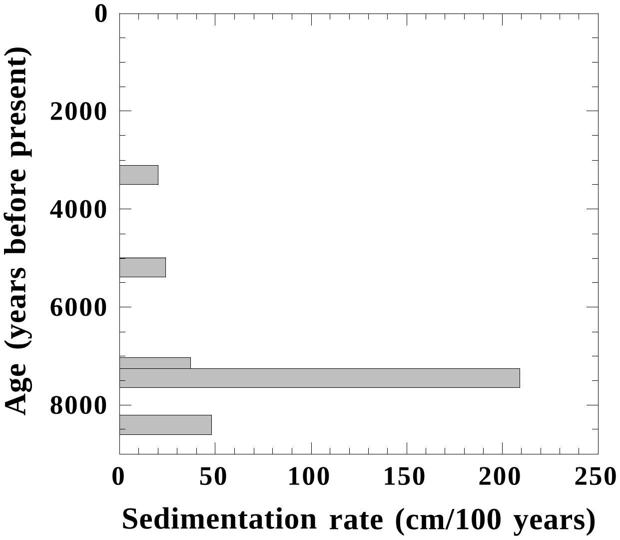


Figure 22: Sedimentation rates in the South Bay, showing that order-of-magnitude higher rates occurred during the period 7,000 to 8,000 years BP, but subsequent rates have been on the order of 20 to 40 cm per century.

Core Analyses — Summary of Results and Interpretations

This study of the history of sediment accumulation in Tillamook Bay is based principally on analyses of sediment cores collected from within the Bay, with additional information obtained from bathymetric surveys undertaken during historic times. Interpretations of the core samples are made difficult by the extreme burrowing activities of organisms, which tend to vertically homogenize the sediments. One result of this burrowing, for example, is the absence of distinct layers of charred material within the sediments that could be attributed to the Tillamook Burns.

It also made difficult the interpretation of measured lead-210 profiles, which can sometimes be used to directly assess changing rates of sediment accumulation. In spite of such difficulties, our investigations of core samples, together with those undertaken earlier by the USGS (Glenn, 1978), provide an improved understanding of the history of sedimentation in Tillamook Bay. The data support the following conclusions:

- Between about 7,000 and 8,000 years BP, soon after the initial formation of Tillamook Bay by the rising level of the sea, sediments rapidly accumulated within the deep water of the Bay, with sedimentation rates having been on the order of 200 cm per century.

- After about 7,000 years BP, the natural rates of sedimentation decreased to about 20 to 40 cm per century, and persisted with these rates up to historic times.

- Carbon-14 and lead-210 measurements in near-surface cores indicate that sedimentation rates during the past 300 to 500 years have ranged approximately 7 to 138 cm per century, with the higher rates found in the southeastern part of the Bay near the river sources.

- The bathymetric surveys undertaken in 1867, 1954 and 1995 indicate that whole-Bay sedimentation rates have declined from 68 cm per century between 1867 and 1954 to only 5 cm per century between 1954 and 1995.

- The bathymetric surveys document that during historic times, significant sediment accumulation has occurred along the margins of the Bay and at the shallower depths, while many areas below the Mean Lower Low tidal elevation have become deeper.

- Geochemical analyses of sediments within the cores, principally the Al:Ti ratios, demonstrate that during the past there has been substantially more marine beach sand input into the Bay relative to the contribution made by the rivers. In the southwest part of the Bay this input of marine sand was episodic, while in the north Bay adjacent to the main channel there was a persistent dominance of marine sand, greatest at a 60-cm depth within the sediment and declining up to the present.

The changing rates of sediment accumulation and variations in relative inputs of marine beach versus riverine sediments can be interpreted in terms of estuarine processes and the tectonic setting of Tillamook Bay. The interpretations are somewhat speculative, and are based in part on the known occurrence of a subduction earthquake on 26 January 1700, an event that likely caused the abrupt subsidence of the Tillamook area and the occurrence of a tsunami that would have swept across the Bay. This interpretation is discussed at greater length in the Synthesis section that follows.

SYNTHESIS — SEDIMENT SOURCES, HISTORY OF SEDIMENT ACCUMULATION, AND MANAGEMENT IMPLICATIONS

The objective of this study has been to acquire a better understanding of the factors that have affected the accumulation of sediment in Tillamook Bay. Underlying the need for this knowledge are questions regarding the impacts of human activities that may have resulted in increased quantities of sediment entering and accumulating in the Bay, leading to higher rates of shoaling. These human activities have included logging the river watersheds and the occurrence of major forest fires, land-use practices such as the conversion of low lands surrounding the Bay into pastures or urban areas, and the breach of Bayocean Spit during 1952-56 that carried large volumes of beach sand into the Bay. The hope is that a better understanding of the history of sediment accumulation in Tillamook Bay and an awareness of the role of humans in the degradation of this estuary will lead to an improved management of this resource.

This investigation of Tillamook Bay sediments, supported by TBNEP, began in June 1996. With only 18 months allotted to the study and with only limited funds, we have had to restrict the scope of our investigations. Although it is clear that most of the human activities affecting sediment accumulation in Tillamook Bay are occurring in the watersheds of the five rivers draining into the Bay, the present study has been restricted in its focus to Tillamook Bay itself. Our study, therefore, has attempted to answer questions regarding the sources of the sediment now found in the Bay, the relative importance of those sources at present and whether their contributions differed in the past, and whether there have been discernible changes in rates of sediment accumulation, specifically whether there has been a marked increase in sediment filling during historic times when human activities potentially could have increased amounts of sediment delivery to the Bay. Although estuaries are complex environments in terms of their sedimentation processes, making scientific investigations difficult and interpretations of the results uncertain, for the most part we have succeeded in meeting our overall objective and specific tasks, so that we now have a much better understanding of the sources of sediment accumulating in Tillamook Bay and the long-term history of sedimentation. The present report, and those prepared earlier (Bostrom and Komar, 1997; Komar, 1997), are the products of this investigation. In this final report we have described our efforts to collect field sediment samples, the laboratory techniques employed to analyze those samples, and our interpretations of the results in terms of defining the sources of sediment and this history of sediment accumulation in the Bay. The purpose of this Synthesis is to provide an integrated summary of our results, and to offer additional insights into the factors affecting sedimentation in Tillamook Bay, insights that at times remain somewhat speculative.

Sources of Sediment in Tillamook Bay

It was recognized from the onset of this study that the sediments accumulating in Tillamook Bay are derived from the five principal rivers that discharge into the Bay and from the marine beach. Beach sand is presently carried into the Bay by tidal currents that flow through the inlet, and in the recent past was washed into the Bay through the 1952-56 breach in the south part of

Bayocean Spit. Our analyses showed that there are major differences in the sediments derived from the rivers versus the sand contributed by the ocean beaches, differences in terms of their grain sizes, mineral compositions, and major and minor elements as measured by geochemical techniques. Such distinctions made it possible to analyze the sediment samples collected from the Bay in terms of the relative proportions contributed by the rivers and marine-beach sources, and to trace the movement of these sediments through the Bay from their sources. We therefore now have a much improved understanding of sediment sources and processes presently operating in the Bay.

Although we had recognized from the onset of the study that the rivers and marine beach are the principal sources of sediment found in Tillamook Bay, there were surprising results in terms of the relative significance of these respective sources. We had expected that the Bay sediments would be dominated by the river source, but we found just the opposite. Based on the detailed mineral composition analyses of the surface sediments, a total budget of sediments indicates that about 60% of the sand in the Bay came from the marine beach, 40% from all of the rivers. This is partly explained by another surprising result, the finding that the Bay sediments are overwhelmingly sand, with comparatively small amounts of clay and silt (mud). Large quantities of clay and silt are delivered each year to the Bay from the rivers, but this fine-grained sediment is quickly flushed through the Bay to the ocean, with only a very small amount being permanently deposited within the Bay. In contrast, sand carried by the rivers, and also by tidal currents flowing into the Bay from the ocean, settles out and accumulates in the Bay. Thus, a major portion of the river derived sediment is passed through the estuary to the ocean, rather than contributing to the filling of Tillamook Bay.

One disappointing result in our study has been the inability to differentiate between sand being supplied to Tillamook Bay by the five individual rivers. In spite of analyses of mineral compositions, and geochemical analyses of major, minor and even trace elements, no differences could be established. This result was not entirely unexpected in that previous studies had similarly failed, and the uniform nature of the sediment derived from the five rivers is understandable due to the uniformity in types of rocks found within the watersheds of these rivers, the erosion of which yields the sediment entering Tillamook Bay. This inability to distinguish between sediments supplied by the individual rivers has had little consequence in meeting the objectives of this TBNEP study, but we had hoped that such a distinction would be possible so that in future investigations we could relate the sediment yields from the five rivers to differences in land-use practices in their watersheds.

History of Sedimentation

The history of Tillamook Bay began with its inception about 9,000 years before the present (BP), when the rise in sea level at the end of the Ice Age flooded the lower valleys of the five rivers that now drain into the Bay. The history of the Bay is recorded in the sediments that have accumulated during the past thousands of years since its inception. This record has been recovered through the collection of cores. Sediments in the cores have been analyzed to examine rates of sediment fill, and to document whether or not there have been changes in sediment sources — rivers versus marine beaches — back through time.

The analyses of the core samples have shown that in the early stages after the initial formation of Tillamook Bay, sediment accumulated rapidly with measured rates of sedimentation having been on the order of 200 cm per century. After about 7,000 years BP, however, the rate of sediment accumulation slowed considerably, the rates having been reduced to 20 to 40 cm per century. These latter "pre-historic" rates are on the same order as those measured in this study from short cores that penetrated about 1 meter into the bottom of the Bay and reached back to sediment that was deposited up to 300 to 500 years BP. Analyses of sediment accumulation rates in these cores proved to be very difficult due to the burrowing activities of organisms, principally ghost shrimp, with the burrowing tending to homogenize the sediment. Our first evidence for mixing by burrowing organisms was the absence of observed layering of sediments in the cores, and specifically the absence of dark layers of concentrated charred material that might have been derived from the Tillamook Burns. The homogenization of this sediment made it particularly difficult to use measured down-core profiles of lead-210 to examine whether there have been changes in rates of sediment accumulation. However, the average sedimentation rates determined from lead-210 profiles largely agree with those based on the carbon-14 dating of shells found within the cores, and with bathymetric surveys of Tillamook Bay undertaken in 1867, 1954 and 1995. The lead-210 and carbon-14 assessments of sediment accumulation yielded rates ranging from 7 to 138 cm per century, with the higher values found in the southeastern part of the Bay near the river mouths. The bathymetric surveys can only provide values for total-Bay sedimentation rates, but yield the surprising result that sedimentation has decreased substantially during the last 50 years (i.e., during the first half of this century sedimentation may have been as much as a factor 10 greater than during the second half of the century). Analyses of the details of these surveys further demonstrate that the highest rates of sediment accumulation have occurred along the margins of the Bay and in shallow water depths above the Mean Lower Low tidal elevation. This outward growth of the shoreline, and the expansion of marshes and intertidal areas, may have led to the perception of dramatically increased rates of sedimentation. However, when considering the entire Bay, many areas below Mean Lower Low tide have deepened, yielding the result that the overall amount of sediment accumulation has actually decreased during the last 50 years.

The results of the down-core geochemical analyses of major and minor elements have yielded interesting results which document that there have been significant changes in sources of sediment through time, results that might help explain the decreasing rate of sediment accumulation during the last 50 years. Cores collected in the southwestern part of the Bay reveal that there have been times during the last 500 years when large quantities of beach sand were carried into the Bay from the ocean. The down-core profiles of elements indicate that this input was episodic, suggesting that it may have resulted from a temporary beach or washover of Bayocean Spit, similar to the breach that occurred between 1952-56, only much larger during those past events in terms of the quantities of beach sand carried into the Bay. However, a somewhat different interpretation is suggested by a core obtained from the northeastern part of the Bay, adjacent to the main channel crossing the Bay that serves as the main conduit for the movement of river water and sediment. This site can be expected to be particularly sensitive to changes in proportions of river versus marine beach sand entering the Bay. Of interest, the down-core geochemical analyses indicate that in the past, at about 60 cm depth in the sediment, there was a large influx of beach sand, overwhelming contributions made by the rivers. This core and others obtained in the Bay demonstrate that generally in the past the beach has been an even more important contributor of sediment to Bay filling, greater even than its presently 60% contribution as documented in the surface sediments. The results further show that the contribution made by the beach has steadily declined up to the present. This pattern is less likely to be explained by an episodic breach or washover of Bayocean Spit, and instead suggests a more dramatic shift in sedimentation that has spanned the last several hundred years. This shift in sediment sources, together with changing rates of sediment accumulation, might have resulted from the dramatic changes brought on by a subduction earthquake in the year 1700 that is known to have profoundly affected the Northwest coast.

The evidence is now clear that during the past few thousand years a series of destructive earthquakes have occurred along the Northwest coast, interpreted as having resulted from the subduction of the Juan de Fuca ocean plate beneath the continental North American Plate (Atwater, 1987; Atwater and Yamaguchi, 1991; Darienzo and Peterson, 1990, 1995). Each earthquake caused extensive areas of the coast to abruptly subside by 1 to 2 meters, and generated extreme tsunami waves that swept inland. The initial discovery was made by Dr. Brian Atwater, who noted the presence of thick layers of marine sand along the banks of rivers that drain into Willapa Bay, Washington. Similar sand layers have been identified subsequently within most estuaries and on low-lying areas along the Oregon coast, including along the margins of Tillamook Bay (C. Peterson, pers. communication). The sand layers in estuaries cover marshes that subsided during the earthquake, followed by the tsunami that laid down the sand layers. At most sites there are several such layers, implying that there has been a recurrence of such extreme events, a major earthquake followed within minutes by a giant tsunami. It is now known that the most recent subduction earthquake and tsunami occurred on 26 January 1700; this evidence comes from the recorded arrival of the tsunami on the coast of Japan, where the level of damage that far away provided direct evidence for the generation of a large tsunami off the Northwest coast by a major earthquake of approximately magnitude 9 (Satake, Shimarazaki and Ueda, 1996).

Such an extreme event 300 years ago undoubtedly had a major impact on Tillamook Bay, so we would expect to see the consequence in the sediment record as revealed in the cores. The general subsidence of the area, caused by the release of crustal strain at the time of the earthquake, would have abruptly increased water depths within the Bay and lowered the elevation of Bayocean Spit. The extreme tsunami waves arriving within minutes after the earthquake should easily have washed over the lower elevations of the Spit, carrying beach sand into the Bay. This episodic input of beach sand by tsunami would have been followed by a continued enhanced influx of beach sand through the tidal inlet leading to greater contributions of beach sand, just as found at depth within the cores. Assuming that this appearance of large amounts of beach sand at 60 cm depth in the cores was produced by the subduction earthquake in 1700, the subsequent average sedimentation rate would have been 20 cm per century, within the range of sedimentation rates directly measured from the carbon-14 and lead-210 data. Actually, initially following the subduction earthquake and deepening of the Bay, the rate of sediment accumulation would have been rapid, declining with time up to the present. Having occurred only 300 years ago, the continuing effects of that subduction earthquake can explain the measured decline in sedimentation rates inferred from the historic bathymetric surveys, and also the systematic decrease in the marine beach source relative to contributions of sediments from the rivers.

Although speculative, the above interpretation is based on the known occurrence of a subduction earthquake in the year 1700, the expected changes in Tillamook Bay resulting from that extreme event, and offers a plausible explanation for our measurements of changing sediment sources and rates of sediment accumulation, changes that have occurred during the last few hundred years.

Human-Induced Factors

If the above speculation is correct that the last subduction earthquake in 1700 had major effects on the input of sediments into Tillamook Bay, then the natural tectonic related processes become a complicating factor in discerning whether human activities have significantly altered sedimentation rates. As discussed above, the subduction earthquake likely produced a subsidence of Tillamook Bay, leading to rapid rates of sediment accumulation that progressively decreased with time. Human activities would have tended to reverse this trend, leading to increased rates of sedimentation in the Bay. Generally we tend to think that our adverse activities began with European settlement, in the case of the Northwest coast beginning during about the mid-nineteenth century. However, this ignores the activities of Native Americans and natural processes of climate change, which could also have increased sediment input into the Bay. Accounts by early explorers and western settlers in the Northwest noted the frequent occurrence of forest fires, often set by Native Americans to clear vegetation. Furthermore, recently completed research has provided direct evidence for the occurrence of major forest fires in the Coast Range, even prior to the occupation of the area by Native Americans. Impara (1998) investigated the fire history through analyses of tree rings in over 4,000 stumps located in a 25 by 55 km area of the central Coastal Range. It was determined that within this small area a total of 27 fires had occurred during a 516 year period, with areas burned ranging 18 to 544 km^2. Fire size estimates were smaller during the pre-settlement period (1478-1845) than in the post-European settlement period (1846-1909). However, less frequent, large "wildfires" were found to have occurred, two in the 1500s and two in the mid-1800s, each having affected more than 50% of the study area. Long (1995) extended the record back further by a study of sediments in lakes in the Coast Range. Layers of charcoal within the lake sediments provided direct evidence of forest fires extending back in time by more than 9,000 years. This long record provided evidence for major climatic cycles in the Northwest, with wet periods and forest growth alternating with dry periods when the accumulated vegetation and forest litter led to large scale fires. Thus, although it is likely that human activities during historic times since European settlement did lead to increased sediment delivery to Tillamook Bay, pre-historic activities of Native Americans and natural processes causing forest fires cannot be discounted.

Human effects on the environment in the Tillamook area during historic times undoubtedly have tended to increase quantities of sediment entering the Bay. These activities have included logging the river watersheds and the occurrence of major forest fires such as the Tillamook Burns, land-use practices such as the conversion of low lands surrounding the Bay into pastures or urban areas, and the breaching of Bayocean Spit during 1952-56 as a result of jetty construction on the inlet to the Bay. The effects of these activities in the watersheds of the rivers cannot be directly assessed in terms of expected increases in sediment yields from the drainages. Clear cutting and forest fires are known to result in an increase in sediment yields, but the increase is temporary, lasting only a few years until vegetation cover is re-established, and appears to mainly produce an increase in the yield of fine-grained sediment, clays and silt. As we have seen, this fine-grained sediment is largely flushed through the Bay, so the impact on Bay sedimentation may not have been as significant as one intuitively expects. However, much of the sediment accumulation along the margins of the Bay and in the shallower depths consists of fine-grained sediment, and the increased rates of Bay filling in those areas during the past 50 to 100 years as shown by the bathymetric surveys may have been the result of poor land-use practices, particularly deforestation. Furthermore, deforestation would have altered the hydraulics of the streams, making them more prone to flooding. Flooding would also be promoted by the diking of the rivers along their lower reaches and the conversion of marshes into pasture land. Flooding could be expected to enhance the transport of sediment into the Bay, the delivery of sand and gravel as well as of fine-grained sediment. Such questions have become the focus of a three-year study that was recently funded by EPA/NSF. In that study, our attention is directed more toward the sources of the sediments, particularly the watersheds of the five principal rivers entering Tillamook Bay. In brief, the objectives relate to land-use practices in the watersheds and their effects on sediment supplies and water quality. Similar to our work in the Bay, the investigations include detailed analyses of the compositions, grain sizes, and geochemistry of sediments in the rivers. The objective is to relate these factors and the rates of sediment yield from the watersheds to land-use practices. It is apparent that when we have completed that investigation of the sediment sources, we will have acquired a more complete understanding of sedimentation in Tillamook Bay.

Management Implications

When we began this TBNEP study, the expectation was that our research would lead to a better understanding of the history of sediment accumulation in Tillamook Bay, a documentation of the role of humans in causing increased amounts of sediment delivery to the Bay, and that this acquired knowledge would lead to an improved management of this resource. These expectations underestimated the natural complexity of estuarine systems in general, and Tillamook Bay in particular. The bays and estuaries along the Northwest coast were formed only a few thousand years in the past by the rise in sea level at the end of the Ice Age, and in geological terms are out of equilibrium with the supplies of sediments and with the processes of waves and currents that transport those sediments. It is natural that bays and estuaries tend to accumulate sediment, shoaling and constricting their margins until they approach a size where the currents are better able to transport sediments through to the ocean, an eventual near-equilibrium condition. To a large degree, Tillamook Bay fits this pattern and the accumulation of sediment documented in our study is for the most part a natural process. A major complication is produced by the tectonic setting, with the occurrence of a subduction earthquake in 1700 having caused the subsidence of the Northwest coast, leading to the deepening of its bays and estuaries. In effect this deepening represents a rejuvenation of the estuary, but the natural response is the more rapid influx and accumulation of sediment, progressively slowing as the near equilibrium condition is again approached.

With these natural complexities in the system, we should have anticipated that discerning the impacts of humans on rates of sediment accumulation in Tillamook Bay would be extremely difficult. Our best chance to have accomplished this was expected to come from the detailed profiles of lead-210 measured in the cores, but mixing of the sediment by burrowing organisms precluded that possibility. Of special interest are the results of analyses of the bathymetric surveys which document that during the past 50 years rates of total-Bay sediment accumulation have actually decreased compared with earlier in the century. Our initial hypothesis was that the higher rates of sedimentation early in the century corresponded to the times of major deforestation and forest fires — human impacts — but the down-core composition changes demonstrated that beach sand was the main input, not an enhanced amount of sediment derived from the rivers. Our interpretation is that the lingering effects of the last subduction earthquake in 1700 remain stronger than the human induced effects. Also of interest in the analyses of the bathymetric surveys is that while the total-Bay sedimentation has decreased during the past 50 years, there has been significant accumulation in the shallower portions of the Bay leading to the outward growth of the shorelines and more extensive tidal flats. This pattern of sediment accumulation could result in the perception of a massive influx of sediment into the Bay, and an interpretation that it has been caused by human activities leading to deforestation of the watersheds. This remains a possibility in that deforestation releases fine-grained clays and silt from the watersheds, and it is mainly these fine sediments that account for the outward growth of the Bay shoreline and the expansion of tidal flats.

In conclusion, human activities have affected the input of sediment into Tillamook Bay from its sources. This is most obvious in the case of the influx of marine beach sand through the 1952-56 breach in Bayocean Spit, having been caused ultimately by the construction in 1917 of a jetty on the inlet connecting the Bay with the ocean (Terich and Komar, 1974; Komar and Terich, 1977; Komar, 1997a). More problematic has been the impacts of human activities in the watersheds of the rivers draining into Tillamook Bay. It can be expected that logging and forest fires resulted in increased quantities of fine grained sediments (clays and silt) transported by the rivers. Although we have seen that this fine sediment is relatively insignificant in producing the general shoaling of Tillamook Bay, since most of it is flushed through to the ocean, its enhanced loads in the rivers might account for the rapid outward growth of the shoreline and expansion of tidal flats. Furthermore, increased concentrations of fine-grained sediment in the rivers are known to be detrimental to fish, as are other water quality factors. Thus, if there are to be changes in the management of Tillamook Bay and its surroundings, the focus should be on human activities in the watersheds of the five major rivers, activities that can lead to increased yields of fine-grained sediments. It is our hope that the new EPA/NSF supported research that focuses more on sedimentation and water quality issues in the watersheds of the rivers will lead to a better understanding of human activities that have resulted in the degradation of those riverine environments, and ultimately result in a degradation of Tillamook Bay.

REFERENCES

Anderson, R.F., R.F. Bopp, K.O. Buesseler, and P.E. Biscaye (1988) Mixing of particles and organic constituents in sediments from the continental shelf and slope off Cape Cod: SEEP—I results. *Continental Shelf Research* 8: 952-946.

Atwater, B.F. (1987) Evidence for great Holocene earthquakes along the outer coast of Washington state: *Science*, v. 236, p. 942-944.

Atwater, B.F., and D.K. Yamaguchi (1991) Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state: *Geology*, v. 19, p. 706-709.

Avolio, G.W. (1973) Granulometric analysis of recent sediments of Tillamook Bay, Oregon: M.S. thesis, Department of Earth Sciences, Portland State University, Portland, Oregon, 67 pp.

Bernert, J.A. and T.J. Sullivan (1998) *Bathymetric Analysis of Tillamook Bay: Comparison Among Bathymetric Data Bases Collected in 1867, 1957 and 1995*: Tillamook Bay National Estuary Project, Garibaldi, OR.

Bostrom, G. and P. D. Komar (1997) *Rocks of the Tillamook Bay Drainage Basin, the Coast Range of Oregon — Sources of Sediment Accumulation in the Bay*: Report for the Tillamook Bay National Estuary Project, March 1997, 6 pp.

Darienzo, M.E., and C.D. Peterson (1990) Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon central Cascadia margin: *Tectonics*, v. 9, p. 1-22.

Darienzo, M.E., and C.D. Peterson (1995) Magnitude and frequency of subduction-zone earthquakes along the northern Oregon coast in the past 3,000 years: *Oregon Geology*, v. 57, no. 1, p. 3-12.

Glenn, J.L. (1978) *Sediment Sources and Holocene Sedimentation in Tillamook Bay, Oregon: Data and Preliminary Interpretations*: U.S. Geological Survey, Open File Report 78-680, 15 pp + tables and figures.

Globerman, B.R. (1980) Geology, Petrology, and Paleomagnetism of Eocene Basalts from the Black Hills, Washington Coast Range. M.S. Thesis, Western Washington University.

Hanson, G.N. (1980) Rare Earth elements in petrogenetic studies of igneous systems. *Ann. Rev. Earth Planet. Sci.* 8: 371-406.

Impara, P.C. (1998) *Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range*: PhD thesis, Oregon State University, Corvallis.

Komar, P.D. (1996) The budget of littoral sediments — Concepts and applications: *Shore & Beach*, 64 (n. 3): 18-26.

Komar, P.D. (1977a) *The Pacific Northwest Cost: Living with the Shores of Oregon and Washington*: Duke University Press, Durham, North Carolina, 195 pp.

Komar, P.D. (1997b) *Sediment Accumulation in Tillamook Bay, Oregon, A Large Drowned-River Estuary*: Report for the Tillamook Bay National Estuary Project, May 1997, 23 pp.

Komar, P.D., and T.A. Terich (1977) Changes due to jetties at Tillamook Bay, Oregon: *Proceedings 15th Conference on Coastal Engineering*, Amer. Soc. Civil Engrs., p. 1791-1811.

Komar, P.D., J. McManus, G. Bostrom and R.V. Kovar (1998) *Data Report — Surface Sediments and Core Samples Collected and Analyzed*: Report for the Tillamook Bay National Estuary Project, Garibaldi, OR

Lewis, D.W. (1984) *Practical Sedimentology*: Hutchinson Ross Publishing Co., Stroudsburg, Pennsylvania.

Long, C. (1995) Unpublished Masters Thesis, University of Oregon, Eugene.

Mix, A.C., and others (1992) Color reflectance spectroscopy: a tool for rapid characterization of deep-sea sediments: In *Proceedings ODP, Initial Reports*, 138 (Part 1), p. 67-77, Ocean Drilling Program, College Station, Texas.

Satake, K., K. Shimazaki, Y. Tsuji and K. Ueda (1996) Time and size of giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: Nature, 379: 246-249.

Terich, T.A., and P.D. Komar (1974) Bayocean Spit, Oregon: History of development and erosional destruction: *Shore & Beach*, 42: 3-10.

APPENDIX

Lead-210 (^{210}Pb) is derived from the radioactive decay of radon in the atmosphere, a radioactive gas that in turn is the daughter of the decay of uranium isotopes. When lead-210 forms, being a solid it "rains out" from the atmosphere and accumulates in sediments that are simultaneously being deposited. Thus, the quantity of lead-210 in the sediment can serve as the basis for an assessment of the rate of sediment accumulation. The actual profile of lead-210 downward within the sediment depends not only on the changing rates of sediment accumulation, but also on the rate of vertical mixing of the sediment as might be produced by the burrowing activities of organisms.

The accumulation and vertical mixing of sediment and the lead-210 it contains can be represented by the relationship, as adopted from Anderson et al. (1988):

$$\rho \frac{\partial A}{\partial t} = \frac{\partial}{\partial z} \bullet \frac{D_b \partial \rho A}{\partial z} - \frac{S \partial \rho A}{\partial z} - \lambda \rho A \qquad (1)$$

where A is the activity of excess ^{210}Pb (dpm g^{-1}), t is time, z is depth downward within the sediment, ρ, is sediment density, D_b is the sediment mixing rate ($cm^2\ y^{-1}$), S is the sedimentation rate ($cm\ y^{-1}$), and λ is the radioactive decay constant for ^{210}Pb. If we can assume that D_b is constant throughout the mixed layer, and that ρ is uniform with depth, then the solution of equation (1) is:

$$A = A_0 \exp \left[\frac{(S - S^2 \text{ x } 4D_b\lambda)^{0.5}}{2D_b} \bullet z \right] \qquad (2)$$

where A_0 is the excess ^{210}Pb activity at z = 0 and A is the activity at depth z. The reduced forms for when $D_b = 0$ and S are negligible are respectively:

$$A = A_0 \exp \left[\frac{-\lambda}{S} \bullet z \right] \qquad (3)$$

$$A = A_0 \exp \left[\left(\frac{-\lambda}{D_b} \right)^{0.5} \bullet z \right] \qquad (4)$$

Applications of these relationships involve measurements of lead-210 activity profiles a depth within sediment cores, that is, the determination of A versus z. The above equations are then fit to the measured profile to determine "best fit" values of the sedimentation rate S and mixing rate D_b.