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Rates of Sediment Accumulation, Bioturbation and Resuspension in Back Bay, Virginia, a Coastal Lagoon

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Abstract: Back Bay is the northernmost section of the Albemarle-Pamlico lagoon-estuary system. Back Bay lagoon and its associated barrier (Currituck Spit) are moving landward in response to post-glacial sea level rise (2.6 mm yr^{-1}). The long term (100 year time scale) landward migration rate of Currituck Spit may be on the order of a meter per year.

Sediment accumulation, resuspension and bioturbation are processes in Back Bay that control the residence time of organic matter in the bay floor. and therefore, effect the rate of nutrient release. As burial proceeds, nutrients in the zone of mixing may be remineralized and recycled back to to water column, or may pass downwards into the zone of permanent burial.

X-radiographs indicate that Back Bay sediments are bioturbated by the community of insect larvae, polychaetes and oligochaetes that constitute the benthic infauna of this oligohaline water body. However, analysis of wind records suggests that in some respects, wave resuspension is a more important mixing process. Under mild to moderate conditions, waves in the bay are fetch limited. However, under hurricane conditions the bay surface saturates with breaking waves before peak winds are attained. For a 6 km fetch (a typical long fetch for the Bay), the resuspension threshold is 6 ms^{-1} (13.5 knots). This value is exceeded 35.7 percent of the time, and sediment is resuspended in about 40 events in a year. Radiogeochemical analyses suggest that long term (100 yr) accumulation rates are of the order of 2-3 mm yr^{-1}.

The Bay is floored by mud (silt and clay), with an admixture of sand. Sediment introduction probably occurs largely as a result of 'wind pumping'. During winter storms, strong southerly winds set down southern Back Bay, and drive turbid water from Currituck Sound through the Knotts Island Passage. As the storm progresses, the wind shifts to the north and northwest, sets up lower Back Bay against the Knotts Island Passage, and flushes sediment and water back into Currituck Sound.

In this model, Back Bay is a sediment-accumulating sink. The shallow (1-2 m) floor of Back Bay is controlled by an equilibrium between the rate of sediment supply and mean annual wave power. Concentration profiles of ^{210}Pb and ^{137}Cs measured in 1984 indicate that the short term (30 year) accumulation rate was then twice that of sea level rise. The period of record corresponds with Eurasian Milfoil invasion. The historically dense growth of this plant would have modified the equilibrium by damping wave currents, accelerating the sedimentation rate and shifting the Bay floor to a shallower equilibrium depth. The Bay floor appears to presently be undergoing a reduced rate of sedimentation with some local erosion, perhaps in conjunction with a return to an earlier regime.

Introduction

Physical Setting. Back Bay is the oligohaline northernmost portion of the Albemarle-Pamlico estuarine system (Fig. 1). It differs from the larger lagoons and estuaries to the south in its shallow depths, low salinities and susceptibility to wind tides. The average depth is 1.1 m. Time-averaged salinities measured during a 1983 study ranged from 5 to 21 ‰ (Anonymous, 1984). At this time, salt water was being pumped into the Bay in order to improve water clarity. Since the pumping of salt water has ceased, salinity has dropped to less than 2.0 ‰. Astronomical tides are negligible in the Bay (< 8 cm). Wind tides up to 1m amplitude, accompanied by resuspension of bottom sediment, occur throughout the winter period of frequent storms. More intense resuspension events, associated with extreme northeaster storms and hurricanes, occur at somewhat longer recurrence intervals.

The present physical state of Bay must be understood in terms of processes occurring at long time scales. The barrier-estuary-lagoon system of the North Carolina—Virgina Coast has shifted some 200 km across what is now continental shelf, since the beginning of post glacial sea level rise, at 18,000 years ago (Niedoroda et al., 1985). Back Bay lagoon and its associated barrier (Currituck Spit) are presently moving landward in response to a sea level rise rate of 2.6 mm yr^{1} (Nichols et al., 1989). The consequent long-term (100 yr time scale) landward migration rate of the Currituck Spit-Back Bay system may be on the order of a meter per year. (Swift et al., 1972). Migration of Currituck spit is accomplished by storm erosion of the barrier face (an annual to decadal process), by storm washover of sand (a decadal process) and by inlet breaching (at intervals greater than a century) The mainland coast of the lagoon migrates landward by extension of marsh over the subaerial surface in response to sea level rise, and by storm wave erosion of the marsh face (annual processes).

Management problem. Back Bay is relatively pristine portion of the Albemarle-Pamlico estuarine system. Nevertheless, it has experienced a series of environmental problems associated with sport fisheries and wildlife management. The bass fishery and waterfowl populations have declined through a period which saw the advent and cessation of salt water pumping, and also the accidental introduction, proliferation, and abrupt decline of non-native aquatic vegetation (Eurasian Milfoil). Salinity, water clarity, and primary productivity changes are implicated in these events, but their roles are not well understood (Anonymous, 1984). In this paper, we examine the sedimentation history of the lagoon floor, and compute sediment resuspension frequencies and accumulation rates, in order to better understand physical processes controlling water clarity and nutrient cycling in Back Bay.

The Physical Problem. Sediment resuspension and accumulation are aspects of the Back Bay ecosystem which need to be better resolved for environmental management purposes. Sediment resuspension by wind events effects the ecosystem directly, by decreasing the amount of light available for photosynthesis, and indirectly, by controlling the release of regenerated nutrients from the bottom to the water column. The cycling of nutrients controls the trophic state of the bay and resuspension, together with accumulation and bioturbation determine the dynamics of the nutrient cycle.

Nittrouer and Sternberg (1981) describe the uppermost portion of the seabed as a zone of temporary storage, characterized by resuspension and mixing. The zone of storage is underlain in turn by a zone of permanent burial (Fig. 2). These zones move upward with the aggrading water-sediment interface, so that a sediment particle passes first through the zone of storage, and finally into the zone of permanent burial. From the geological point of view, the zone of storage and mixing is important as the zone in which the stratal record is formed. In geological terms, sequence of storm-created strata (beds) is a signal impressed on the sediment as it passes downwards through the zone of mixing. The zone of mixing is thus the 'recording head' for the unreeling tape of the stratigraphic record, as it accumulates in the zone of permanent burial (Fig. 2).

From the ecological point of view, the zone of mixing in the lagoonal floor is a critical "valve" or regulating mechanism in the nutrient cycle. The schematic diagram in Fig. 3. illustrates the processes that we believe to be most important in explaining nutrient cycling in Back Bay. Rates of primary productivity by both salt marsh plants (Morris, 1987; Priest, 1991) and phytoplankton in the Bay water column (Marshall, 1991) are high. These rates, plus high rates of nutrient regeneration in the shallow lagoonal (Nixon, 1987; in press), will lead to rapid nutrient cycling through the bay system.

The zone of mixing regulates the nutrient cycle by controlling the rate of remineralization. As burial proceeds, nutrients must either be remineralized from organic matter and released back to the water column, or pass downwards into the zone of permanent burial. Thus the rate of nutrient release is a function of the residence time of organic matter in the mixed layer, and therefore of the sediment accumulation rate. Our goal in this study is therefore to examine biogenic mixing intensities, compute resuspension frequencies and intensities, and measure the accumulation rate.

Sediment Types, the Benthic Community, and Biogenic Mixing

The Bay is floored by sand, and by mud (silt and clay), with an admixture of sand (Fig. 4). Sediment types vary continuously across the Bay floor, but have been divided for convenience in Fig. 4 into three facies, a sand facies, a silt facies and a mud facies. The bottom is sandiest on the ocean side, indicating that the sand comes from storm washover across Currituck Spit. The mud source is problematic. Supply from the main lagoonal system is limited because the lower Bay is blocked off by Knotts Island from Currituck Sound. The bay's subaerial drainage area is extremely small, and has historically provided even less sediment, although construction activity may be beginning to change this pattern (personal communication, Yates Barber, North Carolina fish and wildlife service).

X-ray radiographs from cores of Back Bay reveal heavily bioturbated bottom sediment. Cores are structureless, or, near the sandy ocean side, weakly laminated. Studies by Lane and Dauer (1991) indicate that in terms of biomass, the dominant macrobenthic species (71.1 %) in the muddy facies is the larval stage of the insect *Chironomus riparius*, distantly followed by the spionid polychaete *Scolecolepides viridis* (8.5%) and several oligochaete species. No information is available concerning the bioturbation efficiency of *Chironomus riparius*, but it is apparently high enough to erase stratification induced by resuspension events

In the Silty facies (Lane and Dauer's 'mixed group'), *Chironomus riparius*, and *Scolecolepides viridis* are subequal contributors to biomass, and in the sandy facies, the abundances by biomass are the reverse of those of the muddy facies.; *Scolecolepides viridis* constitutes 69.9 percent of the biomass, while *Chironomus riparius* constitutes 6.8 percent. *Scolecolepides viridis* is reported by Rhoads (1967) from Barnstaple Harbor, MA, as being a weak bioturbator; the extensive bioturbation observed in the X-ray radiographs is due to the large numbers of individuals present. Myers (1977) reports that the related *Scoloplos robustus* burrows to 13 cm in Narragansett Bay.

Storm Resuspension of Bottom Sediment

The bottom sediment of Back Bay is easily resuspended. In July 1987, total suspended solids ranged from 27 to 64 mg 1^{-1}, with 30 to 80% of the suspended material consisting of organic matter. Chlorophyll-a concentrations ranged from 43 to 71 g 1^{-1} (Carter and Rybicki,1991). In April, 1988 during a period of strong winds, total suspended solids increased to 78 to 214 mg 1^{-1} versus 20 to 30 % organic carbon and 34 to 88 mg 1^{-1} Chlorophyll-a (Carter and Rybicki,1991).

Winds in the region are most commonly from the northeast in the winter, and from the south in the summer (Fig. 5, Table I). Strongest winds are north and southeast winds associated with winter frontal passages (personal communication, National Weather Service, Norfolk, VA). The intensity of wave resuspension of the bottom in response to a given wind strength at a point on the Bay floor is controlled by the maximum value, u_{max}, of wave orbital velocity on the bottom. Wave orbital velocity on the bottom is directly proportional to fetch, and inversely proportional to water depth.

In order to understand wave resuspension on the Bay, it is necessary to determine which of these two controls is the most important. As wave height reaches 78 percent of water depth, waves break. The issue therefore becomes: as wind speed increases, does wave height increase until the entire Bay is a breaker zone? A further increase in wind speed would then have no further effect on wave orbital velocity, and waves on the Bay would be depth-limited. Or does the limited fetch prevent such saturation of the Bay surface by wind waves from occurring? The Bay would then be fetch-limited.

The Bay is very shallow (1-2 m deep), but fetches are short. Even a north wind, aligned with the Bay axis, has a maximum unbroken fetch of only 10 km. Wave tables (U.S. Army Corps of Engineers, 1984) indicate that for an average north wind (11 knots or 5 m s^{-1}), waves can build to heights of half a meter near the south end of the Bay. However, they will not break until their height is approximately 78 percent of their depth so for average north winds, waves on the the Bay is fetch-limited, not depth-limited. For a moderate north wind, breaking occurs only a narrow nearshore surf zone, along the southern sides and south end of the Bay.

This pattern continues for north winds of increasing strength. Figs. 6a and 6b present the fetch lanes, wave heights and surf zone widths for a north wind of 15 ms^{-1} (30 knots) and 26 ms^{-1} (50 knots). The computations show that the Bay is fetch-limited for north winds up to about 50 knots. Beyond 50 knots, the breaker zone (stippled area, Fig. 6b) expands rapidly. For such intense north winds, the Bay surface is saturated with wave energy before hurricane conditions are reached, and the waves become depth-limited.

The wind direction, intensity, and frequenc data of Table I can be applied to stations in Bac Bay, in order to estimate wave height frequencies. Note that frequencies in Table I and all subsequent tables are presented as percentages. As a first step, wave heights can be determined for each wind speed class, for each of the 16 compass directions of Fig. 5 by means of the shallow water wave tables (U.S. Army Corps of Engineers, 1984). They can then be associated with the appropriate frequency (Table II).

The frequencies of Table II form an irregula band across the middle of the page, with blan zones above and below. For many directions in Table II, no frequencies are reported for the lowe wave height classes (upper side of the band). These are cases of longer fetch, where the lowes wind class can produce higher wave heights.

The lower blank zone is present for a differen reason. In each wind direction of Table II, the array of decreasing probabilities terminates at the wave height produced by the strongest wind clas for which a frequency is available. The values range from .21 to .25 meters. Stronger winds and higher waves occur but for most of the directions, the binning of Table 1 is too coarse to catch these less frequent events.

The wave height frequency data of Table II can in turn be used to compute into the frequency with which the bottom is resuspended to a given depth, by means of the algorithm described by Niedoroda et al.(1989). The algorithm is based on the complex behavior of the near-bottom fluid boundary layer (zone of flow retarded by frictional interaction with the bottom) during wind events. During such events, wave orbital currents stir the bottom. At the same time, wind stress sets the entire water mass into motion, so the Bay floor is subjected to a velocity field that includes both a high-frequency wave component and a mean flow component. The mean flow boundary layer grows slowly as the mean flow develops, to an eventual thickness of a meter or more. However, as waves pass over the bottom, a wave boundary layer must form at the base of the mean flow boundary layer every few seconds. Since it forms then decays rapidly, it can never be more than a few centimeters thick.

Sediment entrainment in such a flow field is directly proportional to the shear stress exerted by the flow on the Bay floor. The wave and mean flow components of the stress, however, are not additive, but rather are multiplicative The mean flow boundary layer sees the the wave boundary layer at its base as an added roughness element (Grant and Madsen, 1979), As a result, the bottom shear stress exerted on the bottom by the combined-flow boundary layer is markedly greater than the sum of the wave stress and mean flow stresses that would occur if each existed in isolation. Shear stresses exerted by a combined flow boundary layer were computed by the Niedoroda algorithm to determine to resuspension depths presented in Table III.

If sufficient wind frequency data is available, it is possible to codify it as an extreme event distribution (Gumbel distribution, Ward et al., 1978). It would be then possible to prepare a plot of resuspension depth versus frequency for Back Bay. However, as noted, the data in Table I does not have the necessary resolution of low frequency events. In order to prepare a Gumbel distribution, it would be necessary to examine the 24 year data set of wind observations on which Fig. 7 is based. The data would have to be reprocessed in such a way as to recapture the 'lost' low frequency data.

Such an analysis is beyond the scope of this paper. It is possible, however, use the data of Table I to place limits of the frequency and intensity of sediment resuspension. In Table III, Some resuspension depths have been computed for a 6 km fetch at station BBI (see Fig. 1 for location). Resuspension appears as the wind speed exceeds 6.01 m s^{-1} (13.5 knots). The resuspension depth changes little as the wind increases through moderates speeds, but increases abruptly above 30 knots. Winds of 64 and 78 knot resuspend 2 to 3 cm of sediment. Above these speeds, the Bay becomes depth-limited, hence greater resuspension depths will not occur.

Table I indicates that the resuspension threshold for this particular data set, 13.5 knots, is exceeded 35.7 percent of the time, or 3127 hours per year. Wind events at Back Bay are associated with the passage of mid-latitude low pressure systems. They are also associated with the much less frequent hurricanes. These more intense storms can have no greater effect, since, as noted, the Bay surface becomes saturated with breaking waves before the peak winds occur.

If a typical wind event is assumed to last 72 hours, then our calculations show that 43 such events can occur per year, or about 4 per month. In fact, weather systems cross Back Bay more frequently (every 4 to 7 days) in the winter, and less frequently in the summer, when the Bermuda high sets in.

Radiogeochemical Measurements of Sediment Accumulation Rates

Radionuclides such as ^{210}Pb and ^{137}Cs are useful for determining sediment mixing and accumulation rates because their input function may be precisely defined. ^{210}Pb has a half life of 22,3 years. It is a naturally occurring radionuclide that has been used extensively for reconstructing the history of shallow marine deposits at 100 year time scales (Koide et al., 1972). It is a daughter product of the ^{238}U decay series, generated by cosmic rays. Its precursor, ^{222}Rn is a short lived noble gas with a half life of 3.8 days, that is continuously released to the atmosphere from the lithosphere. Atmospheric ^{222}Rn decays to ^{210}Pb, which is removed from the atmosphere primarily by wet deposition. This atmospheric source is the dominant source of ^{210}Pb in shallow coastal lagoons (Benninger, 1978). Once ^{210}Pb enters the water column, it tends to associate with the particulate phase, and thus becomes a tracer with which to define sedimentary processes.

^{137}Cs, on the other hand, is an artificial radionuclide with a half life of 34.1 years. It enters the aquatic environment primarily via global fallout as a product of atmospheric tests of nuclear weapons. although it may locally be released from nuclear reactors. In fresh and brackish water, ^{137}Cs also tends to associate with the particulate phase and also serves as a tracer for sedimentary processes. ^{137}Cs was first introduced to the environment in significant quantities in 1954.

The depositional rate peaked in 1964, then tapered off in response to an international moratorium on atmospheric bomb tests. These dates provide valuable time lines in the sedimentary column for establishing recent accumulation rates (Krishnaswamy et al., 1971; Santschi, 1986).

The distribution of tracers such as ^{210}Pb and ^{137}Cs in the sedimentary column is the result of a combination of all of the sedimentary processes. Two major processes are accumulation and mixing. When the distribution of more than one tracer is known it is possible to deconvolve the distributions , and to separate accumulation and mixing rates.

In order to apply these concepts to Back Bay, we collected a core in 1980,and measured the concentration profiles for ^{210}Pb and ^{137}Cs. Two further cores were collected in 1990, and analyzed for ^{210}Pb only. The ^{210}Pb concentration was determined by measuring the activity of its short-lived daughter, ^{210}Po, which is assumed to be in secular equilibrium with its parent. The ^{210}Po activity was measured by isotope dilution alpha spectrometry (Oertel et al., 1989). The activity of ^{137}Cs was determined by gamma spectrometry, using a NaI-T1 detector (Wong and Moy, 1984).

In the 1980 core, (BB1, Fig. 7), 90 percent of the core by weight is less that 63 m in diameter (is mud). The concentration of ^{210}Pb is uniform in the top 4 cm (mixed layer). Below this depth, it decreases exponentially to a depth of 18 cm, at which the concentration of both ^{210}Pb and ^{137}Cs drops abruptly to background level. If the 18 cm level is taken to be the 1954 horizon, when ^{137}Cs was first introduced into the global environment in measurable quantities, then the mean accumulation rate for the overlying layer can be estimated as 6.9 mm yr^{-1}.

It can also be assumed that the concentration of ^{210}Pb below 18 cm is the 'supported' level, consisting of ^{210}Pb released by the decay of radioisotopes brought to the depositional site within the lattices of clay minerals. This assumption permits an estimate of the accumulation rate, based on the ^{210}Pb gradient in the overlying layer, as 6.0 mm yr^{-1}. The two rates are indistinguishable from each other within their experimental uncertainties.

The inventory of excess ^{210}Pb in the core corresponds to a depositional flux of 1 dpm cm^{-2}yr^{-1}. Todd et al. (1989) report an atmospheric depositional flux of ^{210}Pb of 0.8 dpm cm^{-2}yr^{-1}. Such total retention of ^{210}Pb is characteristic of fine-grained sediments, and suggests that in the period preceding 1980, at least this part of Back Bay was an efficient fine sediment trap.

The two cores collected in 1990 present rather a different picture (BB3, BB9, Fig. 8a, b). Excess ^{210}Pb was found only in the top 8 cm of BB-3, and in the top 6 cm of BB-9. The accumulation rate for both cores, estimated from the concentration gradients of ^{210}Pb, is about 0.6 mm yr^{-1}. Thus the accumulation rate as estimated from the ^{210}Pb distribution is an order of magnitude lower in 1990, with respect to the 1980 value. The inventory of excess ^{210}Pb in 1990 corresponds to depositional fluxes of 0.3 and 0.2 dpm cm^{-2} yr^{-1}, at B-3 and BB-9 respectively.

These depositional fluxes can account for only 25 to 40 percent of the atmospheric depositional flux. They suggest that these areas were *not* efficient fine-sediment accumulating areas in the 1980-1990 period. If they are representative of the bay as a whole, then a significant fraction of fine grained sediment was not being retained in the Bay during this period. The grain size of sediment in the 1990 cores is less uniform than that observed in the 1980 core. In core BB-3, the fine-grained ($<$ 63 μ) fraction varies from 56 to 89 percent. A lens of coarser sediment with less than 70 percent by weight of fine-grained sediment is found between 8 and 20 cm. In core BB-9, the percentage of fine grained sediment varies between 84 and 97 percent. Sediments with less than 90 percent fine-grained sediment occur in a lense between 4 and 120 cm.

Discussion and Conclusions

Given these rates of resuspension and accumulation, it is possible to put some bounds on the recent depositional history of the Bay. Joseph Barrell, in 1917, was the first person to to notice that the depth of coastal lagoon is a function of its fetch. The relationship occurs because lagoonal floors are graded, or equilibrium, surfaces. Coastal lagoons are typically such efficient sediment traps that their depths are wind-maintained. They are serviced by tidal circulation, which brings sediment in, and takes the excess away. In the presence of an abundant sediment supply, they aggrade (become shallow). As the water column decreases, wave orbital currents near the bottom become more intense, and more sediment is resuspended. Finally, sediment introduction is balanced by sediment loss, and the lagoon floor is stabilized. Depth remains constant until sea level, the sediment supply, or the wave climate changes, whereupon the lagoon can either shoal again or deepen, depending on the new settings of of the depositional variables. Sea level, steadily rising through the post glacial period, has generally been the controlling variable for coastal lagoons such as Back Bay (Nichols, 1989). Should the Bay aggrade more rapidly than sea level rise, then storm wave resuspension from the shallow Bay floor would be so intense that more sediment would be lost than gained. Should it lag behind, wave resuspension would lose efficiency in the deeper water, and sediment trapping by the Bay floor would increase.

With some 40 events a year capable of eroding the bottom (see above), the response time of Back Bay to changes of equilibrium is clearly short. However, Back Bay has no significant tides, hence the model must be modified. Circulation in Back Bay occurs instead as a result of 'wind pumping' (Fig. 9). During winter storms, strong southerly winds set down the southern part of Back Bay, and drive turbid water from Currituck Sound through the Knotts Island Passage. As the storm progresses, the wind shifts to the north and northwest, sets up the southern part of Back Bay against Knotts island, and flushes sediment and water back into Currituck Sound. As a consequence of its role as conduit, the Knotts Island channel has been overdeepened by storm erosion. Its maximum depths (2.5 m) exceed any values to the north (Back Bay) or south (upper Currituck Sound).

The radioisotope concentration profiles appear to record a recent shift in the values of these process variables. Profiles of ^{210}Pb and ^{137}Cs in 1984 indicated a short term (30 year) sedimentation rate twice that of sea level rise. The period of record corresponds with Eurasian Milfoil invasion. The historically dense growth of this plant would have modified the equilibrium by damping bottom wave currents, accelerating the sedimentation rate, and shifting the Bay floor to a shallower equilibrium depth. At present, The Bay floor appears to be reverting to the previous regime. Concentration profiles of ^{210}Pb at 2 stations indicate accumulation rates less that sea level rise. Sandy layers at or near the sea floor suggest recent winnowing, and anecdotal accounts suggest that much of the Bay floor may be 'sandier'

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Table 1. Resuspension Depths in Back Bay

Fetch=6 km, Grain Size=.062 mm (4 Phi) Depth=1.5 m

Wind Speed knots	Wind Speed m/s	Wave Ht. meters	Wave Period seconds	Current cm/s	Resus. Depth cm
13.50	6.01	0.24	1.80	7	0.60
19.50	8.68	0.30	2.00	7	0.60
19.50	8.68	0.34	2.30	10	0.60
24.50	10.90	0.38	2.20	10	0.60
31.80	15.00	0.53	2/80	10	0.60
63.60	30.00	0.81	3.40	13	2.70
78.20	37.00	1.05	3.96	15	2.80

Table 2. Wind Direction and Frequency Versus Speed
From National Weather Service, Norfolk, VA

Wind Dir.	0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>40	Total Freq.
N	0.2	1.2	3.4	4.4	1.1	0.2	0.1			10.6
NNE	0.1	1.0	2.7	2.6	0.5	0.1	0			6.9
NE	0.2	1.6	3.5	3	0.4	0.1				8.7
ENE	0.2	1.6	1.8	1.1	0.1					4.8
E	0.4	1.8	1.8	0.7						4.9
ESE	0.3	1.2	1.1	0.4						3.1
SE	0.3	1.6	1.9	0.7						4.4
SSE	0.3	1.6	1.5	0.5						4
S	0.5	3.8	5.4	2.9	0.3					13.6
SSW	0.3	2	3.3	3.2	0.4	0.1				9.3
SW	0.3	1.6	2.7	2.9	0.6	0.1				8.1
WSW	0.2	0.9	1.4	1.6	0.3	0.1				4.6
W	0.2	1	1.9	1.9	0.3		0.1			5.4
WNW	0.1	0.7	1.1	1	0.2					3.2
NW	0.1	0.6	1.4	1.5	0.3					3
NNW	0.1	0.5	1	1.7	0.3					3.6
Calm	0.7									1.7
Total F1	**55.6**	**22.8**	**35.9**	**30.1**	**4.8**	**0.7**	**0.1**	**0**	**0**	**100**

Table 3. Wave Height Frequencies, Station BB1

	Direction and Fetch in km																
Wave Height Cm	**N (2)**	**NNE (2)**	**NE (3)**	**ENE (2.5)**	**E (2.5)**	**ESE (4)**	**SE (5)**	**SSE (6)**	**S (4.5)**	**SSW (3)**	**SW (6)**	**WSW (4)**	**W (4.5)**	**WNW (5)**	**NW (5.5)**	**NNW (6.5)**	**Total Freq.**
Calm																	1.7
17	0.2	0.1															0.3
18	1.2	1			0.4												2.6
19	3.4	2.7	0.2	0.2	1.8				0.5				0.2				9
20	4.4	2.6	1.6	1.6	1.8	0.3	0.3		3.8	0.3		0.2	0.9	0.1	0.1		18.1
21				1.8	0.7	1.2	1.6	0.3	5.4	2	0.3	0.9	1.4	0.7	0.6	0.1	17.5
22	1.1	0.5	3.5	1.1		1.1	1.9	1.6	2.9	3.3	1.6	1.4	1.6	1.1	1.4	0.5	24.9
23	0.2	0.1	3			0.4	0.7	1.5		3.2	2.7	1.6		1	1.5	1	16.9
24			0.4	0.1				0.5	0.3		2.9		0.3			1.7	5.2
25	0.1		0.1							0.4		0.3					0.9
26										0.1							0.1
27																	
28														0.2			0.2
29											0.6						0.6
30																	
31																0.3	0.3
32																	
33																	
34															0.3		0.3
35																	
36													0.1				0.1
37												0.1					0.1
38											0.1						0.1
Total Freq.	10.6	6.9	8.7	4.8	4.9	3.1	4.4	4	13.6	9.3	8.1	4.6	5.4	3.2	3	3.6	100

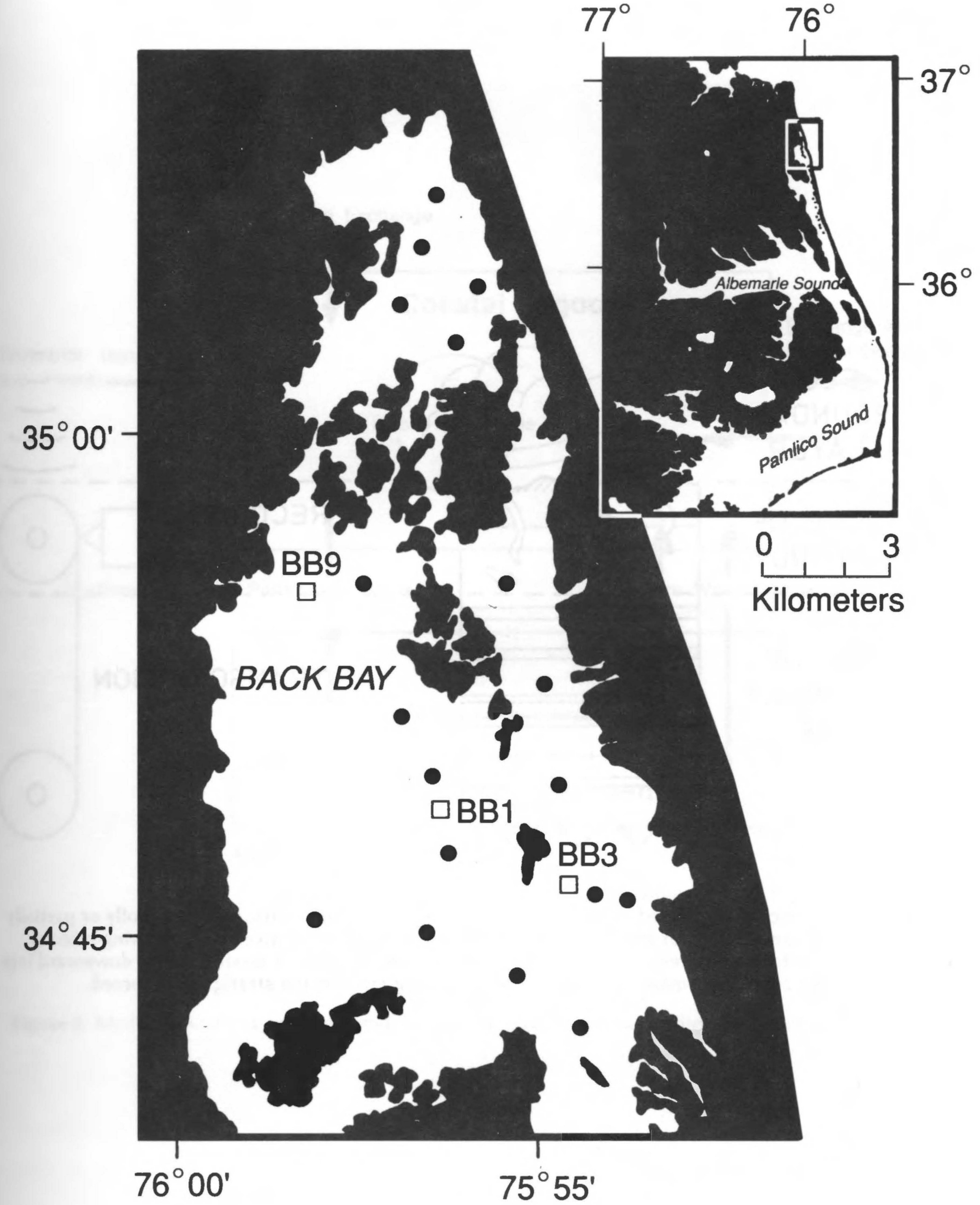

Figure 1. Back Bay showing location of stations, and relation to Albemarle-Pamlico lagoon-estuary system.

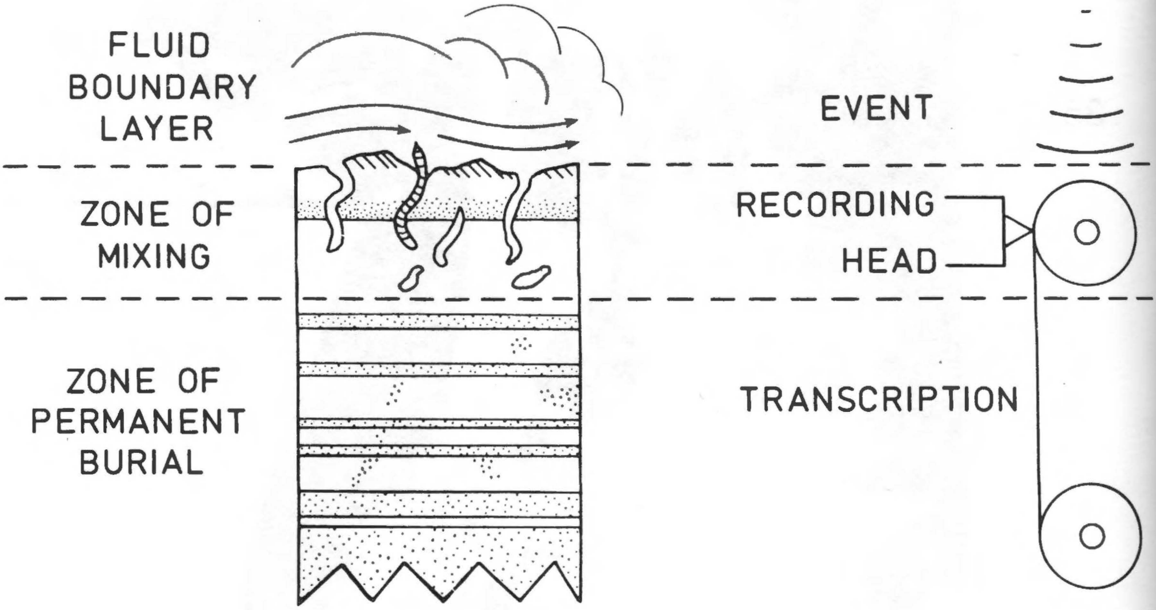

Figure 2. Dynamics of the mixed layer. Strata are formed by storm events, and are wholly or partially resuspended by later events. Strata are erased and sediment mixed by burrowing infauna. Signal formed by resuspension and bioturbation in the zone of mixing passes downward into of the zone of permanent burial as the "unreeling tape" of the stratigraphic record.

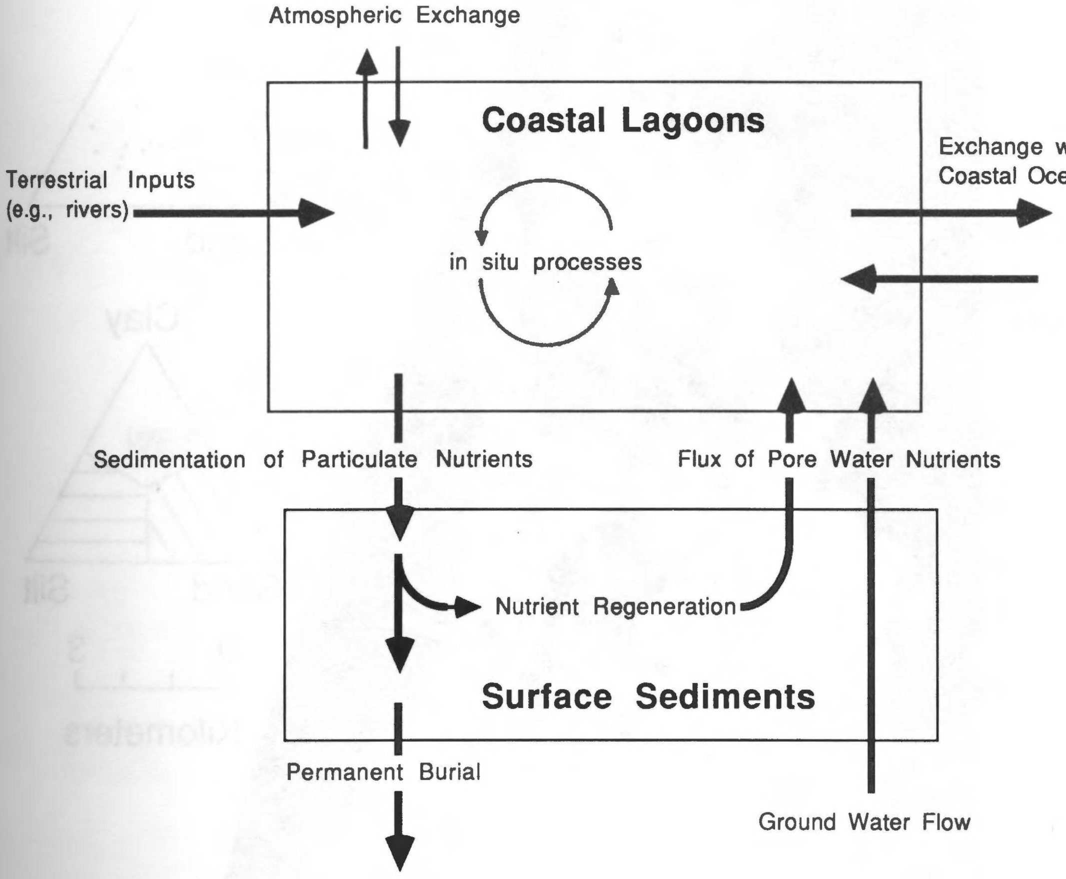

Figure 3. Model of nutrient cycle in a middle Atlantic lagoon (David Burdige, personal communication).

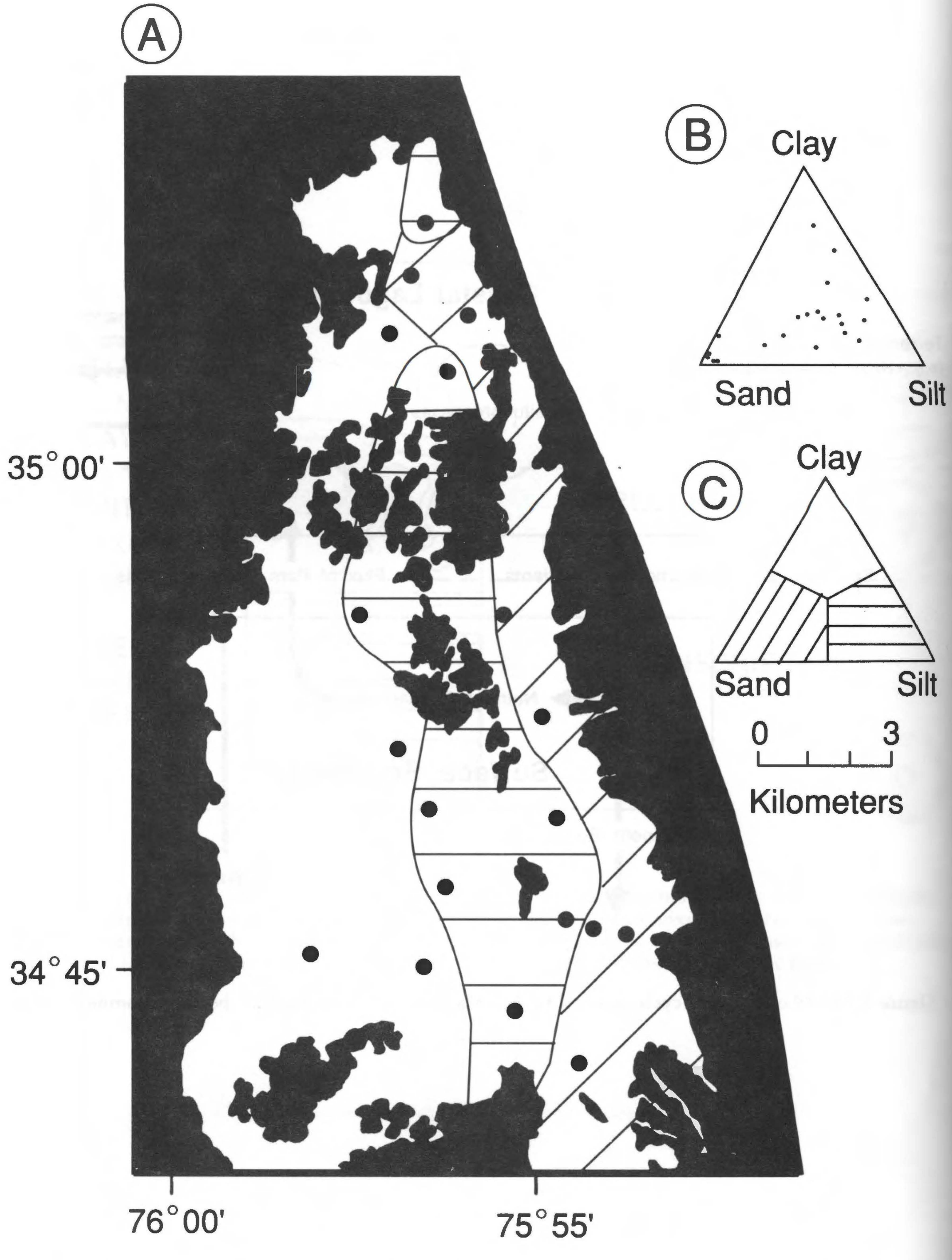

Figure 4. Sediment types of the Bay floor. A) distribution map. B) Sand silt clay diagram. C) Key to sediment types on map.

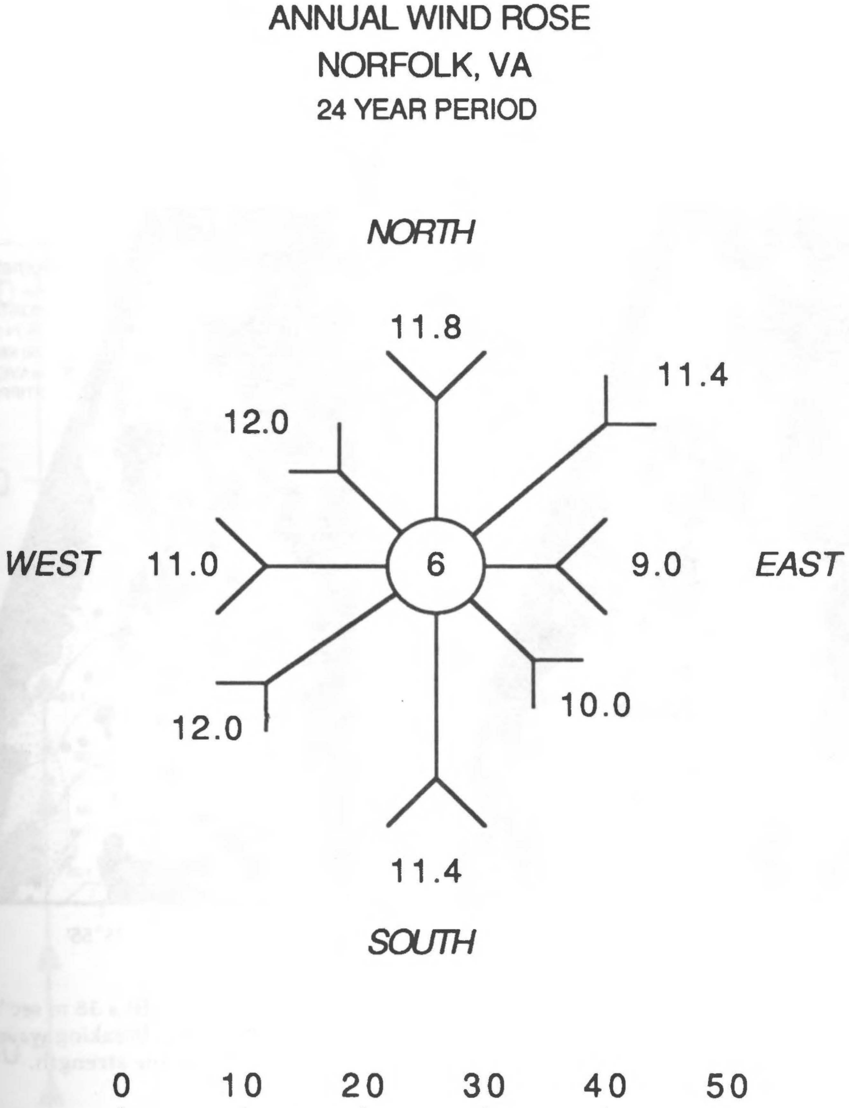

Figure 5. Annual wind rose for Norfolk, VA. Arrows point in the wind direction. Numbers by the tails of the arrows are average velocities in nautical miles per hr. Lengths of shafts, as measured on scale, indicate percent frequency. Personal communication National weather service, Norfolk, VA.

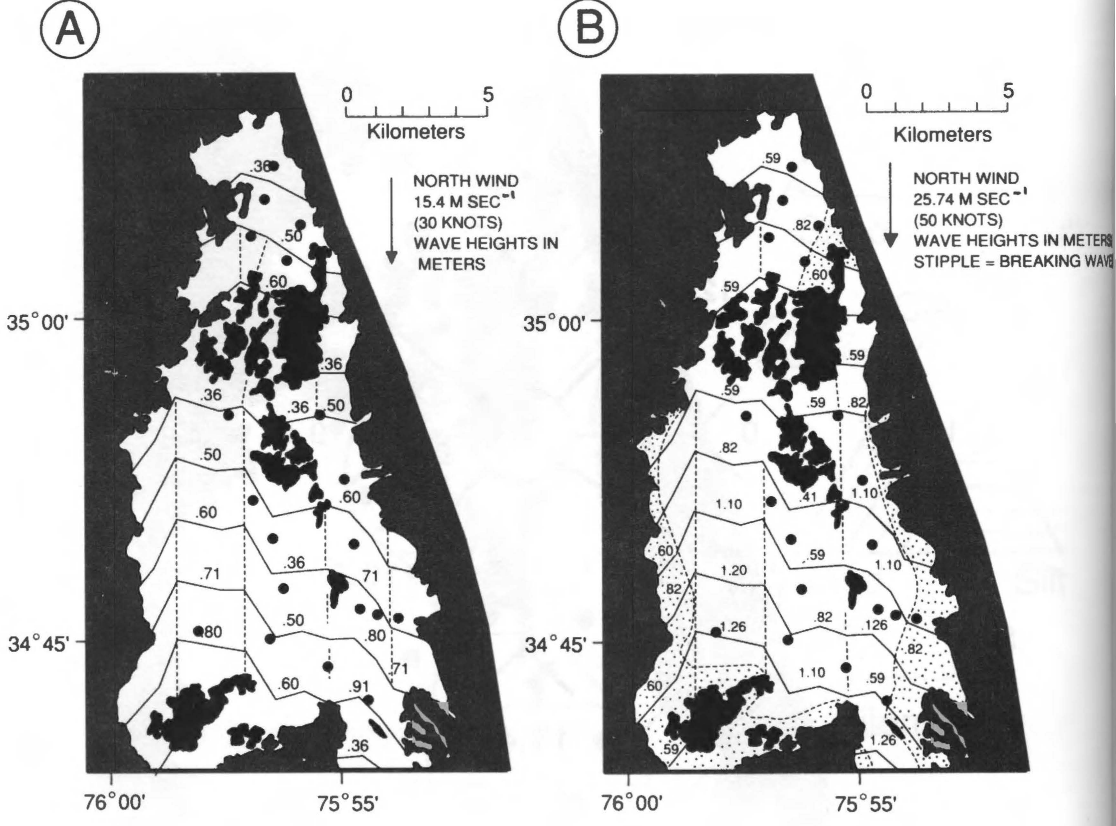

Figure 6. Wave heights in Bay for A) 15 m Sec^{-1} (30 knot) north wind and B) a 38 m sec^{-1} (75 knot) nor wind. Dashed lines separate fetch lanes. Stippled area is zone of breaking waves. Bay is fetc limited rather than depth-limited for winds of less than hurricane strength.

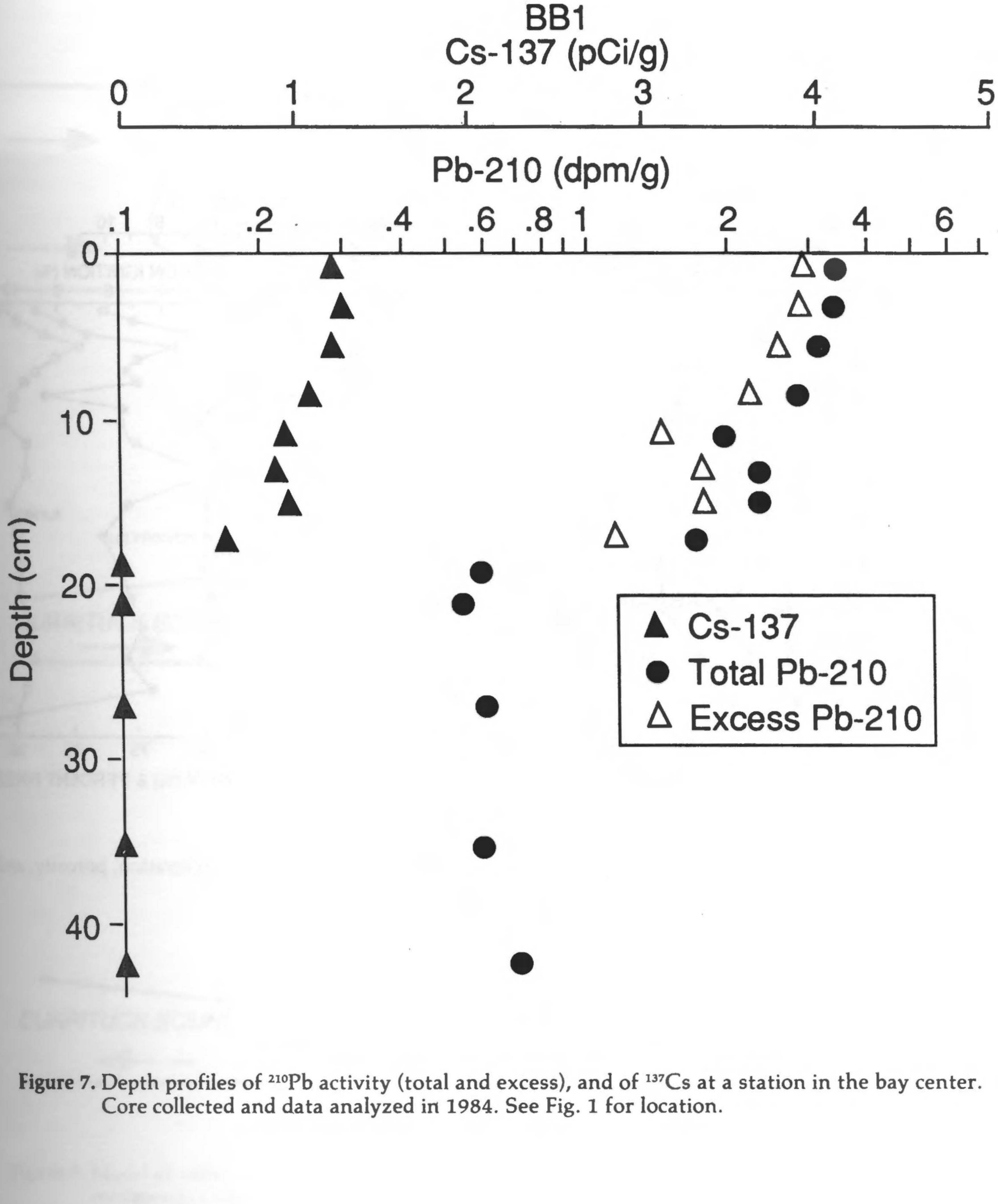

Figure 7. Depth profiles of ^{210}Pb activity (total and excess), and of ^{137}Cs at a station in the bay center. Core collected and data analyzed in 1984. See Fig. 1 for location.

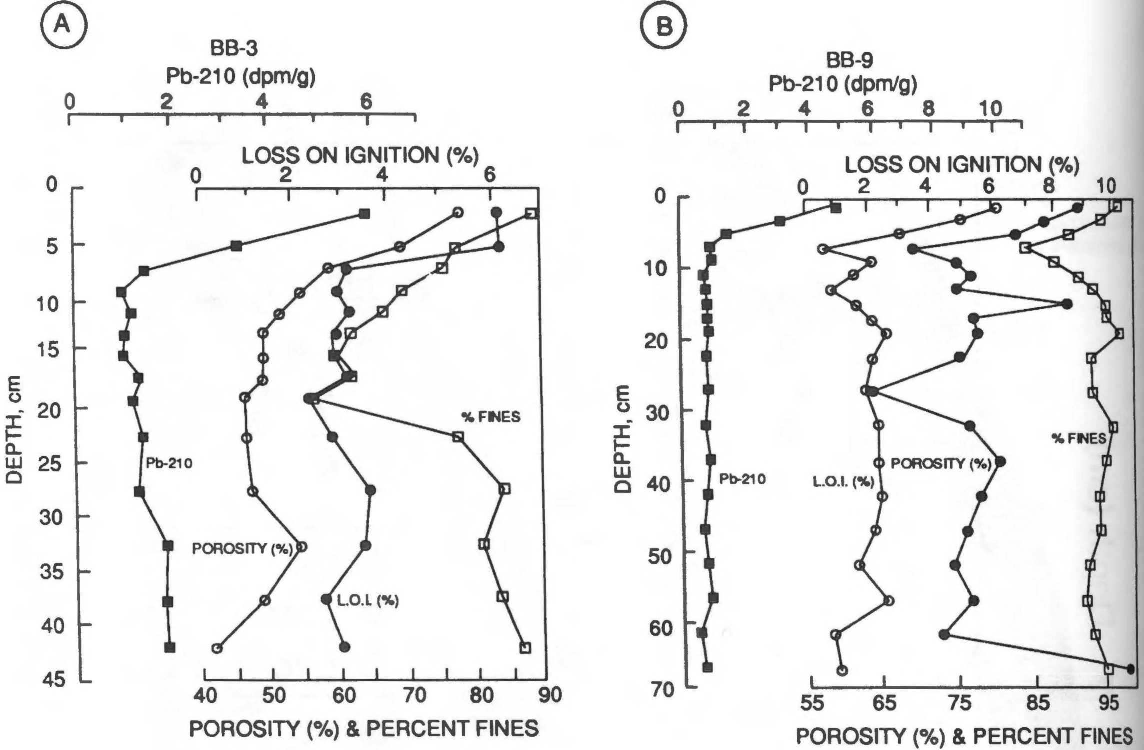

Figure 8. ^{210}Pb profiles from 2 cores collected in 1990, plotted against loss on ignition, porosity, and percent fines.

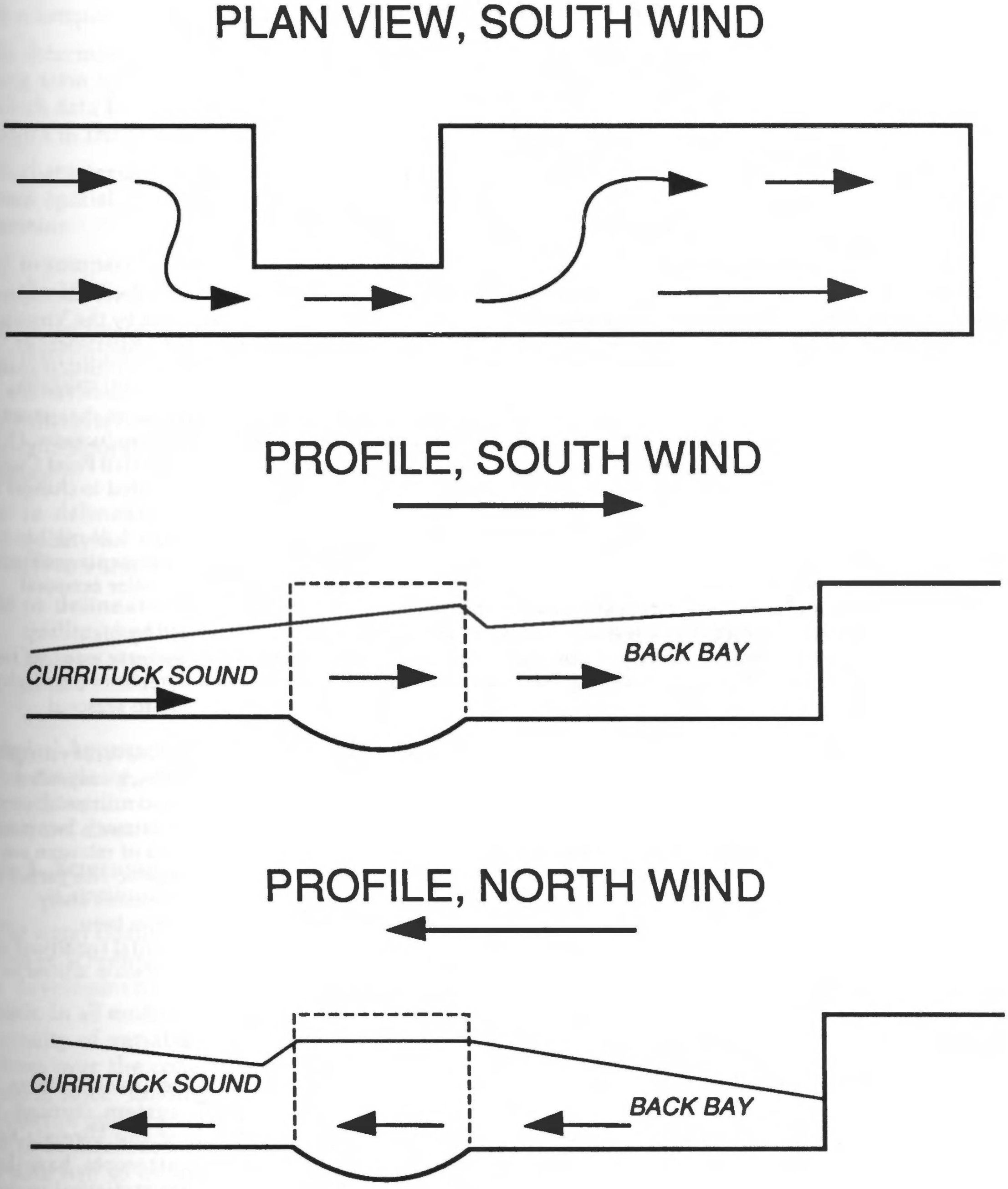

Figure 9. Model of wind pumping mechanism for sediment supply. A) At onset of storm, south wind resuspends sediment in Currituck Sound and sets up Currituck sound against Knotts Island, forcing suspended sediment and water through Knotts Island passage. B). After passage of front, north wind sets Back Bay up against Knotts Island; water and excess sediment is returned through Knotts Island Passage. Dashed line in figure is outline of Knotts island, located behind the plane of the paper. Knotts Island Passage is overdeepened by scour.