PRE-CONSTRUCTION *SABELLARIA VULGARIS* MONITORING AT BROADKILL BEACH AND PORT MAHON SAND PLACEMENT SITES, KELLY ISLAND AND SLAUGHTER BEACH (CONTROL)

DRAFT REPORT

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Introduction

The sandbuilder worm or "reefworm," *Sabellaria vulgaris* Verrill 1873 is a tube-building, annelid polychaete worm common on the Mid-Atlantic coastline of the USA (Gosner 1978, Lippson and Lippson 1997, Pollock 1998). This species ranges from Cape Cod to Georgia, occurring from low in the intertidal zone to shallow subtidal in waters with salinity above 15 ‰ (ppt, or parts per thousand) (Gosner 1978, Ruppert and Fox 1988). Their life cycle includes a planktonic larval stage (Curtis 1973, 1975) that settles gregariously on a wide variety of substrata, including rocks and cobbles, clamshells, oyster bars, horseshoe crab carapaces, other worm tubes and pilings (e.g., Hidu 1978, Karlson and Shenk 1983).

Sandbuilder worm tubes are built of sand grains cemented together into a hard encrustation. Worm tubes may be found singly or in small clusters attached to various substrata, and the worms protrude their crown of tentacles from the tube openings (Fig. 1) for both feeding and tube construction. In Delaware Bay, sandbuilder worms are also found in dense aggregations where the tubes grow in straight, parallel, spaghetti-like bundles that completely cover the substratum (e.g., Wells 1970). These bundles may be firm enough to walk on and extend 20 cm or more above the substratum, and they often become sufficiently large to be termed a worm reef. The surface of the reef is brown with honeycomb-like tube openings (Fig. 2), each representing an individual sandbuilder worm. Reef development appears to be a unique characteristic of Delaware Bay populations, although Wells (1970) describes masses on a shipwreck in North Carolina that closely resemble Delaware reefs in consistency, morphology and tidal elevation.

Sandbuilder intertidal reefs in the lower Delaware Bay have been documented by Amos (1966), Wells (1970), Curtis (1973, 1975, 1978), Pembroke (1976) and Woodard (1978), ranging from Woodland Beach (Maurer and Watling 1973, cited in Pembroke 1976) to South Bowers Beach to the Inner Breakwater Harbor at Lewes (Wells 1970). In particular, Wells (1970) lists both the Old Inlet Jetty and Broadkill Beach as sites of well-developed reef masses. Curtis (1973) used the jetty as a site in his field experiments and reported live colonies at nearby Beach Plum Island and Primehook Beach. Curtis (1975) also notes that intertidal colonies at Broadkill Beach are associated with firm substratum; Woodard (1978) provides a photograph of Old Inlet Jetty in her Plate 1.

The distribution of the intertidal colonies and reefs of sandbuilder worms at Broadkill Beach is to a large degree limited to artificial rock or wooden pilings (Miller 2002). At other beaches previously studied by Miller and his students (Miller et al. 2002a, Muir 2002), sandbuilder worm reefs are found on the sand near the beach slope break where cobble-sized or larger (i.e., ≥6.4 cm across) natural stone, bricks or other construction debris are present. Beach sand near the reefs and elsewhere ranges from fine to coarse in grain size (Miller 2002). Sandbuilder worms are epifaunal and require water flow and wave action to provide sand grains for tube building. Beaches supporting *Sabellaria* colonies are fully exposed to the Delaware Bay to the northeast and experience sufficient resuspension of sand to allow tube growth. Rees (1976) reported that sandbuilder worms from Big Stone Beach used coarse and medium sand to build tubes and employed increasing grain sizes with time.

From their sizeable reef structure and outward appearance, these aggregations are sometimes known locally as "corals." This term is taxonomically inaccurate as well as potentially misleading, and it will not be used in this report. Reef-forming corals are members of another phylum (the Phylum Cnidaria, Class Anthozoa, in part, known as hermatypic corals) and characteristic of warm, clear tropical waters (Lalli and Parsons 1997). Because of their particular habitat requirements, reef-forming corals are not found in the Mid-Atlantic region. However, at least one species of non-reef forming, true coral, *Astrangia danae*, is found in the region in subtidal habitats though it has little tolerance for brackish water and high turbidity (Gosner 1978). It is important to note that because of differing habitat requirements, this star coral *A. danae* is not associated with the sandbuilder reefs.

The ecology of sandbuilder worms has been studied in the region, and in the Delaware Bay in particular, in a number of studies over the past 30 years, for example, Amos (1966), Wells (1970), Curtis (1973, 1975, 1978), and Pembroke (1976). Sandbuilder worms have a persistent and well-documented distribution within the Delaware Bay. Subtidal populations are thought to be more widespread and seasonally stable. Intertidal populations are more limited by availability of stable substratum and controlled by seasonal recruitment and winter mortality. These sandbuilder reefs form a habitat that is physically far more stable (termed "worm rocks" by Gosner 1978) and considerably more ecologically diverse than would otherwise be found on bare rock or sand substratum. Thus, the reef structure and associated invertebrates are likely to provide food for fish and therefore represent a productive nearshore marine habitat.

The Army Corps of Engineers is proposing to use dredge material from the deepening of the Delaware River Federal Navigation Channel for shoreline restoration at Broadkill Beach (USACE 1997) and other sites along the southwestern shoreline of Delaware Bay. This area has been known historically (e.g., Curtis 1975) and recently (R. Martin, personal communication 2000, D. Miller, personal observations, 2000-2004) to have sandbuilder worm reefs. Since shoreline restoration has the potential to bury and disrupt these reefs, it is necessary to determine the extent and location of present reefs as baseline data prior to construction activities.

Purpose / Objective of Study

The purpose of this study was to document the presence, extent and locations of *Sabellaria vulgaris* colonies and reefs at Broadkill Beach, Kelly Island, and Port Mahon with respect to habitat type, tidal stage, and other environmental factors for both intertidal and subtidal colonies. Colonies at Slaughter Beach were be surveyed as a control site, and various substrates at Broadkill and Slaughter Beaches were monitored for colonization over several months.

Intertidal Survey and Recruitment Monitoring

Methods

A survey of the intertidal sandbuilder worm colonies and reefs at Broadkill Beach, Slaughter Beach, Port Mahon and Kelly Island (Fig. 3) was conducted on the spring tides in late June and early July 2004. The basic methodology used was identical to that employed previously in the July 2001 survey of Broadkill Beach (Miller 2002).

Within an hour of the afternoon low water, the beach was walked by the contractor and his associates on dates chosen to be near the lowest spring tides of June and July, 2004, which represented the best opportunity for the colonies to be observed and measured in the intertidal at the study sites. The following operational definitions were used: a **colony** is defined as an aggregation of worm tubes, usually small in size (< 1 m across) and somewhat isolated from other worm tubes. A **patch** is a region of scattered colonies (i.e., separate and unconnected) but within approximately 5-10 m of one another, i.e., the resolution of our hand-held GPS system. A **reef** is defined as a larger structure of worm tubes, a meter or more across, with 5 cm or more of vertical worm tube growth.

Where sandbuilder colonies, patches or reefs were observed, their location was determined with a handheld GPS (Garmin model GPSMAP 76) and associated with nearby streets or landmarks. The dimensions of a reef, along the shore and distance seaward from the beach-slope break, were determined with a measuring tape. Reef area was determined by approximating the irregular shape of the reef by separately measured triangles and rectangles and summing these individual areas. Various digital photographs of the whole reef, as well as close-up sections, were made to document the reef shape and structure. At Slaughter Beach, sections of the reef were photographed from the slight elevation of the shoreline with a square 1.5 m x 1.5 m white quadrat frame in the image for scale and rectification. Perspective corrected images were examined individually and the outline of reef sections was digitized manually to compute the bottom area covered. Areas were summed and overlaps eliminated in order to estimate the total area covered by the reef along the shoreline.

An on-site determination of the overall condition of the reef was made as indicated by new tube growth (tubes with a “flare” or “porch,” Wells 1970), tube erosion, and over-settlement by mussels or tube worms, crab burrows, *et cetera*. Observations and notes were recorded in the field on data sheets (see below and included in appendices) and additional observations were made on the study area shoreline, especially where rock, cobbles and gravel were present at the tidal level typically associated with sandbuilder reefs. At the *Sabellaria* reefs and at other sites along the beach, additional measurements were made to more fully characterize environmental conditions in the study area. These included: seawater temperature and salinity (handheld YSI model 30 meter), beach slope (inclinometer), and sediment grain size (standard dry sieving methods).

Following the intertidal surveys, settling plates were deployed at Broadkill (2 August at the Georgia reef, adding the Alabama reef on 1 September) and Slaughter Beaches (29 August) and monitored monthly on low spring tides. These plates were replicate pairs of numbered stone pavers (20 cm x 20 cm x 2-3 cm thick) of slate (designated "S" and greenish in color) and quartzite ("Q" and whitish in color) stone material placed on or adjacent to the reef in accessible locations. Deployment coincided with noticeable new, small *Sabellaria* tubes visible at both sites. These plates were monitored for *Sabellaria* settlement and tube growth through December, 2004. Additional plates were deployed in September, October and December as needed to monitor for additional settlement. Recovered plates were photographed and measured in the field, and then either returned to their location in the field or in some cases returned to the laboratory for further analysis. In addition to photographing the natural reef on monthly site visits, additional water column and sediment measurements were made.

Results

Sabellaria colonies were widely distributed at Broadkill Beach, Slaughter Beach and Port Mahon, but no colonies were found on the Kelly Island shoreline.

Broadkill Beach—Broadkill Beach (Fig. 5) was surveyed in two segments: Broadkill North on 28 June 2004 from north of California Avenue south to Virginia Avenue (38° 50.244' N 75° 13.155' W to 38° 49.812' N 75° 12.767' W), and Broadkill South on 29 June 2004 from Beach Plum Island State Park access north to Virginia Avenue (38° 49.375' N 75° 11.352' W to 38° 49.809' N 75° 12.781' W). Colonies were observed along most of the north segment, but reefs are most extensively developed at Alabama and Georgia Avenues and at the Old Inlet Jetty.

From the north end of the survey area, scattered colony chunks were found in the wave swash, broken and laying sideways on the sand, from 38° 50.205' N 75° 13.255' W south to Alabama Avenue. At the Alabama and Georgia Avenue rock groins, there were two large *Sabellaria* reefs consisting of mostly old and eroding tube material with scattered new tube growth. The Alabama reef (38° 49.994' N 75° 12.968' W, Fig. 6) was triangular in shape and covered 35 m^2. The Georgia reef (38° 49.994' N 75° 12.968' W, Fig. 7) was larger (137 m^2) and more elongated perpendicular to shore, and had extensive tube material along the sides of the rock groin.

To the south (that is, North Carolina Avenue and southward), colonies were found on the vertical surfaces of wooden groins (Fig 8). *Sabellaria* colonies here exhibited new growth and were part of a diverse epifaunal community including blue mussels and rubbery bryozoans. Small *Sabellaria* colonies were found scattered along the beach in this segment. In this section of the beach, a sand pumping pipe (36-cm diameter) was found running out of the beach offshore at least 35 m away from the beach (38° 49.465' N 75° 12.379' W, Fig 9). The top surface of this pipe was covered with low *Sabellaria* colonies at least this distance from shore.

The reef observed at the Old Inlet Jetty (2.4 km south of Route 16 and 800 m north of the Beach Plum boundary, 38° 48.476' N 75° 11.668' W, Fig. 10) is by far the largest on Broadkill Beach. The jetty extends an estimated 115 m bayward, and the reef on both sides extends the full length of the jetty from 3 - 6 m wide, from the beach slope break. The total area of this reef is approximately 295 m^2. Coverage at the bay-end is essentially 100% by sandbuilder worm tubes, though most of this was dead tube material. Isolated live *Sabellaria* patches were seen along the jetty amongst a diverse hard bottom community consisting of red sponges, rubbery bryozoan, small crabs (mud and Asian shore), feathery hydroids and burrowing nereid polychaete worms.

No *Sabellaria* colonies were found south of the Old Inlet Jetty to the dune-crossing beach access from Beach Plum State Park. Pooled data from both north and south section surveys indicates that water temperatures in the survey area ranged from 23.6 – 26.9 °C and salinities from 25.3 – 28.0 ppt. Sediments were medium to coarse sand, with the exceptions of one fine sand and one gravel location.

Slaughter Beach—Slaughter Beach (Fig. 11) was surveyed in three segments: South on 30 June 2004 (midway between Maryland and Virginia Avenues to Simpson Avenue, to 500 m south), North on 1 July 2004 (from Bridgeham Avenue to Cedar Avenue), and Middle on 3 July 2004 (Virginia Avenue north to Cedar Avenue).

Within the North and Middle segments of Slaughter Beach, clumps or colonies (< 30 cm across) were numerous between 38° 55.056' N 75° 18.426' W (midway between North Delaware Avenue and Pavilion Street) and Virginia Avenue. A single large colony above the waterline was observed 75 m out from the beachface at Cedar Avenue at 38° 54.732' N 75° 18.085' W. South of this point and towards Simpson Avenue, colonies trend into reefs, becoming larger and more continuous.

Sabellaria colonies are most extensively developed near Simpson Avenue (38° 54.334' N 75° 17.734' W), the southernmost public access from Slaughter Beach. Here the reef is ribbon-like, 1-2 m wide, up to 5-10 m from shore and run along the beach to the north as well as a considerable distance to the south (Fig. 12). Reef segments have variable width and are elongated along the shoreline, extending 20-30 cm high above the sand (Fig. 13). From Simpson Avenue, the reef extended 100 m to the south and covered an estimated 89 m^2 in area (i.e., mean width 0.89 m along the beachface). From Simpson Avenue northward, reef sections extended approximately 450 m to just north of Virginia Avenue. In total area, these reef sections covered 328 m^2 (i.e., mean width 0.73 m along the beachface). Combined data from the three sections shows that water temperatures ranged from 24.8 – 29.4 °C and salinities from 24.2 – 27.7 ppt. Sediments were very coarse to granule sand throughout the survey area.

Port Mahon—Port Mahon's shoreline (Fig. 14) was surveyed in its entirety on 2 July 2004, extending from near the mouth of the St. Jones River (39° 11.349' N 75° 23.919' W) south to 39° 10.791' N 75° 24.280' W where the Kent County Road 89 meets the bay shoreline. Within this area, newly growing *Sabellaria* colonies were seen on the gravely sediment (Fig. 15), pilings, broken culvert pipe (Fig. 16), and on old steel bulk heading

(Fig. 17). Water temperature was 29-31 °C and salinity ranged from 12-19 ppt. Sediments were medium to coarse sand, with pebbles in one location.

Kelly Island—Kelly Island's shoreline (Fig. 18) was surveyed from near the mouth of the St. Jones River (39° 11.616' N 75° 23.768' W) north to 39° 12.504' N 75° 23.810' W) on 2 July 2004. Kayaks were used to cross the St. Jones River from the boat ramp and to gain access to Kelly Island. All sites were along the coastline at the time of the survey; their distance inland from the plotted shoreline reflects the high rate of shoreline erosion at this site. The shoreline here consists of a steep beachface and / or scattered large clumps of fine grained sediment with embedded plant material presumed to be old, eroding salt marsh layers (Fig. 19). Patches of sand wash in between the mud clumps and the nearly vertical beachface. No *Sabellaria* colonies were found anywhere along the shoreline within the survey area, although one horseshoe crab was found with *Sabellaria* tubes attached to its carapace (Fig. 20). At various points along the shoreline, sediment and water measurements were taken along with digital photographs of the shoreline. Water temperature was 28-30°C and was 17.3 ppt. Sediments were medium to coarse sand throughout the survey area.

Settlement plates and monthly monitoring—In order to better determine favorable times and substrata for settlement, stone pavers were deployed at both Georgia and Alabama Avenue reefs on Broadkill Beach (Fig. 21), and near Simpson Avenue on Slaughter Beach (Fig. 22). The reefs and plates were monitored monthly, and showed obvious *Sabellaria* settlement within four weeks (Fig. 23). Several attempts to recover plates, especially at Slaughter Beach in October and November were prevented by higher than expected tides. However, several pairs, including those from an initial deployment were recovered in early December (Tables 1 and 2). Both types of plates (slate and quartzite) quickly became covered by *Sabellaria* tubes, which essentially camouflaged the plates, making them difficult to locate in turbid low tide swash. The deployment schedule was driven by the desire to keep new plates deployed often enough to record settlement events. While some plates were returned to the lab for photographs and preservation, most plates were left in the field to gauge tube growth rates.

The twice recovered pair #4 from the initial Slaughter Beach deployment show that plates were colonized within a month, and that tube growth rates of 3-6 cm in three months are possible (Fig. 24). Similarly, pair #8 from Georgia Avenue showed 4.5 cm of growth in two months. Plates from pairs #14 (deployed late September), #16, #17 and #19 (late October) at Broadkill Beach showed some settlement, but lacked extensive tube growth. While plates of either type of rock are favorable for settlement, those deployed in late August or early September appear most favorable for tube growth in the form that results in reef formation. It may be significant that bay water temperatures remain relatively warm, >20°C, until October (Tables 1 and 2), and that (low tide) salinity values are relatively stable. Although plates were not deployed early enough to gauge settlement from earlier spawners, no obvious settlement was seen on natural reef substrata until late summer.

Discussion

Sabellaria colonies were widely distributed at Broadkill Beach, Slaughter Beach and Port Mahon, but no colonies were found on the Kelly Island shoreline. Although medium to coarse sand appropriate for tube growth was present, and water temperature and salinity appeared suitable for *Sabellaria,* their absence at Kelly Island is most simply explained by the lack of suitable, stable substratum since the beachface consists of muddy and eroding marsh sediments. On 15 July 2004, the contractor surveyed the north jetty of Roosevelt Inlet (near Lewes) and the southern 1500 m of Beach Plum Island State Park. While the jetty rock and shipwreck timbers appeared suitable for *Sabellaria* colonies, none was found despite careful search. The explanation for *Sabellaria*'s absence there (although they have been documented both to the north and south along the shore) is not clear, although it is obvious from the shape of the shoreline that the sand beach is eroding. Likewise it is not clear whether *Sabellaria* colonies will develop on the newly constructed south jetty at Roosevelt Inlet.

The large reefs at Broadkill Beach, the low linear reefs at south Slaughter Beach and the relatively small colonies at Port Mahon have all been observed by the contractor in at least two different calendar years and likely represent long-lasting temperate reef habitat. In fact, according to Wells (1970), the Old Inlet jetty reef is depicted in the photograph in Amos (1966). Overall, these results reinforced our belief that *Sabellaria* reef is a persistent feature of these sites, and that reefs can exhibit dramatic changes monthly in the fall related to new tube growth, and that that low winter temperatures control seasonal succession of the reef (see below)`. Reefs at Broadkill and Slaughter Beaches and Port Mahon are persistent enough to be suitable to study of the annual cycle of reef growth and decay.

The longevity of the small, isolated colonies at Slaughter Beach and Broadkill is more difficult to characterize. These may represent localized settlement of randomly exposed, suitable stable substratum, such as partly buried cobble, shell or rock. Settlement plates suggest that even in a relatively small area, several centimeters or more of tube growth is attainable under favorable conditions. Alternatively, other isolated colonies appear to be broken off larger reef masses. We observed this form of material loss from the reefs during our summer sampling at Broadkill Beach. At Slaughter Beach in late September, we observed the area between the reef and the beachface to be covered with reef chunks (10 – 20 cm across) with new tube growth. Some colonies at Slaughter Beach, especially those North and Middle segments and south of the ribbon reef at Simpson Avenue are lower in relief (<10 cm as compared to 20-30 cm for the reef) and appear partly buried. It is known from laboratory studies that worm survival is severely affected by a covering of even 1-2 cm of sandy sediment (Muir 2002, Miller et al. 2002a).

Miller's (2002) survey of Broadkill Beach in July 2001 did not find *Sabellaria* colonies on the wooden groins. These groins were inspected closely by the survey team, and the absence of colonies is documented with several photographs (e.g., their Figs. 9 and 16). The contractor has however observed colonies on vertical wooden surface the in the present survey, and in summer 2003 he supervised undergraduate intern projects on colonies there at North Carolina Avenue. Since the wood substratum is certainly stable and supports a biofouling community, it is not entirely clear what factors explain these year-to-year differences in *Sabellaria* colonies.

The area estimates for the Broadkill groins and Old Inlet jetty reefs from this study are larger than those reported by Miller (2002) from the same sites. This difference is an artifact of the field conditions experienced. The 2001 rock groin dimensions were made under higher than expected tide levels due to wind setup (compare their Fig. 4 with the present Fig. 6). We have subsequently visited the reefs on extremely low tides (Fig. 6 and 7) and are confident in the dimensions reported here that were made under good tidal exposure. The length used for the length of the jetty in 2001 was an estimate from aerial photographs, the value used here comes from directly GPS measurements on-site, and this accounts for the difference in area values.

Our preliminary, pre-survey work as well as the June and July sampling described above noted that most of the reef mass at Broadkill and Slaughter Beaches was eroding and dead. Live, growing tubes and dead, eroding reef material are easy to distinguish. Actively growing *Sabellaria* makes tubes with well-defined edges, usually somewhat lighter in color, and the worm itself can often be seen even when withdrawn into the tube. Dead tubes are filled with sediment, have rounded openings and can compress or crumble under human weight. Disintegrating tube masses can in fact make the reef surface slippery and treacherous to walk upon.

Although the reefs at Slaughter and Broadkill Beaches were initially characterized as "mostly dead" with isolated new growth, we observed a strong settlement in September, first noticeable as a low 2-3 mm high layer of randomly oriented tubes on the surface of the old reef or bare rock. Over subsequent months, tube growth became more erect and coalesced. By late October, enough tube growth had occurred that rocks disappeared beneath the tube mass, filling voids between rocks and rounding over the surface. The tubes eventually will grow together to form a remarkable uniform and level surface.

In January 2004, bitterly cold weather allowed ice to form on exposed worm reef. Temperatures measured in the reef mass (embedded 2 - 4 cm) were –2 to –6 °C, intermediate between slushy seawater (-1.4 °C) and the air (-8 °C). Low winter temperature was suggested by Curtis (1975) as a major source of mortality for intertidal *Sabellaria* colonies. Our January, 2004 observations of ice on the Broadkill colonies (combined with measurements of low temperatures) support this hypotheses. Miller and his students documented a strong settlement in the fall of 2003. Following the winter 2004 cold snaps little life was seen on the reefs, and their condition deteriorated through the spring and early summer, just before the initiation of the present survey.

In this survey and in other studies over the past few years, we have documented sandbuilder reef locations at Port Mahon, Slaughter Beach, Primehook Beach, Broadkill Beach and Cape Shores (Miller 2002, Miller et al. 2002a, Muir 2002). Since 1999, we have noted the seasonality of recruitment and reef development: small tubes of new recruits become evident in late fall. Intertidal beach colonies are the most ephemeral and least developed, while those on rock jetties and groins are more persistent. Although *Sabellaria vulgaris* is the dominant structural species, other species include macroalgae and blue mussels, other tube-building polychaetes, the Asian shore crab and small eels. Studies undertaken to date have not been comprehensive enough to fully characterize the reef-associated community nor to assess the habitat value for near shore invertebrates and fish.

Subtidal Colony Surveys

[This section will be a summary of the results of the side scan and QTC survey of the subtidal distribution of *Sabellaria* conducted in mid November by Gary Smith and associates at Random Motion LLC. Validation of the acoustic results will be conducted by Willy Burton of Versar, based on dredge sampling (approximately 60 samples over the three subtidal survey areas) to be conducted during the week of 20 December 2004 (personal communication, 15 December 2004). This report section will include Methods description (text), Results (text and summary graphics) and Discussion (interpretation and analysis of remote sensing and benthic sampling) to be provided by Gary Smith and Willy Burton of Versar, Inc.]

General Discussion

Intertidal sandbuilder worm habitat in lower Delaware Bay

The results of the present study confirm published, historical studies and personal observations by the contractor show that intertidal sandbuilder colonies and reefs extend along the shoreline throughout the study area. Sandbuilder intertidal reefs in the lower Delaware Bay have been documented by Amos (1966), Wells (1970), Curtis (1973, 1975, 1978), Pembroke (1976) and Woodard (1978), ranging from Woodland Beach (Maurer and Watling 1973, cited in Pembroke 1976) to South Bowers Beach to the Inner Breakwater Harbor at Lewes (Wells 1970). In particular, Wells (1970) lists both the inlet jetty and Broadkill Beach as sites of well-developed reef masses. Curtis (1973) used the jetty as a site in his field experiments and reports of live colonies at nearby Beach Plum Island and Primehook Beach. Curtis (1975) also notes that intertidal colonies at Broadkill Beach are associated with firm substratum. Woodard (1978) studies Old Inlet Jetty populations and provides a photograph in her Plate 1. While the species ranges from Cape Cod to Georgia (Gosner 1978), the formation of reef structures seems unique to Delaware Bay (with a single documented exception in North Carolina, Wells 1970).

The vertical distribution of sandbuilder colonies with respect to the tides is described by both Wells (1970) and Curtis (1975). At Big Stone Beach, Delaware, Wells (1970, Fig. 3) shows beach colonies bayward of the slope break, ranging from 0.0 to 0.35 m above mean low water (MLW). Curtis (1975) related the vertical distribution to exposure times during extreme spring tides at the Mispillion jetty sandflat. Almost no live worms were found above exposures of 175 minutes, and most of the live colony was found in the 101 – 150 minute exposure zone.

Beach sand near the reefs and elsewhere ranged from fine to coarse in grain size (Table 2). Sandbuilder worms are epifaunal and require water flow and wave action to provide sand grains for tube building. The beaches surveyed in this study are fully exposed to the Delaware Bay to the northeast, and this provides sufficient resuspension of sand to allow tube growth. Rees (1976) reported that sandbuilder worms from Big Stone Beach used coarse and medium sand to build tubes and employed increasing grain sizes with time.

The distribution of the intertidal colonies and reefs of sandbuilder worms at the surveyed beaches is limited to rock, gravel or cobble as well as other, artificial materials, including wood, bulk heading, concrete, old tires. At Broadkill Beach, colonies near the Alabama and Georgia reef appear to remains of material broken off nearby reefs. At Slaughter Beach, sandbuilder worm reefs are found on the sand beach near the beach slope break where cobble-sized or larger (i.e., ≥6.4 cm across, Gray 1981, Table 2.1, p. 13) natural stone, bricks or other construction debris are present at the beach slope break. Shoreline dynamics and sediment sources for the lower Delaware Bay are discussed by Maurmeyer (1978). The lack of cobble some beaches could be due to a lack of natural or artificial source or that coarse material has been removed or buried. Burial could have been facilitated by the sand trapping action of the groins currently on the Broadkill Beach.

Subtidal sandbuilder worm populations are believed to be more widely distributed subtidally both in Delaware Bay (Pembroke 1976, Fig. 1) and throughout this geographic distribution (Wells 1970, Gosner 1978). Sandbuilder worms inhabit a variety of hard-bottom communities, including the Bay's oyster beds (e.g., Maurer and Watling 1973) as well as the serpulid reefs located nearby offshore (e.g., Haines 1978, Haines and Maurer 1980a,b).

Subtidal sandbuilder habitat in lower Delaware Bay

[This section will analyze a summary of the subtidal survey findings (as given in a section above) and present an interpretation of intertidal and subtidal results from this project.]

Sandbuilder worm life history and settlement

The life history of the sandbuilder worm in the lower Delaware Bay was extensively studied by Curtis (1973, 1975, 1978) and Pembroke (1976). Wells (unpublished, cited in Curtis 1975) noted that each winter there was a nearly complete kill of the sandbuilder worm adults in the intertidal region. Settling plate studies have found that sandbuilder larvae begin to settle from the plankton in late May or early June. Curtis (1973) extended these studies and reports (e.g., Curtis 1978) that larvae occur in the plankton from mid-April through October and settle in late May through October, with peaks in early summer and later in autumn. Subtidal adults appear to have much higher survival rates and thus are the main contributor of the spring larvae. The intertidal colonies are settled by larvae spawned mainly by subtidal adults. Curtis (1973) proposed that lunar or tidal spawning phasing and positive phototaxis were required to retain larvae in the adults habitat, although Pembroke (1976) concluded that a light-dependent vertical migration was not capable of retaining larvae within the Bay. Eckelbarger (1975) reported gregarious settlement of larvae in laboratory experiments. Woodard (1978) concluded that subtidal and low intertidal worms contribute most heavily to the breeding population in Delaware Bay.

Temperate worm reefs: biology, ecology and habitat value

Although sandbuilder reefs are essentially unique to Delaware Bay, worm-built reefs are found in shallow temperate waters around the world, and the common names attached to their fauna—sandbuilder worm, "coral beds" [sic], reefworm (Pollock 1998), honeycomb worm, mason worm (Ruppert and Fox 1988), sandcastle worm, even Sydney coral—reflect their dominant role in creating benthic habitat. Reefs may either be constructed by secreted calcium carbonate tubes of serpulid polychaetes (e.g. the local example, limy tubeworm - *Hydroides dianthus*, or *Galeolaria* spp.) or formed by cementation of individual sand grains by sabellariids (*Sabellaria* spp., *Phragmatopoma* spp.). Worm-built reefs are probably best known from southeastern Florida (sandcastle worms, *Phragmatopoma lapidosa,*) and along the California coastline (*P. californica*), but in addition to Delaware, reports range from western Europe (Wilson 1968a,b, 1970a,b, 1971, 1974, Riesen and Reise 1982, Gruet 1986, Dias and Paula 2001), Chile (Zamorano et al. 1995), New Zealand (Smith and Witman 1999), Australia (Minchinton 1997, and Bolton and Havenhand 1997) and even to Antarctica (Ramos and San Martin 1999, and see additional references in Pawlik 1986).

Phragmatopoma spp. dominates the literature. Florida reefs are constructed by *P. lapidosa*, (Eckelbarger 1976, Eckelbarger and Chia 1976; McCarthy et al. 2002), and those in California by *P. californica* (Pawlik 1986, Pawlik and Faulkner, 1986, Pawlik 1988a,b, Pawlik, 1990, Pawlik et al. 1991, Pawlik and Chia 1991, Pawlik 1992, Pawlik and Butman 1993). Early literature reports describe the reefs and their locations, most often in a geological context of beach-processes (Scholl 1958, Gram 1968, Kirtley and Tanner 1968, Nelson and Main 1985). Later work investigates in detail the life history (Thomas 1994b), larval biology (Pawlik 1986, Pawlik and Faulkner, 1986, Pawlik 1988a,b, Pawlik, 1990, Pawlik et al. 1991, Pawlik and Chia 1991, Pawlik 1992, Pawlik and Butman 1993), and tube structure (Thomas 1994a) of these species. Although constructed by a different species in the same polychaete family, sandbuilder reefs appear to have many similarities in their location with respect to tidal height, tube material and recruitment biology. Significantly, there remains a general lack of knowledge of precisely which mechanisms (e.g., Pawlik and Chia 1991, Pawlik 1988a,b, Toonen and Pawlik 2001b), circumstances or conditions permit reef formation, development and persistence at a critical point of the beachface.

Recent work has concentrated on the reproduction, larval biology, settlement and metamorphosis of reef-forming polychaetes. Investigations have been directed at individual organisms and small-scale flows (Pawlik and Butman 1993) as well as chemical and surface cues relevant to their gregarious settlement (Pawlik and Faulkner, 1986, Pawlik, 1990, Toonen and Pawlik 2001a,b). Chemical cues (especially from biofilms and conspecifics, Pawlik and Chia 1991, Toonen and Pawlik 1996, 2001a) have an undeniable role in substratum choice and metamorphosis (Pawlik 1992) once larvae are in the vicinity of the substratum. Furthermore, experiments in hydrodynamically simple, laboratory flows clearly demonstrate a significant role for the boundary layer (Pawlik et al. 1991). Unfortunately, seawater tables and flume flows fail to replicate the turbulent, spatially complex and oscillatory flows present where these worms in fact do settle (Pawlik and Butman 1993).

Temperate reefs can be built by many invertebrates other than polychaetes (bivalves, sponges and colonial forms), and thus numerous benthic species become ecosystem engineers (Jones et al. 1997). These otherwise unremarkable species greatly modify the local environment and thereby determine which other species can and cannot comprise the reef community. In most cases, the reef community is one of enhanced biomass (e.g., with respect to *Sabellaria*, Dias and Paula 2001), greater trophic complexity and higher biodiversity (Steimle and Zetlin 2000, Dayton et al. 2002).

Temperate reefs pale in comparison with true coral reefs in many respects including species richness, productivity and visual appeal (Steimle and Zetlin 2000). Nevertheless, temperate reefs have a considerable role in providing habitat, prey and protection for many finfish (Thrush et al. 2001), including those with recreational and economic importance (e.g., tautog for Delaware's sandbuilder reefs). This benthic structure is easily destroyed by fishing activities, although the effects of trawling on *Sabellaria* reefs remain controversial (Reise 1994, Vorberg 2002, Dubois et al. 2002). Dredging, sand mining, trawling and anchor damage are all harmful to subtidal reefs (Hall 1994, Newell et al. 1998, particularly Vorberg 2000, Dubois et al. 2002), and beach nourishment may, by design, bury and obliterate reefs near the shore (Miller 2002). It is well documented that loss of benthic structure and habitat is a critical threat to the economic value of benthic habitats and associated species (Cranfield et al. 2001, Dayton et al. 2002).

Potential impacts of shoreline restoration and possible restoration options

Shoreline restoration may impact *Sabellaria* colonies and reefs in the lower Delaware Bay. Analysis of the literature and the survey conducted here indicate that sandbuilder worm populations (intertidal and subtidal) are persistent in lower Delaware Bay. Because sandbuilder worms are tube dwelling and sessile, burial with substantial depths of sand will smother the worms and kill the intertidal colonies and reefs (Muir 2002, Miller et al. 2002a).

Restoration options should focus on providing sufficiently stable rock substratum during the late summer, especially September, settlement period accessible to planktonic larvae from source populations. Accordingly, potential strategies include:

1. Placing suitable substratum, large rock in groins or jetties or cobble-sized gravel on sand beaches at the 0.0' MLW tidal level in September following shoreline restoration
2. Removal of the current reef masses to new shoreline locations to reconstruct or re-seed mitigated reefs via enhanced larval settlement
3. Reestablishing reefs by emplacement of colonized rocks from an extensive source population, e.g. that at the Mispillion jetty (Curtis 1975)

Based on the settlement observed on our plates as well as the surrounding reefs at Broadkill and Slaughter Beaches, the success of option 1 critically depends on the timing. September is most favorable, although plates were not deployed early enough to gauge settlement from earlier spawners. It would also be useful to know the exact location and distance to the nearest intertidal and subtidal populations. Emplacement of bare substrata at other times would allow colonization by other hard-bottom species such as barnacles (early spring settlers) and mussels (early summer). The degree to which *Sabellaria* can settle in and/or out-compete these species for substratum has not been determined.

Outside the late summer - early fall settlement window options 2 and 3 could be used to restore reefs. Transplant experiments have not been conducted to our knowledge, nor has the degree to which the reconstructed reef regains ecological function been determined. If sandbuilder worms can successfully out compete barnacles and mussels for intertidal rock surface, then it may be feasible to emplace substratum prior to the *Sabellaria* larval settlement period.

The efficacy of such restoration measures could be assessed in terms of the overall number or area of reef habitat created as compared to that presently occurring at one or more control sites. Successful establishment of new intertidal reef should be apparent as settlement, and new tube growth should be easily visible within a few months.

Suggestions for future studies

The results presented here suggest possibilities for future survey, monitoring, or research projects with the identified *Sabellaria* reefs. At Slaughter Beach, *Sabellaria* a reef was observed to extend some distance to the south beyond the survey area towards Fowler Breach, and in previous work (Muir 2002) reefs have been observed at Primehook Beach. Intertidal surveys could be conducted at both the sites and their relationship with reefs at Slaughter Beach (to the north) and Broadkill Beach (to the south) should be investigated. As part of this study, reef and non-reef areas should be cored or excavated to determine what material underlies the existing reef and whether the presence of a particular substratum determines reef distribution. Subtidal colonies have recently been reported from off Bowers Beach (B. Wilson, personal communication, 2004), and since this beach lies between Port Mahon and Slaughter Beach, additional surveys in this region could prove valuable.

The settlement plates were used successfully to determine timing of settlement and estimate tube growth rates. Future experiments should employ a more staged and rigorous sequence of deployments and recovery for both settlement rate and tube growth. This study should be conducted at multiple sites, including sites which are various distances from established colonies and reefs. Since *Sabellaria* settle and grow well on a wide variety of substrata, efforts should be allocated to more replication and additional sites, particularly in the subtidal, rather than varying substratum type. Techniques for rapidly characterizing the dimension of small colonies should be developed, for example, through image analysis of digital photographs. Image processing methods proved useful for quantifying the areas associated with the ribbon reefs at Slaughter Beach.

The benthic community associated with the reefs should be characterized in terms of a species lists, and seasonal estimates of abundance would help determine the overall biodiversity and habitat value of the reefs. If may be possible to determine the usage by finfish of the submerged reef habitat by underwater video for the shore at high tide. Additionally, we and others have noted that small crabs (especially mud crabs and the Asian shore crab) are often associated with the reef. Since they presumably are both predators on the reef biota and burrowers in (and thus destructive to) the reef itself, the relationship should be further investigated.

Conclusions

In a summer 2004 survey of four intertidal sites in lower Delaware Bay, *Sabellaria* colonies and reefs were widely distributed at Broadkill Beach, Slaughter Beach and Port Mahon, but no colonies were found on the Kelly Island shoreline. This distribution is explained by the availability of stable substratum near mean low water. Favorable substrata for sandbuilder worm settlement and reef development appears to be any material of sufficient size not to be overturned by wave action. Natural substrata include gravel and rip rap rock, but colonies were also found on wood groins, horseshoe crab carapaces, sand-pumping pipe and discarded tires. Smaller colonies, formed by settlement in situ or by fragmentation are present near the large reefs. While these smaller colonies were in some cases observed to have live worms and exhibit active tube growth, the longevity of these colonies is uncertain. Some colonies with low vertical relief appear susceptible to burial by natural sedimentation.

Monthly monitoring of settlement plates confirmed the suitability of two different rock substrata for settlement and tube growth, and plates deployed in late August or early September appear most favorable for tube growth in the form that results in reef formation. Tube growth rates of a centimeter or more per month were observed. Timing of available bare substratum appears to be more important than the type of material.

Beach restoration may severely impact *Sabellaria* colonies because they have only a limited capacity to withstand burial under layers of sand. Sandbuilder worms are epifaunal and require water flow and wave action to provide food particles, oxygen and sand grains for tube building. This impact could be compensated by placing suitable substratum, large rock in groins or jetties or cobble-sized gravel on sand beaches at mean low water during the late summer or early fall settlement period following shoreline restoration. Other possibilities include transplanting living reef masses to new shoreline locations to reconstruct or reseed from enhanced larval settlement on the restored reefs, although the minimum necessary distance to intertidal or subtidal breeding colonies has not been determined.

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Table 1. Settlement Plate Monitoring, Broadkill Beach

A. Alabama Avenue reef, 38° 49.994' N 75° 12.968' W

Date	Activity	Comments	Temperature and salinity
2 Aug	Check of reef	New growth visible on reef	24.6°C 26.6 ppt
30 Aug	Check of reef	Extensive new growth on reef	27.6°C 26.0 ppt
1 Sep	Deployed pair #10-12		27.5°C 26.1 ppt
27 Sep	No pairs recovered; deployed pair #15	Extensive new tube growth on reef	23.1°C 22.1 ppt
27 Oct	No pairs recovered; deployed pairs #18-19	Extensive new tube growth on reef; reef rounding over rocks	15.0°C 21.5 ppt
11 Nov	No pairs recovered	Reef eroding at seaward end	11.6°C 23.9 ppt
12 Dec	Recovered Q19	Q19: 1-2 mm tubes	9.2°C 23.8 ppt

B. Georgia Avenue reef, 38° 49.933' N 75° 12.915' W

Date	Activity	Comments	Temperature and salinity
2 Aug	Deploy paver pairs #1-3	New growth visible on reef	24.6°C 26.6 ppt
30 Aug	Recovered pair #3	Settlement on plates: 2-5 mm high tubes	27.6°C 26.0 ppt
1 Sep	Deployed pair #7-9		27.5°C 26.1 ppt
27 Sep	Recovered pair#7; deployed #14	Q7: 10% coverage, 2 mm high tubes S7: 20% coverage, about 2-3 mm tubes	23.2°C 21.3 ppt
27 Oct	No pairs recovered; deployed pairs #16-17	Extensive new tube growth on reef; reef filling in between rocks	15.1°C 21.8 ppt
11 Nov	Recovered 5 plates	S8: 4.5 cm high tubes	11.2°C 24.2 ppt
12 Dec	Recovered #14,16,17	Pairs 16,17 and 14: 2 mm tubes	9.3°C 24.0 ppt

Table 2. Settlement Plate Monitoring, Slaughter Beach

Simpson Avenue, 38° 54.306' N 75° 17.690' W

Date	Activity	Comments	Temperature and salinity
31 Jul	Extend survey to south	Linear reef extends out of sight to south; some new growth, no settlement	32.7°C 26.0 ppt
29 Aug	Deploy paver pairs #4-6		30.3°C 25.5 ppt
26 Sep	Recovered pairs #4 and 5; replaced #5 with pair #13	Settlement on plates: Q4 60% coverage, 2-3 mm high S4: 40% coverage, 2 mm Q5: 80% covered, 2-3 mm S5: 80% covered, 2.5 mm to 2.5 cm	24.1°C 20.3 ppt
9 Dec	Recovered pair #4; deployed pair #21	Q4 100% coverage, 0-3 cm tubes S4: 100% coverage, 2-6 cm tubes	10.3°C 21.8 ppt

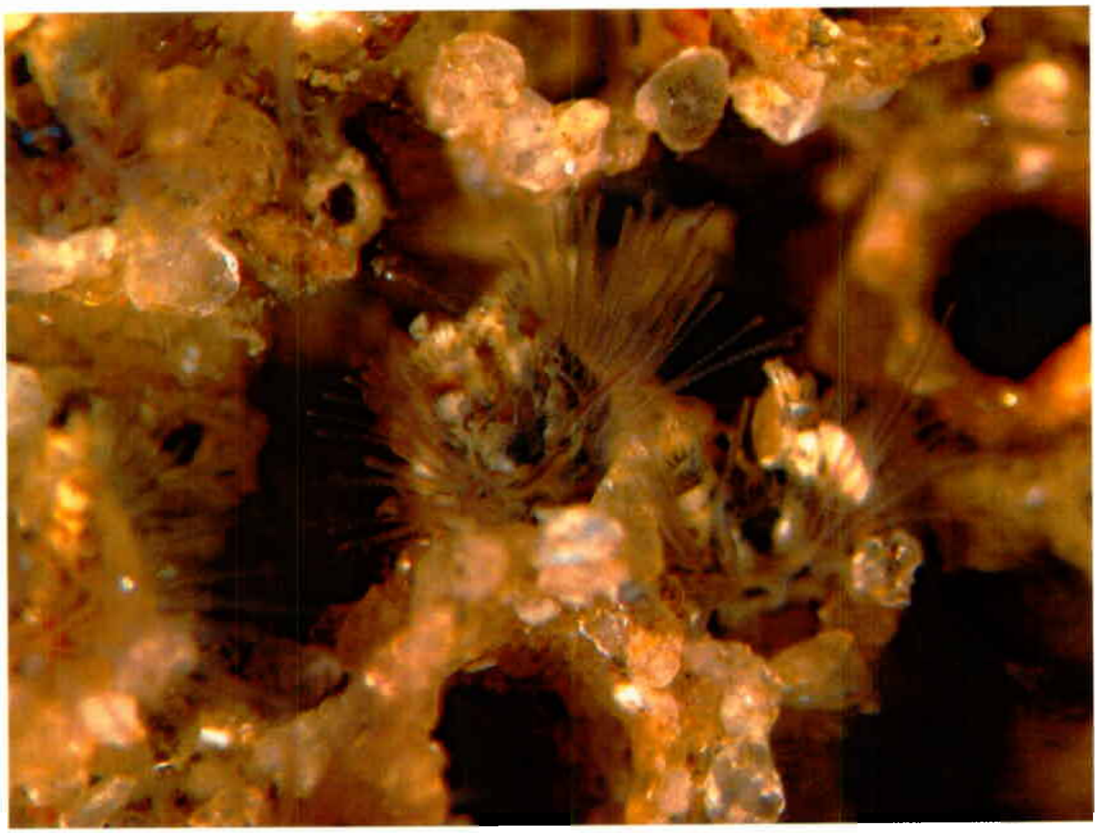

Figure 1. The sandbuilder worm or "reefworm," *Sabellaria vulgaris* Verrill 1873 is a tube-building, annelid polychaete worm common on the Mid-Atlantic coastline of the USA.

Figure 2. Close-up of the brownish reef surface showing honeycomb-like tube openings, each representing an individual sandbuilder worm. Alabama reef (38° 49.994' N 75° 12.968' W) at Broadkill Beach, 11 Nov 2004.

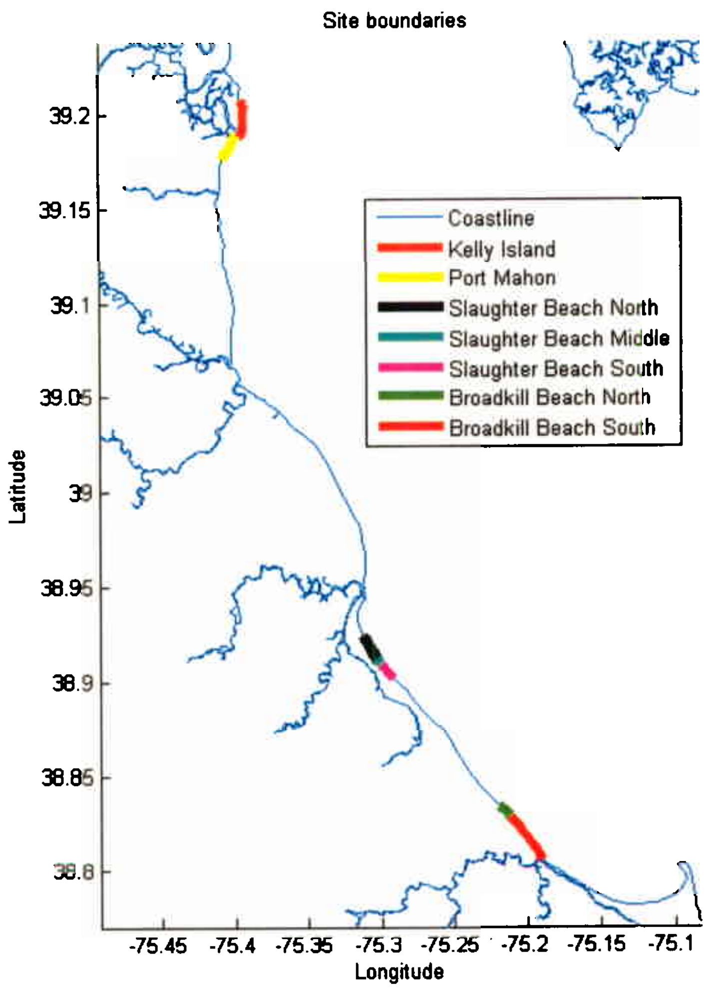

Figure 3. *Sabellaria* monitoring field sites in lower Delaware Bay, 2004, with intertidal survey segments indicated.

Figure 4. *Sabellaria* new tube growth indicated by lighter colored tube openings with a "flare" or "porch," in an epifaunal community including blue mussels and another tube worms, *Hydroides dianthus*. Photographed on the wooden groin at North Carolina Avenue (38° 49.876' N 75° 12.853' W) at Broadkill Beach, 28 June 2004.

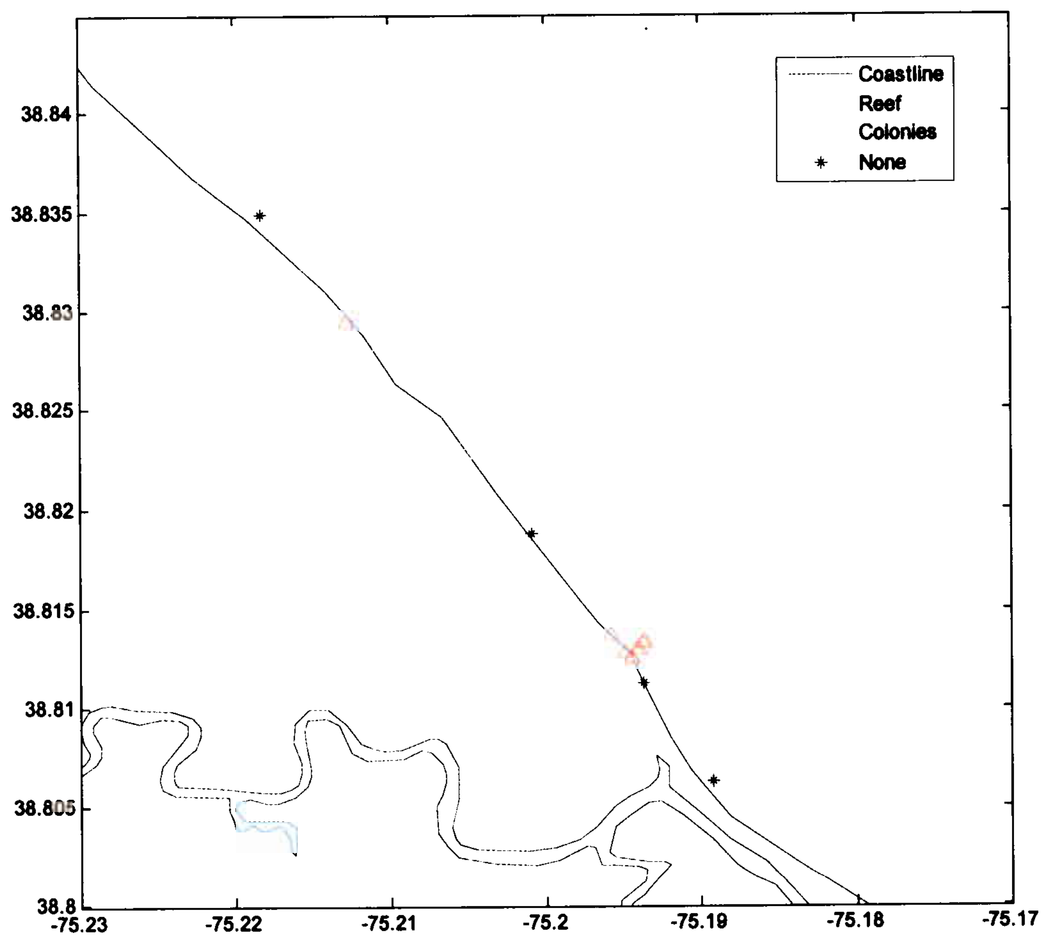

Figure 5. Sampling sites, colonies and reefs at Broadkill Beach.

Figure 6. Alabama reef (38° 49.994' N 75° 12.968' W) at Broadkill Beach, 28 June 2004.

Figure 7. Georgia reef (38° 49.994' N 75° 12.968' W) at Broadkill Beach, 28 June 2004.

Figure 8. *Sabelleria* colonies on wooden groin at North Carolina Avenue (38° 49.876' N 75° 12.853' W) Broadkill Beach, 28 June 2004.

Figure 9. *Sabelleria* colonies on sand pumping pipe with a common sea star *Asterias forbesi* (38° 49.465' N 75° 12.379' W), Broadkill Beach, 29 June 2004.

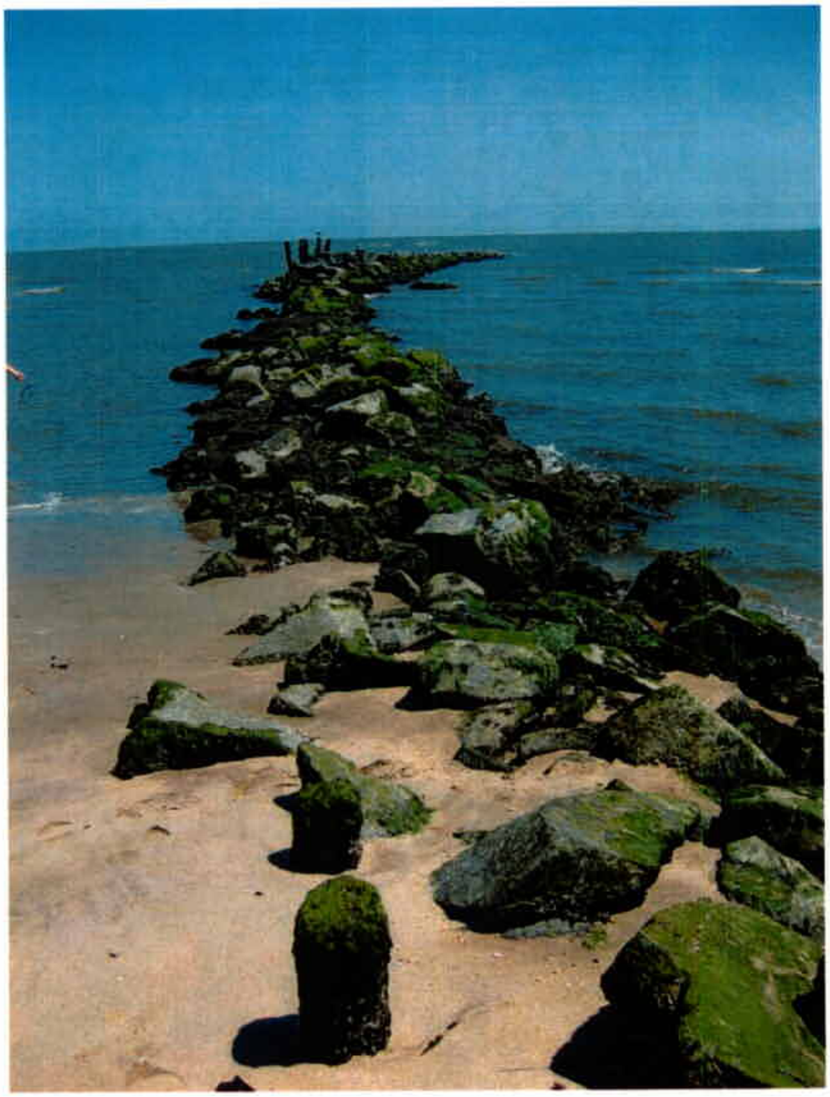

Figure 10. Old Inlet Jetty reef (38° 48.476' N 75° 11.668' W), Broadkill Beach, 29 June 2004.

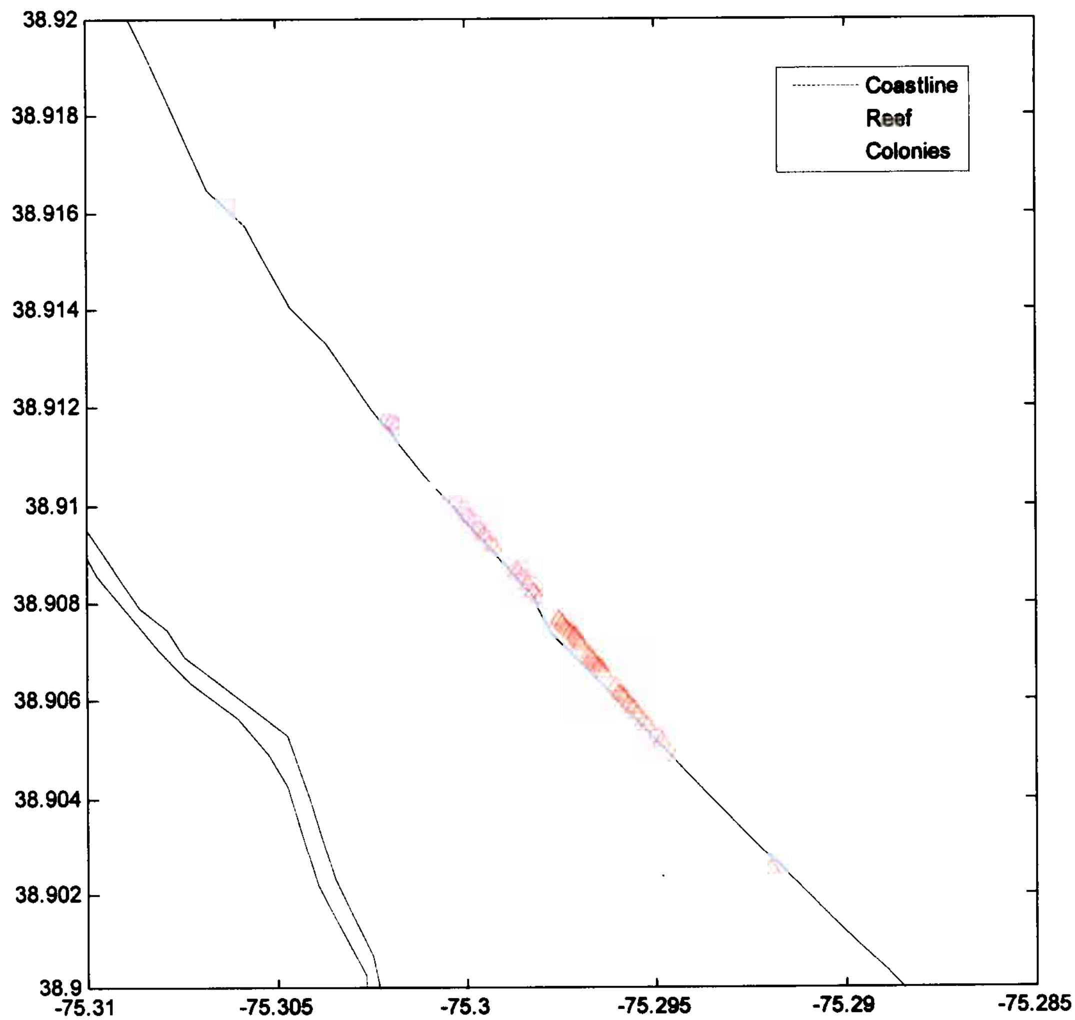

Figure 11. Sampling sites, colonies and reefs at Slaughter Beach.

Figure 12. Ribbon reef south of Simpson Avenue at Slaughter Beach (38° 54.328' N 75° 17.714' W), 30 June 2004, looking south. Reef extends 100 m along shoreline. Quadrat is 1.5 m on each side, flags are spaced 5 m apart.

Figure 13. Broken ribbon reef north of Simpson Avenue at Slaughter Beach (38° 54.461' N 75° 17.855' W, 30 June 2004, looking south towards reefs shown in Fig. 12.

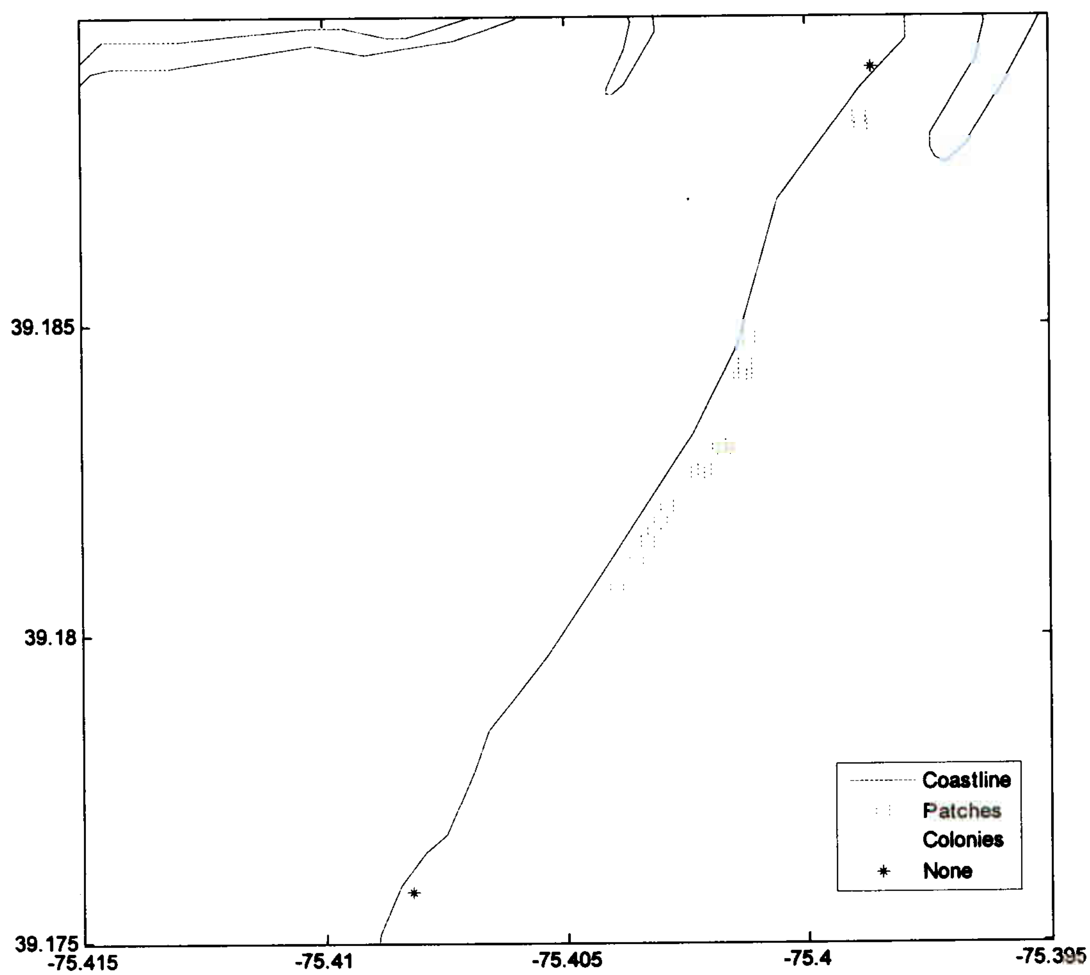

Figure 14. Sampling sites, colonies and patches at Port Mahon, 2 July 2004.

Figure 15. *Sabellaria* patch on gravel bottom at Port Mahon (39° 11.049' N 75° 24.077' W), 2 July 2004. Quadrat is 0.5 m on each side.

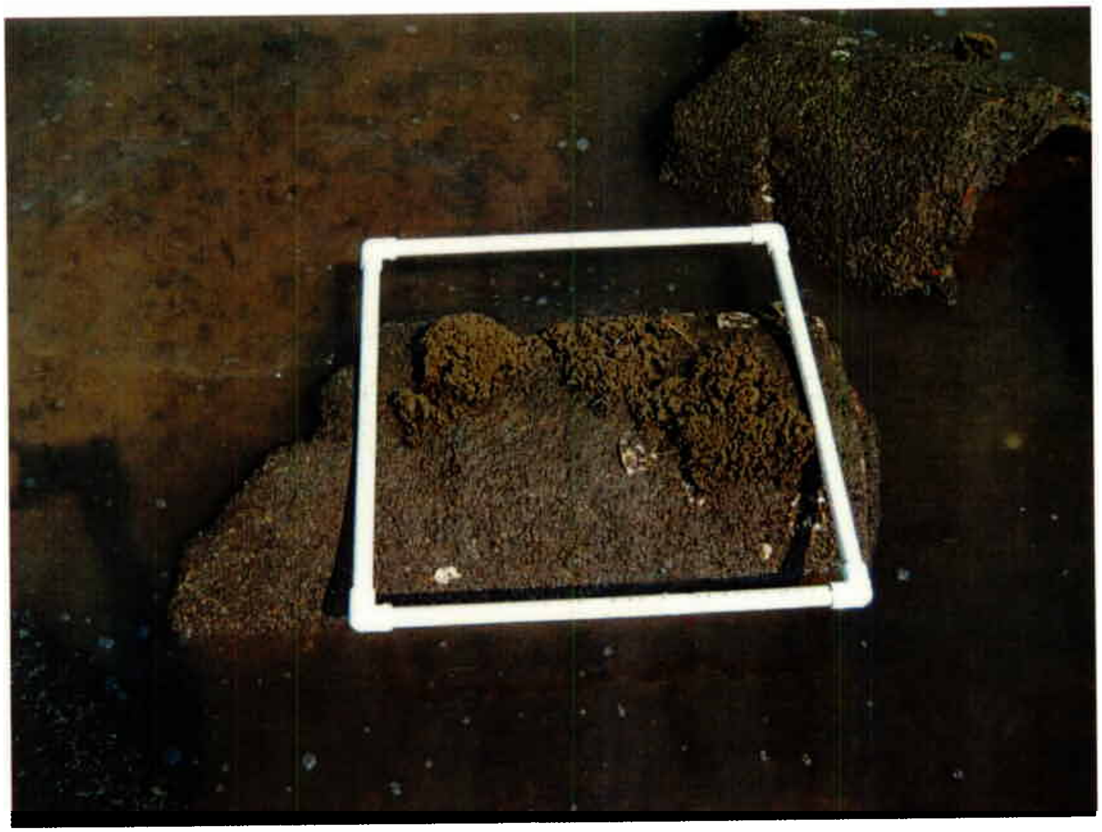

Figure 16. *Sabellaria* colonies on broken culvert pipe at Port Mahon (39° 10.985' N 75° 24.096' W), 2 July 2004. Quadrat is 0.5 m on each side.

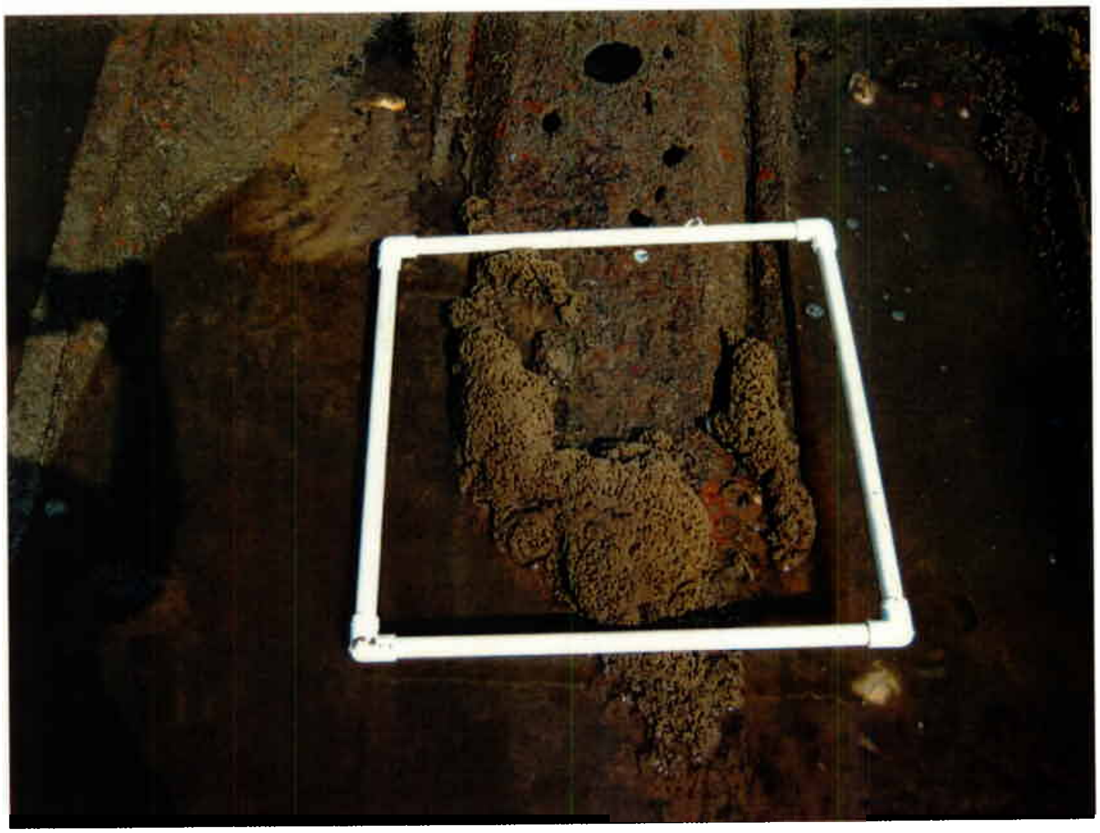

Figure 17. *Sabellaria* colonies on steel bulk heading at Port Mahon Mahon (39° 10.923' N 75° 24.174' W), 2 July 2004. Quadrat is 0.5 m on each side.

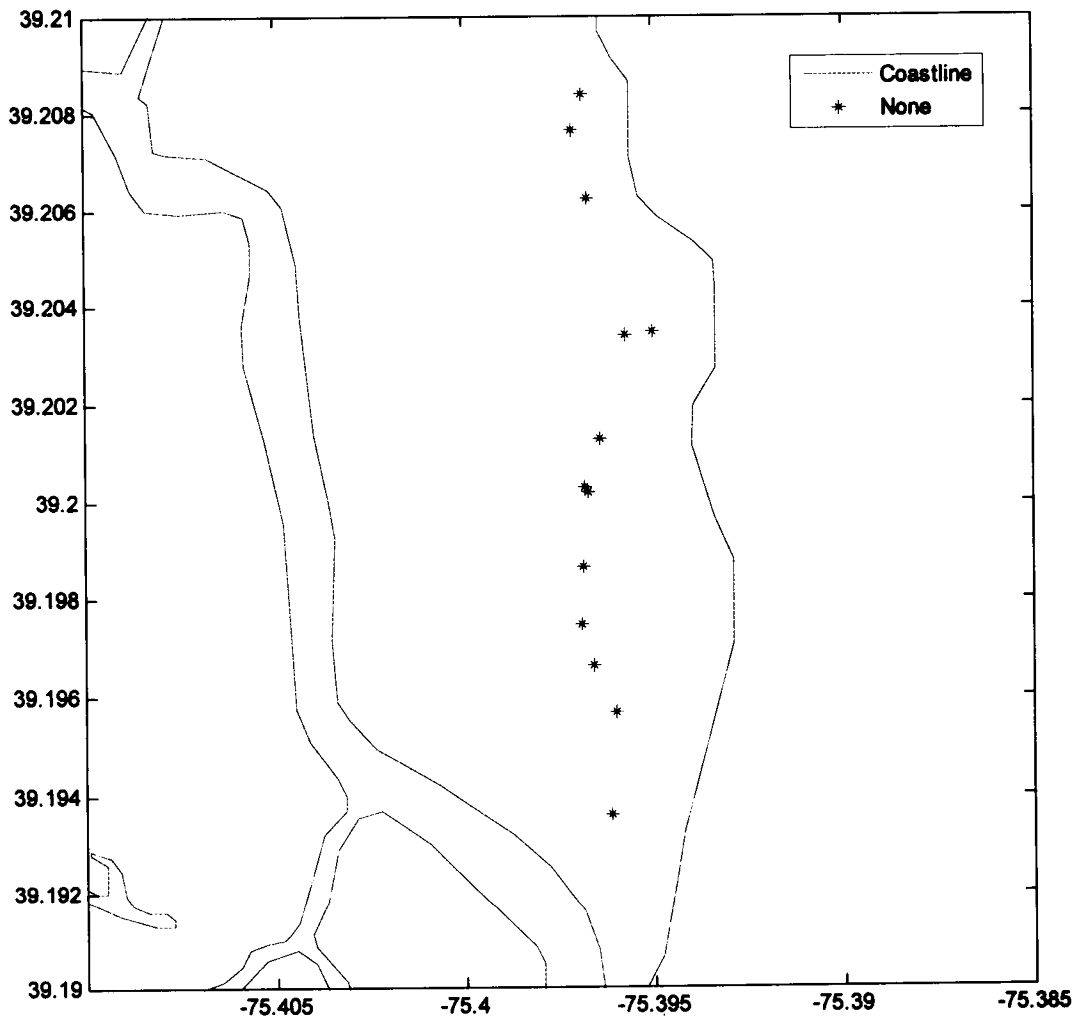

Figure 18. Sampling sites at Kelly Island, 2 July 2004. No colonies were found on the Kelly Island shoreline. All sites were along the coastline at the time of the survey; their apparent distance inland reflects the high rate of shoreline erosion at this site.

Figure 19. Typical high relief, eroding marsh shoreline at Kelly Island (39° 11.798' N 75° 23.795' W), 2 July 2004.

Figure 20. *Sabellaria* worm tubes on horseshoe crab carapace, Kelly Island (39° 12.020' N 75° 23.809' W), 2 July 2004.

Figure 21. Settling plates S2 and Q2, deployed at Georgia reef (38° 49.994' N 75° 12.968' W), Broadkill Beach, 2 August 2004.

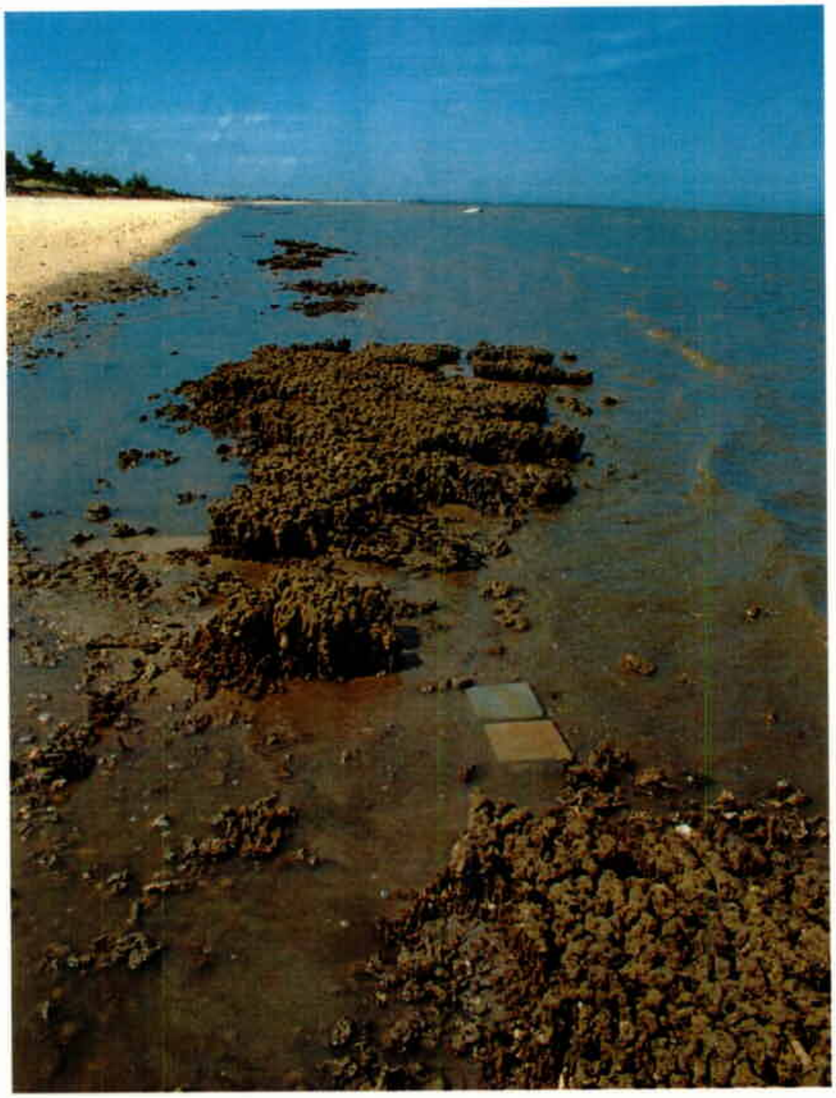

Figure 22. Settling plates S5 and Q5 deployed at Slaughter Beach (38° 54.306' N, 75° 17.690' W), 29 August 2004.

Figure 23. Settling plate Q3 recovered at Broadkill Beach (38° 49.994' N 75° 12.968' W) after 4 weeks, 30 August 2004.

Figure 24. Settling plates S4 and Q4 recovered at Slaughter Beach (38° 54.306' N, 75° 17.690' W) after three months, 9 December 2004.