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ATTACHMENT C

**RECOLONIZATION DYNAMICS AND
BIOTURBATION PROCESSES IN
MARINE SEDIMENTS: RELATIONSHIP
TO PROPOSED CAPPING OF
NEW BEDFORD HARBOR SUPERFUND SITE**

**RECOLONIZATION DYNAMICS AND BIOTURBATION PROCESSES IN
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SUPERFUND SITE**

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INTRODUCTION

The purpose of this report is twofold. Firstly, to assess the short-term and long-term effects that an application of a 45 cm depth sediment cap will have on the benthic community in upper New Bedford Harbor, and secondly to provide an overview of the effects that sediment-reworking activities by benthic organisms will have on the physical and chemical integrity of the sediment cap.

Part I. Benthic recolonization dynamics of the proposed sediment.

A. General overview of benthic recolonization. During the last several decades there has been considerable study on the effect of natural and human-induced disturbances on soft-bottom benthic populations and community structure (e.g., episodes of sediment movement [Johnson, 1973]; red-tide induced mortality [Simon and Dauer, 1972, 1977]; oil spills [Grassle and Grassle, 1974; Sanders et al., 1980], dredging [Rhoads *et al.*, 1977; Saila, 1976]; experimentally controlled [Grassle and Grassle, 1974;

McCall, 1977; Zajac and Whitlatch, 1982a,b]).

Despite differences in the type of disturbance, environmental conditions and species pool in these studies, the results suggest that there are common, shared trends in the course of community establishment and development. For example, the sequence of species colonizing disturbed benthic habitats is customarily described in the same terms as terrestrial forest succession (see Odum, 1969; Connell and Slatyer, 1977). McCall (1977) and Rhoads *et al.* (1978) refined this classification to include different types of colonizers based on temporal population abundance patterns and life history traits (Table 1). Working in a subtidal Long Island Sound benthic station, they recognized Group I or "opportunistic" species as those forms which colonized experimentally defaunated sediment trays in 10-50 days. These species attain high abundances ($10,000-400,000 \text{ m}^{-2}$), are relatively short-lived and typically experience high mortality rates. Group III or "equilibrium" colonizers appear in early successional stages of the community, but maintain relatively constant and low population densities. This group took between 50-225 days to attain maximal population abundance and densities were generally 3-4 orders of magnitude smaller than Group I species. Species characterizing this group are longer-lived, larger and tend to penetrate well below the sediment surface. Species comprising Group II displayed population abundance profiles and life history attributes intermittent

between Group I and Group III.

The early colonists in most disturbed habitats are predominately small polychaeteous annelids with other taxonomic groups (e.g., molluscs, crustaceans) settling later (Grassle and Grassle, 1974; Rhoads *et al.*, 1978). While Simon and Dauer (1977) suggested that this is a general trend in benthic recolonization, other taxonomic groups (e.g., amphipod crustaceans, bivalved molluscs) have been observed to respond opportunistically to disturbance (McCall, 1977; 1978). In addition, polychaete species which are characteristically termed "opportunistic" (e.g., Group I) may not be so in all cases. For example, McCall (1977) observed that the surface-feeding spionid, *Streblospio benedicti*, exhibited a pronounced opportunistic "boom and bust" population response in Long Island Sound, whereas in Tampa Bay, Florida, Simon and Dauer (1977) found that its response to disturbance following redtide mortality was negligible. Zajac and Whitlatch (1982a) noted the ability of estuarine infauna to respond to disturbance was highly dependent on the historical features of a particular habitat.

Later stages of benthic recolonization have been shown to generally consist of the establishment and/or growth of populations of relatively non-opportunistic species and other phylogenetic groups which approach natural conditions after various periods of time (normally 7-12 months. Simon and Dauer, 1977; McCall, 1977). Rhoads *et al.* (1978) also observed a change

in the predominant type of feeding mode in the developing benthic community. While initial colonizers were primarily suspension and surface-feeding deposit feeders, later stages were dominated by organisms feeding below the sediment-water interface (Fig. 1). Rhoads *et al.* (1978) hypothesized that this trend in living mode was a response of the organisms to their sedimentary environment. Early colonists attempt to isolate themselves from the disturbed environment. As the organisms begin to rework the sediments, microbial populations are increased, the redox-potential discontinuity layer is depressed in the sediment and the seafloor becomes increasingly bound by microbial exudates (e.g., increased sediment stability). All these factors are hypothesized to allow deeper dwelling organisms to survive and dominate later stages of a successional sequence.

Patterns of infaunal recolonization in shallow estuarine environments are somewhat different than those described for deeper-water marine communities. Successional sequences are often arrested and are continually dominated by opportunistic species. Zajac and Whitlatch (1982b) found that recovery of shallow southern New England estuarine communities from disturbances occurred over various time-scales with no set seral stages; the dynamics of recovery was primarily influenced by the timing of disturbance and not by the recovery process itself. Opportunistic species tended to dominate all phases of the successional sequence and were remarkably stable in their

composition for a period of at least eight years (Whitlatch and Zajac, 1985). Boesch *et al.* (1976) also noted that estuarine infaunal communities possess "high stability in their resistance to, and resilience from, disturbance".

Patterns of changes in species number with time have also been examined in colonization studies (e.g., McCall, 1977; Simon and Dauer, 1976). The rate of approach to an asymptotic ("pre-disturbance") number of species generally varies greatly depending on the habitat, nature and size of the disturbance and degree of isolation of the disturbed area. For example, in one study over three years were needed to reach an asymptotic number of species (Dean and Haskins, 1964) and Sanders *et al.* (1980) failed to see a complete recovery of a benthic community after an oil spill in a period of more than five years. On a smaller scale, recolonization may take only months or weeks (Grassle and Grassle, 1974; McCall, 1977; Zajac and Whitlatch, 1982b). Recruitment into disturbed areas can be due both to planktonic larval settlement and lateral adult migration from surrounding areas (Dauer and Simon, 1975; Whitlatch and Zajac, 1985). This results in relatively rapid recolonization when compared with marine rocky substrate systems (e.g., Sutherland, 1974; Osman, 1977) in which repopulation is almost exclusively planktonic.

Specific patterns of recolonization following either natural or human-induced disturbances can be affected by many factors. For example, changes in substrate type by erosion and/or

deposition are common in nature (Johnson, 1970) and can result in replacement of one species assemblage by another. In addition, both the frequency and magnitude of the disturbance greatly alters rates of recovery and may determine species composition patterns (see above). Severe disturbances may have very long-lasting effects on benthic communities and the community may never attain the species complement existing prior to the disturbance. Moreover, the species pool from which the colonists are selected will also vary, both geographically and seasonally, and may be expected to affect the course of recolonization.

B. Disturbance associated with the application capping material to upper New Bedford Harbor. Direct burial by sediments used in the capping application of the upper harbor will kill many of the organisms residing in the sediment. In general, death results from the disposal of sediments onto ambient sediments and benthic organisms suffocate before they can migrate laterally or vertically to oxygenated areas.

The ability of benthic organisms to escape burial depends on several factors. For example, Kranz (1972, 1974) found that life habits, morphology and size were extremely important in determining the ability of epifaunal and infaunal bivalves to survive burial. Infaunal non-siphonate suspension feeders were generally able to survive 5-10 cm of overburden, while shallow-burrowing siphonate suspension feeders and juvenile, deep-burrowing siphonate suspension feeders could escape 10-50 cm of sediment burial. Bousfield (1970) suggested that the burrowing

ability of amphipod crustaceans was generally related to morphology. Members of the family Haustoriinae were most efficiently adapted to burrow through sediments. Peddicord *et al.* (1975) noted that two species of epifaunal crustaceans could rapidly move through deposited clay in experimental tanks.

There are fewer studies which have examined the escape responses of soft-bodied benthic organisms; however, life mode and size appear to be important determinants of burrowing ability. Polychaetes which build tubes and remain near the surface are poor burrowers, whereas polychaetes which typically live below the sediment-water interface are better adapted for burrowing (Pettibone, 1963). Thus Maurer *et al.* (1978) found that two burrowing species, *Leitoscoloplos fragilis* and *Nereis succinea* (two species found in the upper estuary), were able to successfully migrate through 30 and 80-90 cm of sediment respectively. Saila *et al.* (1972) found that the large burrowing polychaete *Nephtys incisa* was able to burrow through 21 cm of sediment deposited over a 24 hr period. The small, tube-dwelling polychaete *Streblospio benedicti*, on the other hand, was able to escape only 6 cm of overburden. However, both Myers (1972) and Oliver and Slattery (1973) found that tube-dwelling onuphid polychaetes were able to vertically migrate through 30 cm of deposited sediment.

The physical and chemical nature of deposited sediments can also greatly alter the ability of organisms to survive burial. Kranz (1974) analyzed the escape responses of 30 species of

bivalves and concluded that sediment composition was the most important physical factor altering burrowing response. Exotic sediments (sediments differing in grain size composition from native sediments) always reduced the burrowing activities of the bivalves. Kranz (1972) found no differences in escape response over normal temperature, salinity, and oxygen ranges of the species tested. In laboratory studies, Maurer *et al.* (1978) tested the ability of infaunal organisms to burrow through sediments of differing particle composition, sediment pore-water chemistry (e.g., levels of oxygen, sulfides and ammonia) and temperature. Tests with several species of crustaceans, molluscs and polychaetes revealed no relationship between sediment pore-water chemistry and burrowing ability. Burrowing responses were more influenced by sediment type, burial depth, duration of burial time and temperature.

C. Benthic community response to and recovery from the application of the sediment cap in upper New Bedford Harbor.

The application of a 45 cm sediment cap to the upper harbor will result in following general environmental impacts:

1. *Direct burial and mortality of benthic invertebrates.* The ability of benthic organisms to survive sediment cap application will be dependent upon the physical and chemical nature of the sediment. While it is assumed the applied sediment will be unpolluted, other chemical processes may affect the local benthic community. For example, hydrogen sulfide in the sediment (below the oxic

zone) may be released during application of the cap, and in high enough concentrations this chemical is toxic to benthic invertebrates (e.g., Dubilier, 1988). Accumulated organic materials in the sediment may also be resuspended and some quantities will be rapidly oxidized. Oxidation of organic materials may create some reduction in water column oxygen levels. The net effect of these factors is difficult to predict without specific knowledge of the sediment characteristics and method of their application.

Previous studies indicate that some infaunal organisms are capable of vertically migrating through deposited overburdens (see Part I.B). As discussed previously, the response is generally dependent upon an organism's life habits, morphology and size. The New Bedford estuary is presently dominated by surface-living, tube-dwelling infaunal polychaetes (Sanford Ecological Services [SES], 1987) and they will likely experience total mortality as a result of the cap application. Some of the larger polychaetes and bivalves (e.g., *Nereis succinea*, *Leitoscoloplos fragilis*, *Mya arenaria*), however, may be able to burrow through the sediment cap. These escape burrows could act as conduits for the movement of contaminated materials to the water column and surrounding, unpolluted sediments. Most of the epifaunal macroinvertebrates and demersal fishes should migrate from the disposal area and minimal impacts of these species should occur.

2. *Habitat modification.* The proposed construction of the sediment cap (SES, 1987) involves application of a 45 cm thick sediment layer to the upper estuary, resulting in the conversion of 30 acres of intertidal mudflat habitat to salt marsh habitat and a conversion of 54 acres of subtidal mudflat to intertidal mudflat. These changes result in the loss of 73 acres of subtidal mudflats and the creation of 18 acres of erosion-protected channel. While the alterations result in irreversible losses of subtidal habitat and increases in intertidal habitat, it appears doubtful they will have a demonstrable effect on benthic species composition. Infaunal species diversity of the intertidal areas will likely be lower than adjacent subtidal areas. The most obvious effects of habitat modification will be increased areas for shorebird feeding and one would predict subsequent increases in the numbers and kinds of birds inhabiting the inner harbor. Loss of subtidal habitat may result in a decreased abundance of some species of demersal fish and epifaunal crustaceans.

3. *Post-construction impacts on the benthic environment.* The sediment capping operation should result in a relatively localized disturbance and mortality of the benthos. Subsequent to the capping application, recolonization of the capped area will occur by larvae and adults of infaunal and epifaunal organisms. Given the generally recurring patterns and rates of benthic recolonization, recruitment should be relatively rapid (weeks to

months) and the abundances of recruiting organisms should mimic ambient (undisturbed) areas within 5-12 months (depending upon the time of the year of the disturbance).

Initially, opportunistic species (principally from surrounding populations) will recruit onto the sediment cap. Small, tubicolous (e.g., *Streblospio benedicti*, *Polydora* spp.) and burrowing (e.g., *Capitella* spp., *Podarke obscura*, *Tubificoides* spp., *Eteone heteropoda*) annelids will likely dominate the early stages of recolonization. Other species likely to be found on the sediment cap during the initial stages of recolonization include tubicolous amphipod crustaceans (e.g., *Corophium* spp, *Microdeutopus gryllotalpa*) and the opportunistic bivalve, *Mulinia lateralis*. Densities of all these species are known to be notoriously variable (see Part I.A) and can fluctuate several orders of magnitude over relatively short time periods. For example, Zajac and Whitlatch (1982a) noted month-to-month total infaunal recolonization densities ranged from 30,000 to 760,000 m⁻² in a shallow southern New England estuary. Highest densities typically were found in the spring and were associated with seasonally programmed reproductive cycles of the benthic invertebrates.

It is more difficult to predict species composition and abundance over longer periods of recolonization of the sediment cap, since these will be dependent upon the integrity of the cap, and local physical, biological and chemical conditions (see Part I.A). Since a variety of long-term recolonization/recovery

scenarios are possible in the upper estuary, it is most useful to discuss two hypothetical ends of a recolonization spectrum: (a) a benthic community which is primarily influenced by local conditions surrounding the sediment cap, and (b) a species assemblage reflecting a substantial modification of the local environment as a result of the application of the sediment cap.

The first scenario may occur because the proposed sediment cap is relatively small and the environmental characteristics of the upper harbor will remain relatively unchanged following the disturbance. Under these conditions the benthic community would develop into a pre-capped species assemblage. The major difference will likely be an overall increase in the abundance of infauna since uncontaminated sediment will be used in the capping process.

Under these circumstances the benthic community associated with the sediment capping will be dominated by small, near-surface living opportunistic polychaetes (e.g., *Streblospio benedicti*, *Polydora* spp.), amphipod crustaceans (e.g., *Corophium* spp.) and molluscs (e.g., *Mulinia lateralis*). While densities of these species will fluctuate widely, dependent upon seasonal reproductive activities and biotic (e.g., predation by demersal fish and crabs) and abiotic (e.g., storms, ice accumulation) disturbances, species composition will likely remain relatively constant. Zajac and Whitlatch (1982b) noted that *Streblospio benedicti*, *Capitella* spp., *Tubificoides* spp., *Polydora ligni* and *Leitoscoloplos fragilis* (all

presently found in the upper harbor; SES, 1987) settled within two weeks following a controlled disturbance and remained as dominants until the termination of their study (2.5 yrs). Total densities typically ranged from 9,000 to 190,000 individual m^{-2} in their study conducted in a shallow, southern New England estuary.

Over longer periods of time the sediment cap will likely be colonized by larger and deeper-dwelling organisms. For example, bivalves (*Mya arenaria*, *Tellina agilis*, *Mercenaria mercenaria*, *Ensis directus*) and polychaetes (*Nereis* spp., *Heteromastus filiformis*, *Cistenides gouldii*, *Glycera americana*, *Nephtys incisa*) presently found occurring in adjacent areas (SES, 1987) in the upper harbor may eventually colonize the sediment cap. Based on the results of other studies conducted in similar types of environments (e.g., Whitlatch, 1977) the densities of these larger species will likely be on the order of 10's-100's m^{-2} with modest (relative to the opportunistic species) seasonal fluctuations in abundance.

At the other end of the hypothetical recolonization spectrum is a long-term recovery scenario which assumes the application of the sediment cap significantly alters the local environment, resulting in substantive changes to the benthic community (relative to pre-capping conditions). For example, Kuroda and Fujita (1981; cited in O'Connor and O'Connor, 1983) found that following the application of a clean sand cap over organically polluted muddy sediment in Hiroshima Bay, Japan, a more diverse

benthic community replaced a previously polychaete-dominated species assemblage.

Since the distribution of benthic organisms are often governed by sediment composition (see Part I.A), the application of a clean sand cap over ambient polluted muddy sediments may result in several alterations in the benthic community. For example, the existing polychaete-dominated, deposit-feeding community may be replaced by a suspension-feeding assemblage of organisms. Bivalve molluscs (e.g., *Mya arenaria*, *Mercenaria mercenaria* and *Gemma gemma*) would likely to be more abundant under these conditions. Densities of the first two species typically range from 1-30 individuals m^{-2} (H. Crawford, per. comm.). *Gemma gemma*, a small venerid bivalve, can occur up to several hundred thousand m^{-2} (Whitlatch, 1977; Dobbs, 1981). In addition to the opportunistic polychaetes mentioned previously, the sediment cap would be colonized by a variety of conveyor-belt feeding polychaetes (e.g., *Cistenides gouldii*, *Heteromastus filiformis* and *Clymenella torquata*), characteristic of clean sand shallow water New England environments (e.g., Sanders *et al.*, 1962; Whitlatch, 1977; Dobbs, 1981; Whitlatch, 1982) may colonize the area (Fig. 2). These species of polychaetes typically occur at densities of tens to hundreds m^{-2} (e.g., Whitlatch, 1977; Dobbs, 1982)

Part II. Bioturbation of marine sediments.

A. General overview and species functional categories. It is common knowledge that bottom-dwelling organisms inhabiting marine environments have the potential of greatly modifying the biological, physical and chemical properties of the sediment. For instance, mobile organisms promote sediment mixing through burrowing and foraging activities (e.g., Rhoads and Young, 1970; Myers, 1977 a,b). Sediment reworking also has the potential of greatly modifying or destroying primary sedimentary structures as well as creating unique structures in the sediments (e.g., Rhoads and Boyer, 1982). Many species of deposit-feeding organisms are selective particle ingestors (e.g., Whitlatch, 1980; Taghon, 1982; Jumars *et al.*, 1982) and may increase particle sorting by removing certain sizes and types of particulate material from one sediment horizon and depositing them in another (e.g., Rhoads and Stanley, 1965; Rhoads, 1967; Self and Jumars, 1978). Suspension-feeding organisms can accelerate the transfer of inorganic and organic materials to the bottom through feeding activities (Haven and Morales-Alamo, 1966; Rhoads, 1974). Both infaunal deposit- and suspension-feeders can pump water into and out of the bottom resulting in irrigation of the sediment (Rhoads, 1974; Aller and Yingst, 1978; Aller, 1982). Such activities can significantly alter sediment stability, vertical profiles of solute and particulate materials, sediment diagenesis, the movement of materials across the sediment-water interface, as well as the distribution and abundance of other species in the benthic

community.

An extensive literature is available on bioturbation and organism-sediment relationships in shallow-water marine environments (see reviews of: Rhoads, 1974; Petr, 1977; Lee and Swartz, 1980; McCall and Tevesz, 1982). Typically these studies have shown that the intensity of sediment reworking in intertidal and subtidal sediments is due to faunal composition rather than faunal density. Because of these findings considerable effort has been directed to understanding how different "functional groups" (feeding and/or motility modes) of organisms affect the sedimentary milieu.

By convention, benthic organisms have been divided into generalized groups based on life mode. Epifaunal organisms, those generally living on the sediment surface, primarily include mobile members of the phyla Arthropoda (e.g., crabs, lobsters, amphipods) and Mollusca (e.g., snails), as well as demersal fish and birds which utilize benthic habitats as feeding and resting sites. Infaunal organisms, those living in the sediments, include a taxonomically broader group of organisms ranging from small nematodes and ostracods to larger annelids, crustaceans and molluscs.

Figures 1 and 2 depict the generalized life modes of different groups of infaunal organisms. Two broad groups are recognized:

1. Surface feeders. This group includes those organisms which obtain their nutrition at the sediment-water interface or

from overlying water column. In shallow-water environments this group typically contains tubicolous annelids (e.g., spionid polychaetes) and crustaceans (e.g., amphipods) and suspension-feeding bivalves. A special subset of surface feeders consists of so-called funnel feeders (e.g., *Arenicola marina*, *Saccoglossus kolaweyaksi*, *Leptosynapta tenuis*), which transport sediment from the surface through the animal and deposit it again at the surface.

2. Sub-surface feeders. This category includes organisms which feed below the sediment-water interface and primarily includes deposit-feeding annelids and a variety of meiofaunal taxa (e.g., nematodes, harpacticoid copepods). An important group of subsurface feeders is formed by conveyor-belt feeders (Rhoads, 1974): organisms which transport subsurface sediments to the sediment surface (e.g., *Heteromastus filiformis*, *Cistenides gouldii*, *Clymenella torquata*).

Table 2 summarizes the trophic guilds and feeding relationships of the primary groups of epifaunal organisms utilizing marine benthic habitats.

B. Depths, rates and relative magnitudes of bioturbation.

The relative importance of a species' bioturbation effect on marine sediments is primarily dependent upon depth of feeding, feeding rate and how the organism processes sediment.

1. Depth of feeding. Numerous studies carried out in estuarine and coastal waters have chronicled vertical

distributions of infaunal organisms in different types of sediments and environments (e.g., Myers, 1973; Rhoads, 1974; Levinton, 1977; Rhoads *et al.*, 1978; Whitlatch, 1980, 1982; Hines and Comtois, 1985). Patterns of vertical stratification of infauna generally reflect differences in burrowing abilities, body size and life style, and environmental conditions. Typically, the vertical distribution of infauna exhibit a pattern of large numbers of small organisms in the upper 5 cm of the sediment, while a few large bivalves, polychaete worms and burrowing shrimps are found at depths of 30 cm or more (Fig. 3). These latter organisms are less abundant, but often comprise most of the biomass benthic communities (Fig. 3). For example, Hines and Comtois (1985) noted that most organisms (72-74%) in Chesapeake Bay occurred in the upper 5 cm of the sediment, with few (4-5%) occurring deeper than 20 cm. However, the greatest fraction of the biomass was comprised of mostly clams occurring 10-30 cm below the sediment surface.

Patterns of vertical stratification of benthic organisms can be quite dynamic as a result of an interplay of seasonally varying biotic and abiotic processes. For example, several studies have noted shifts in the vertical distribution of organisms, often related to differences in a species' size structure (Vassallo, 1971; Bloudon and Kennedy, 1982) or as adaptive responses to predation (Reading and McGroarty, 1978). Environmental features can also affect the depths of organism

activity. In physically-disturbed intertidal or pollutant-impacted environments organisms are often restricted to the upper several cms of the sediment, whereas in deeper-water and more pristine environments infaunal organisms often are found to occur at deeper depths within the sediment (e.g., Pearson and Rosenberg, 1978; Rhoads *et al.*, 1978). Hines and Comtois (1985) also noted a slightly greater penetration of organisms in muddy sediments when compared to sandy substrates.

The depths to which epifaunal organisms burrow into sediments is less well known. A variety of demersal fishes forage on infaunal organisms (e.g., see Whitlatch, 1982, Appendix II) and through these activities disturb sediments. Burrowing depths of rays (e.g., *Dasyatis*, *Myliobatis*, *Rhinoptera*) have been recorded from 10-50 cm below the sediment surface (MacGinitie, 1935; Orth, 1975; Howard *et al.*, 1977; Reidenauer and Thistle, 1981; VanBlaricom, 1982). However, most demersal fish restrict their diets to organisms living in the upper several cm of the sediment (e.g., Toole, 1980; Whitlatch, 1982; Becker and Chew, 1987), suggesting limited sediment excavation depths. In contrast, epifaunal crustaceans (e.g., shrimp, crabs) and gastropods are known to actively excavate sediments to depths of at least 10 cm (Turner, 1948; Virnstein, 1977; Woodin, 1978, 1981). Auster and Crockett (1984) noted that excavation activities of crabs often attract other predatory species of crustaceans and demersal fishes which may modify and enlarge the

primary excavation structures.

Birds are also known to be important predators in intertidal and shallow subtidal soft-bottom communities (Goss-Custard, 1977; O'Connor and Brown, 1977; Schneider, 1978; Quammen, 1984). Relatively little information is available, however, on depths of feeding for birds and the role they play in sediment-mixing activities in shallow-water marine environments. Most species utilizing shallow-water areas are "probers" and Recher (1966) noted that bird bill length often correlated with the type of prey consumed by shore bird species. For example, vertical feeding depths (based on bill lengths) of some common New England shorebirds (Fig. 4) indicates that most are restricted to foraging on prey items found in the upper 10 cm of the sediment. While consumption rates of shorebirds on infaunal organisms can be quite high (e.g., 50-90% reduction of infaunal densities; Harrington and Schneider, 1978; Evans *et al.*, 1979), their overall effect on sediment reworking is probably minimal. Other groups of birds, however, are known to be more active bioturbators. For instance, Sibly and McGleery (1983) noted that gulls use "foot paddling" of the sediment in order to float invertebrates to the sediment surface. Ducks and geese are known to feed on intertidal seagrasses and create large pits (0.5 m in diameter and 10-15 cm depth) as they dig out the seagrass rhizomes (Reise, 1985)

2. Rates of sediment mixing and depths of the mixed layer. Specific rates of sediment mixing are related to organism size, feeding mode and environmental conditions. Most of the data on bioturbation rates has been derived from collections of either the amount of fecal material produced by individual organisms or analysis of the burial and redistribution of a distinctive marker (e.g., colored sand, pollen grains, radioactive labeled materials) horizon deposited on the sediment surface. Other indirect methods have also been used (e.g., vertical variations in pore water content, bulk sediment properties, depth of the apparent redox discontinuity layer), although these often provide inadequate or inaccurate insights of bioturbation processes.

With respect to the first approach, Table 3 summarizes representative sediment reworking rates for the major feeding groups of benthic organisms. While these data display considerable variation (primarily as a result of differences in organism size), several general patterns do emerge. Different functional and taxonomic groups display widely differing reworking rates. Overall, epifaunal organisms exhibit relatively higher reworking rates relative to infaunal organisms. This is primarily the result of the generally larger sizes of epifaunal organisms relative to infaunal species. Within the various infaunal functional/taxonomic groups, the surface feeders and funnel feeders tend to display the highest reworking rates. Again, this pattern generally reflects the overall larger sizes

of the organisms (particularly large deposit-feeding bivalves and worms).

There are few studies which have attempted to examine the relative magnitudes of biogenic reworking by the various groups of organisms at a particular location. Grant's (1983) study of a South Carolina intertidal sandflat concluded that physical reworking of the sediments by tidal action contributed most significantly to sediment transport (Table 4). While 30% of the sediment surface of the site was covered by feeding pits of dasyatid rays, sediment reworking by these fish contributed less than 1% that reworked by ripple migration. In contrast, bioturbation by infaunal organisms approached 33% of tidal reworking. There appears to be little generality to the relative importance of different types of infaunal species to biogenic mixing. For example, Myers (1977b) noted that a funnel feeder (*Leptosynapta tenuis*) was the dominant sediment mixer on a shallow-water sand flat, while Rhoads (1967) indicated that foraging activities by predatory gastropods (*Polinices duplicatus*) at an intertidal site were far more important in sediment displacement than the activities of infaunal polychaetes.

As indicated above, exact mathematical modelling of bioturbation is difficult because of the variety, irregularity and complexity of the various bioturbation processes. As an alternative approach studies have lumped all processes together and describe bioturbation simply as a random mixing phenomenon

(e.g., Guinasso and Schink, 1975; Berner, 1980). The equation commonly used to describe mixing by organisms is in the form of a classical diffusion equation (assuming that the time-scale of sediment accumulation is much larger than that of mixing). The measure of the efficiency of biological mixing of sediment particles is called the biological mixing or diffusion coefficient. This coefficient is determined by fitting the observed exponential decrease in concentration of some marker with depth (e.g., Pb^{210} , Th^{234} curves) to the diffusion equation.

Such biological diffusion coefficients derived from the application of mixing models to observed gradients in the sediment are not directly comparable to the bioturbation rates obtained from measurements of the amount of sediment reworked, due to the units required by the diffusion models (cm squared per unit time). However, Guinasso and Schink (1975) and Lee and Swartz (1980) indicate that a rough estimate of this biodiffusion coefficient (D_b) may be obtained using the formula $D_b = LV$ (L = mixing depth [cm], V = sediment reworking rate [$cm^3/cm^2 \cdot sec$])

Table 5 summarizes representative values of D_b for a variety of marine environments. While values of D_b vary about six orders of magnitude, there is a general pattern of decreasing bioturbation rates from intertidal (D_b values approximating 10^{-5}) to deep sea environments (D_b values = 10^{-9}). The range in values is attributable to differences in the magnitude of mixing by different organisms, variations in biomass, and temperature

dependencies as well as other environmental factors.

Besides sediment particle reworking, organisms also perform solute or fluid bioturbation (D_i), particularly through irrigation of their burrows for feeding and/or respiration. While much less data are available on solute mixing, D_i is at least one order of magnitude higher than D_b for shallow water environments (Table 6; Aller, 1978; 1982).

Table 6 also compares values for D_b with data on molecular diffusion in sediments. Obviously, biodiffusion can only be effective if the biodiffusion coefficient exceeds the molecular diffusion coefficient. Another way of viewing these relationships is shown in Figure 5 which illustrates the relationship between penetration and molecular diffusion coefficient. The depth of penetration of a 10% concentration front from a constant source is indicated on the ordinate. Figure 5 shows that free solutions diffuse most rapidly whereas materials bound to crystal lattices show almost no penetration.

C. Bioturbation and its relationship to proposed capping of the New Bedford Harbor Super Fund Site.

This section examines the impact that sediment-mixing activities of benthic organisms may have on the integrity of the proposed capping material of inner New Bedford Harbor.

In order to begin evaluating whether the 45 cm capping application will effectively isolate the polluted underlying sediments, several assumptions are required. First, it is

assumed the proposed capping material is "clean" (unpolluted) and is resistant to erosion by tidal and wind/wave scouring. Secondly, it is assumed the proposed 45 cm cap depth reflects a true measured depth after the sediment has remolded and consolidated following its disposal. Lastly, it is assumed that a capping thickness of at least 35 cm is needed to provide a "diffusion" barrier which effectively isolates the contaminated sediments from the overlying sediments. The upper 10 cm of the proposed cap, therefore, is unaffected by the underlying contaminating sediments.

Given these assumptions, it is important to examine whether the activities of bottom-dwelling organisms will affect the integrity of the cap and its chemical "sealing" properties. Specifically, will benthic organisms inhabiting upper New Bedford Harbor sediment cap penetrate greater than 10 cm into the cap, and if they do, what affect will they have altering movements of contaminated materials to the surrounding environment?

As detailed in Part I, the types and abundances of benthic organisms living in and on the cap will primarily be dependent upon local environmental conditions, the source(s) of potential colonists, and to a lesser extent on the specific type of capping material used. Repopulation by benthic organisms will occur following application of the capping material. Initially, most organisms recruiting to the sediment cap will likely be from nearby populations. Over a longer period of time, however, larvae and juveniles from more distant populations might colonize

the area. Environmental conditions will, however, place a limit on the types of organisms that eventually survive in the area. Many benthic organisms are intimately associated with particular sediment types. Sandy sediments tend to be dominated by suspension-feeding invertebrates, while deposit feeders tend to be more abundant in muddy substrates (Sanders, 1960). Zajac and Whitlatch (1982a,b) noted, however, that in shallow southern New England estuarine environments, most infaunal species displayed relatively low degrees of sediment fidelity.

New England estuarine tidal flat communities have reasonably constant recurring assemblages of species (Whitlatch, 1982), and data collected in upper New Bedford estuary (SES, 1987) indicate an infaunal species complement indicative of typical regional estuarine conditions. The relatively low species number and densities of organisms (SES, 1987) found in the uppermost reaches of the harbor, however, likely reflect polluted conditions of the upper estuary.

Infaunal communities in the upper harbor are presently dominated by relatively small, near-surface dwelling polychaete species. Members of the families Spionidae (e.g., *Streblospio benedicti*, *Polydora* spp.) and Capitellidae (*Capitella* spp., *Mediomastus ambiseta*) dominant and are often considered "indicator species" of polluted and/or physically-stressed environments. Other common indicators of environmental stress include *Mulinia lateralis* (bivalve), *Podarke obscura* (polychaete) and *Tubificoides* spp. (oligochaete). All

of these organisms tend to be found in the upper 5 cm of the sediment (Table 7). It is unlikely that they would ever penetrate the 10 cm cap.

There are, however, a number of benthic species presently inhabiting the inner harbor that could potentially penetrate a 10 cm sediment cap (Table 7). These include the polychaetes *Nereis succinea*, *Glycera americana*, *Heteromastus filiformis*, *Nephtys incisa*, *Spiochaetopterus costarum*, *Amphitrite ornata*, and *Diopatra cuprea*. Bivalved molluscs presently inhabiting the upper harbor which could potentially penetrate the proposed 10 cm sediment cap include *Mya arenaria*, and *Ensis directus*. The only species of crustacean likely to occur at depths in the sediment greater than 10 cm is the mantis shrimp (*Squilla empusa*), found at one sampling site in the middle harbor (SES, 1987). This species is generally restricted to subtidal environments and apparently is not abundant in the upper estuary. It should be mentioned, however, that traditional benthic sampling techniques (e.g., cores, grabs) commonly undersample deep-dwelling organisms like the mantis shrimp, larger bivalves and polychaetes.

A variety of epibenthic fish and crustaceans have been reported to inhabit the inner harbor (SES, 1987). As mentioned previously, many of these organisms bioturbate sediments primarily through foraging activities. Data obtained by SES (1987) indicate, however, that it is unlikely the epibenthic species presently inhabiting the harbor would penetrate greater

than 10 cm into the sediment (Table 8).

Application of the sediment cap will result in an increase in intertidal mudflat habitat in the upper harbor. Consequently, there will be additional habitat available for variety of birds which use tidal flats as feeding sites (Whitlatch, 1982). The feeding depths of shorebirds and gulls presently reported to inhabit the inner harbor are limited to the upper several cm of the sediment surface.

It is exceedingly difficult to predict the relative abundance of organisms which will penetrate the 10 cm sediment cap and the magnitude of this effect may have on the movement of contaminated sediment to the water column and surrounding uncontaminated sediments. As mentioned in Part I, within-species feeding and tube-building depths are strongly correlated to animal size and the size-structure of benthic organisms is often dependent upon local environmental conditions. In addition, the intensity of sediment mixing is more influenced by the types of benthic organisms rather than shear faunal density.

Limited information is presently available on the size-structure of benthic organisms inhabiting upper New Bedford estuary. For instance, while only a few soft-shell clams (*Mya arenaria*) were found in the harbor, SES (1987) reported shell-lengths up to 40 mm. Hines and Comtois (1985) recorded organisms of this size can occur at depths 20-25 cm below the sediment-water interface in subtidal areas of Chesapeake Bay.

Of those species capable of penetrating to depths greater than 10 cm below the sediment-water interface, *Heteromastus filiformis* appears to be the only organism that could potentially feed on sediments occurring below the 10 cm cap. As previously mentioned, this species is a conveyor-belt feeder and is capable of transporting sub-surface sediments to the sediment-water interface. Cadée (1979) reports that *H. filiformis* densities of 500 m⁻² in the Dutch Wadden Sea are capable of bringing a sediment layer of 4 cm to the surface annually. While densities of *H. filiformis* in the upper harbor presently are relatively low (SES, 1987), others have reported densities of hundreds m⁻² to tens of thousands m⁻² in unpolluted shallow water habitats (e.g., Barnstable Harbor, MA [Whitlatch, 1977]; Bouge Sound, SC [Shaffer, 1983]).

All the other species which potentially could penetrate deeper than 10 cm feed on the upper layers of the sediment or are suspension-feeders. Penetration of the 10 cm sediment cap by these species could occur as the result of tube-building or burrowing activities. In addition, these organisms ventilate their burrows and tubes, thereby increasing sediment-water exchanges of both solute and particulate materials. The relative effect of these exchanges on contaminant transport is dependent upon the reactivity of the contaminants and specific ventilation activities of each species. Brannon et al. (1987) noted that the burrowing activities of *Nereis virens* penetrated both a 5 and 50 cm

thick sediment cap covering polluted sediments in laboratory microcosms. Worms penetrating the sediment cap displayed higher tissue burdens of pollutants relative to control organisms. Riedel et al. (1987) noted that *Nereis succinea* affected the distribution and flux of arsenic from the sediments by its production of irrigated burrows. Densities of this species can vary between 50-200 m⁻² (Holland et al., 1977; Mountford et al., 1977; Holland, 1985).

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Table 1.

SUCCESSIONAL PATTERNS IN MARINE BENTHIC SYSTEMS

CHARACTERISTICS	EARLY STAGES	LATE STAGES
Individual/Populational Level		
Life history traits		
Colonizing ability	Good	Poor
Life span	Short	Long
Growth rate	Fast	Slow
Competitive ability	Poor	Good
Colonization mode	Larval & Adult	Larval
Reproductive mode	Brooding	Non-brooding
Community/Ecosystem Level		
Functional/Trophic group	Tubicolous; surface deposit feeders; suspension feeders	Sub-surface deposit feeders; suspension feeders
Species number	Low	High
Production/Biomass	High	Low
Phylogenetic sequence	Polychaetes	Amphipods, Molluscs

Table 2. Trophic guilds of epifaunal consumers on tidal flats
(after Reise, 1985)

Guild	Mode of Feeding	Food	Major Taxa
Herbivores	Cropping of algal mats and sea-grasses	Algae, seagrasses	Fish, birds, crabs
High-tide carnivores	Cropping on visible appendages or digging out prey	Macrofauna	Crabs and fish
Low-tide carnivores	Feeding visually or by probing	Macrofauna, high-tide carnivores	Birds

Table 3. Representative bioturbation rates of various functional groups of benthic organisms.

Functional/Taxonomic group	Reworking depth (cm)	Reworking rate (cm ³ day ⁻¹)
<u>Epifaunal organisms</u>		
Crustaceans ¹	1-8	0.6 - 1200
Fish (rays) ²	5-50	1.6 x 10 ⁴ - 1.2 x 10 ⁵
Gastropods ³	0.2-10	1.4 x 10 ⁻³ - 2000
Birds	1-10	?
<u>Infaunal organisms</u>		
A. Surface-feeders		
Polychaetes ⁴	0.2-5	0.014 - 130
Molluscs ⁵	0.1-20	0.0046 - 630
Crustaceans ⁶	5-410	0.12 - ?
B. Burrowers		
Polychaetes ⁷	2-10	0.2 - 7.5(?)
Crustaceans ⁸	2-10	0.2 - 6
C. Funnel feeders		
Polychaetes ⁹	30-40	0.004 - 80
Enteropneusta ¹⁰	3-80	0.12 - 700
D. Conveyor-belt feeders		
Polychaetes ¹¹	5-30	0.0072 - 3.3

¹ Thorson (1966), Caine (1974), Thomas (1968), Woodin (1978)

² McGinitie (1935), Howard et al. (1977), VanBlaricom (1982), Reidenauer and Thistle (1981)

³ Rhoads (1967), Howard and Dorjes (1972), Edwards and Welsh (1982), Levinton and Lopez (1977), Cammen (1980)

⁴ Rhoads (1967), Aller and Yingst (1978), Schafer (1972)

⁵ Schafer (1972), Rhoads (1963), Bubnova (1971), Black (1980)

⁶ Myers (1979), Meadows (1964)

⁷ Rhoads (1967), Myers (1977a), Cammen (1980)

⁸ Myers (1977a), Howard and Elders (1970)

⁹ Cadee (1976), Hobson (1967)

¹⁰ Burdon-Jones (1962), Thistle (1980), Duncan (1981)

¹¹ Cadee (1979), Mangum (1964), Rhoads (1967), Nichols (1974), Gordon (1966), Myers (1977a)

Table 4. Relative magnitudes of physical and biological sediment-mixing on a South Carolina tidal flat (from Grant, 1983).

Reworking source	Reworked sediment ($\text{cm}^3 \text{ m}^{-2} \text{ hr}^{-1}$)	% of physical reworking
Physical		
Low-intertidal	1.2 x 10 ⁴	
Mid-intertidal	6.1 x 10 ³	
Biological		
Rays		
Low-intertidal (min,max)	6.8, 13.4	<0.1, 0.1
Mid-intertidal (min,max)	12.2, 24.2	0.2, 0.4
<i>Saccoglossus kowalevskii</i>	1.8	<0.1
<i>Acanthohaustorius millsii</i>	69.3	0.6
<i>Pseudohaustorius caroliniensis</i>	60.6	0.5
<i>Paraonis fulgens</i>	432-3886	3.6-32.4

Table 5. Representative values of D_b for a variety of different marine habitats.

Habitat	D_b ($\text{cm}^2 \text{sec}^{-1}$)	Reference
Intertidal	0.7-4.1 x 10^{-5}	Guinnasso and Schink, 1975
Nearshore	4.1 x 10^{-8} to 3.5 x 10^{-6}	Aller et al. 1980; Santchi et al., 1980 Guinnasso and Schink, 1975
Deep-sea	1.6 x 10^{-10} to 1.0-14.0 x 10^{-9}	Turekian et al., 1978; Schink et al., 1975

Table 6. Biogenic mixing and molecular diffusion coefficients (Db) for particle bioturbation; Di for fluid bioturbation.

Molecular diffusion	Fe ⁺⁺	2.4 x 10 ⁻⁶	Lee and Swartz, 1980
	NH ₄	7.0 x 10 ⁻⁶	Lee and Swartz, 1980
	Cl ⁻	5.0 x 10 ⁻⁶	Lee and Swartz, 1980
	¹⁰⁶ Ru	1.0 x 10 ⁻¹¹	Duursma and Gross, 1971
Fluid bioturbation (Long Island Sound)		0.1-3.0 x 10 ⁻⁴	Aller, 1978

Table 7. Predicted vertical distribution of infaunal species inhabiting inner New Bedford Harbor.

Taxon	Depth (cm)	References
<i>Streblospio benedicti</i>	0-10	Hines and Comtois, 1985
<i>Polydora</i> spp.	0-7	Schafer, 1972; Hines and Comtois, 1985
<i>Capitella</i> spp.	0-5	Rhoads et al., 1978.
<i>Mediomastus ambiseta</i>	0-10	Fuller, per. comm.
<i>Mulinia lateralis</i>	?	
<i>Podarke obscura</i>	?	
<i>Tubificoides</i> spp.	0-30	Hines and Comtois, 1985
<i>Nereis succinea</i>	0-30	Cammen, 1980; Hines and Comtois, 1985
<i>Glycera americana</i>	0-15	Ambrose, per. comm.
<i>Heteromastus filiformis</i>	0-35	Rhoads, 1967; Cadee, 1979
<i>Nephtys incisa</i>	1-15	Davis, 1979
<i>Spirochaetopterus costarum</i>	?	
<i>Amphitrite ornata</i>		Aller and Yingst, 1986
<i>Diopatra cuprea</i>	50-60	Mangum et al., 1968
<i>Mya arenaria</i>	0-30	Hines and Comtois, 1985
<i>Ensis directus</i>	0-20	Per. observations
<i>Squilla empusa</i>	212-410	Myers, 1979

Table 8. Foraging depths of common epifaunal organisms inhabiting inner New Bedford Harbor.

Taxon	Depth (cm)	Reference
Molluscs		
<i>Ilyanassa obsoletus</i>	2	Edwards and Welsh, 1982
<i>Acteon punctostriatus</i>	1?	
<i>Mitrella lunata</i>	1?	
<i>Odostomia seminuda</i>	1?	
Crustaceans		
<i>Edotea triloba</i>	0-7	Hines and Comtois, 1985
<i>Microdeutopus gryllotalpa</i>	0-5	DeWitt, per. comm.
<i>Corophium</i> spp.	0-10	Meadows, 1964; Fenchel et al., 1975
<i>Crangon septemspinosa</i>	0-2?	
<i>Pagurus longicarpus</i>	0-2?	
<i>Neopanope sayi</i>	0-5?	

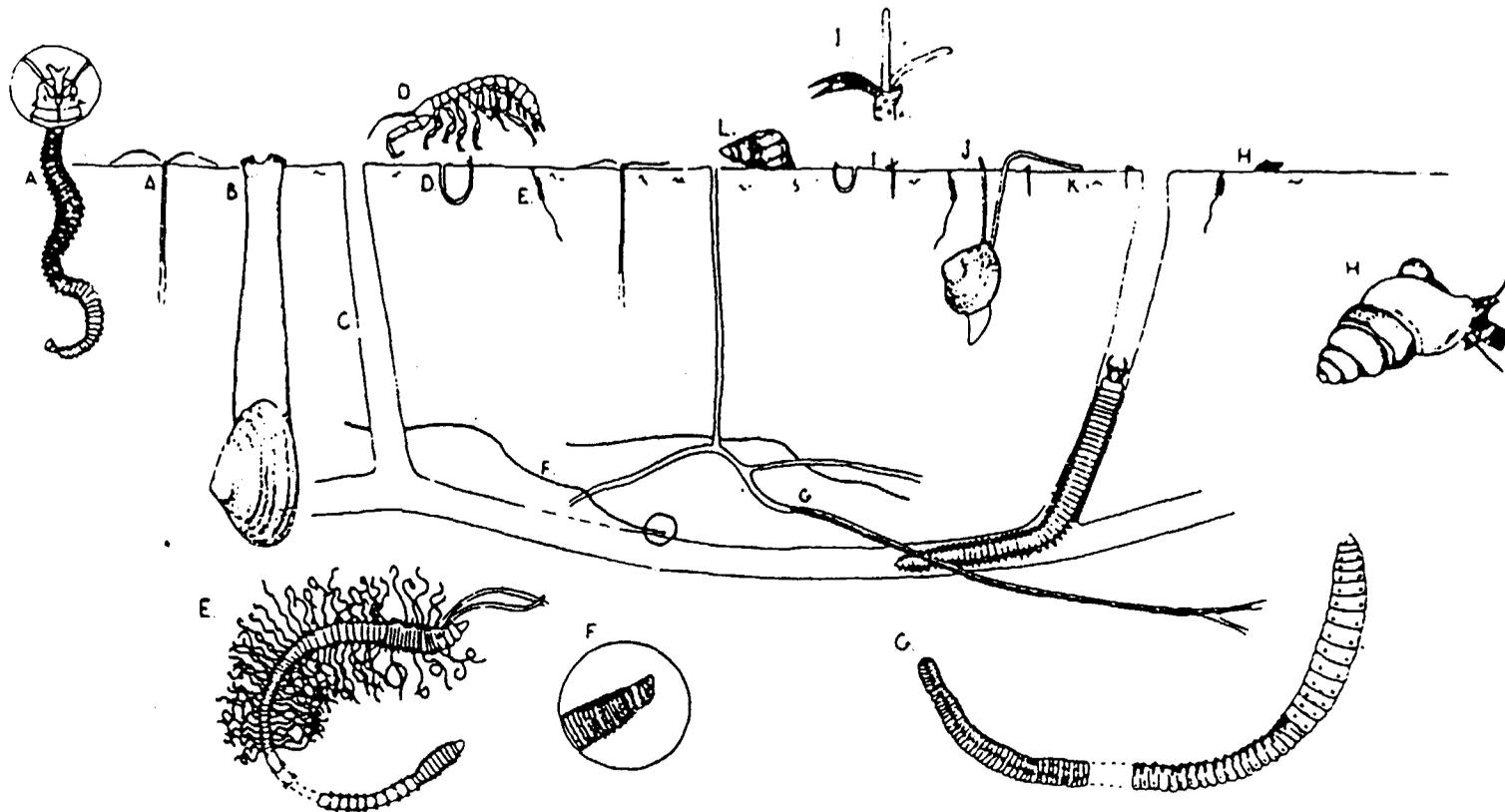


Figure 7. Some representative New England mud flat benthic invertebrates.

Suspension feeder:

B = Mya arenaria (soft-shelled clam)

Surface deposit feeders:

- A = Polydora ligni (spionid polychaete)
 D = Cyrophium spp. (gammaridean amphipod)
 H = Hydrobia totteni (hydrobid gastropod)
 I = Streblospio benedicti (spionid polychaete)
 J = Macoma balthica (bivalve)
 L = Ilyanassa obsoleta (mudsnail)

Burrowing omnivore:

C = Nereis virens (nereid polychaete)

Burrowing deposit feeders:

- E = Tharyx sp. (cirratulid polychaete)
 F = Lumbrinereis tenuis (lumbrinerid polychaete)
 G = Heteromastus filiformis (capitellid polychaete)
 K = oligochaete

Scale

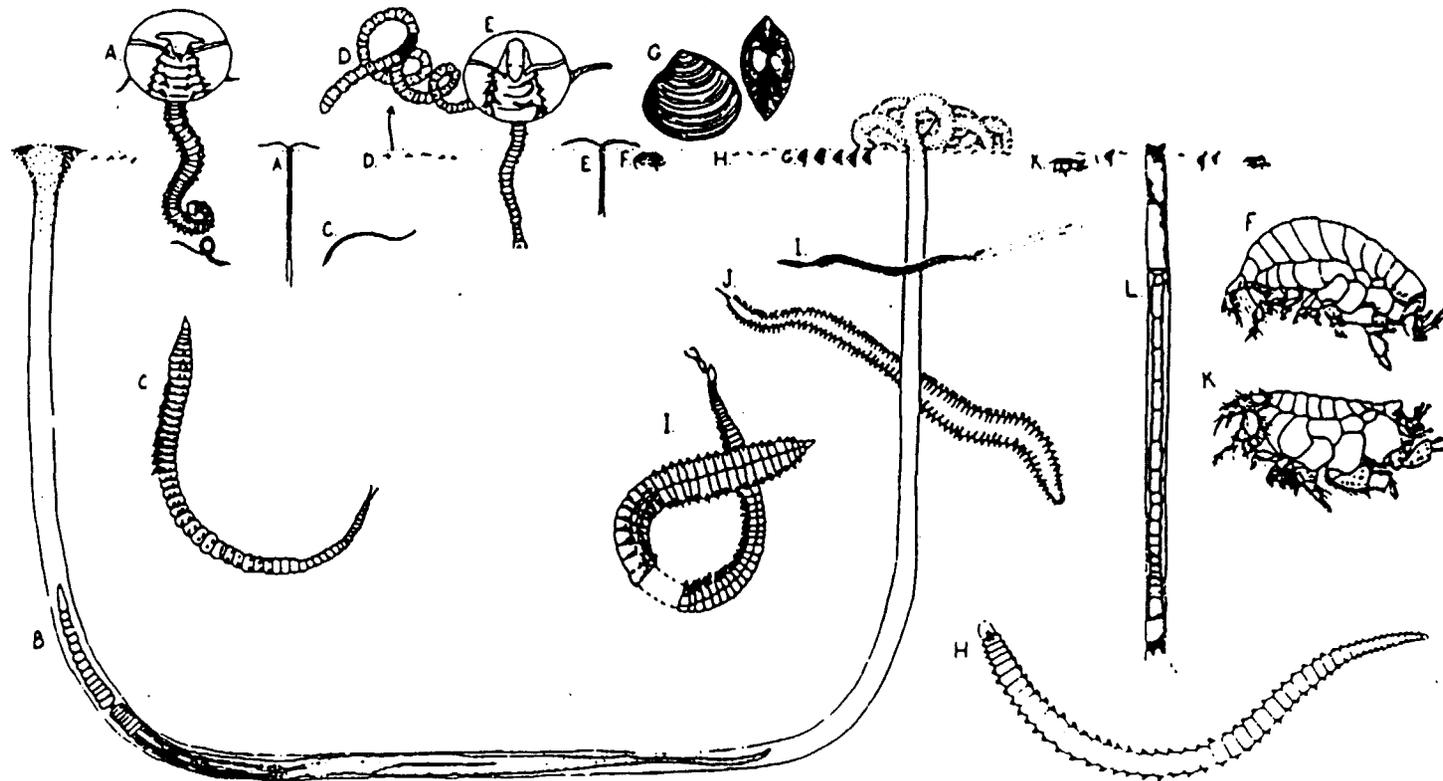


Figure 2. Some representative New England sand flat benthic invertebrates indicating general life habits.

Surface deposit feeders:

- A = *Spiophanes bombyx* (spionid polychaete)
- B = *Saccoglossus kowalewskyi* (protochordate)
- E = *Pygospio elegans* (spionid polychaete)

Burrowing deposit feeders:

- C = *Aricidea* sp. (paraonid polychaete)
- D = *Oligochaete*
- H = *Exogone hebes* (syllid polychaete)
- I = *Scoloplos* spp. (orbiniid polychaete)
- J = *Nephtys* spp. (nephtyid polychaete)

Suspension feeders:

- G = *Gemma gemma* (venerid bivalve)
- F = *Protohaustorius deichmannae* (haustorid amphipod)
- K = *Acanthohaustorius millsii* (haustorid amphipod)

Conveyor-belt deposit feeder:

- L = *Clymenella torquata* (malidanid polychaete)

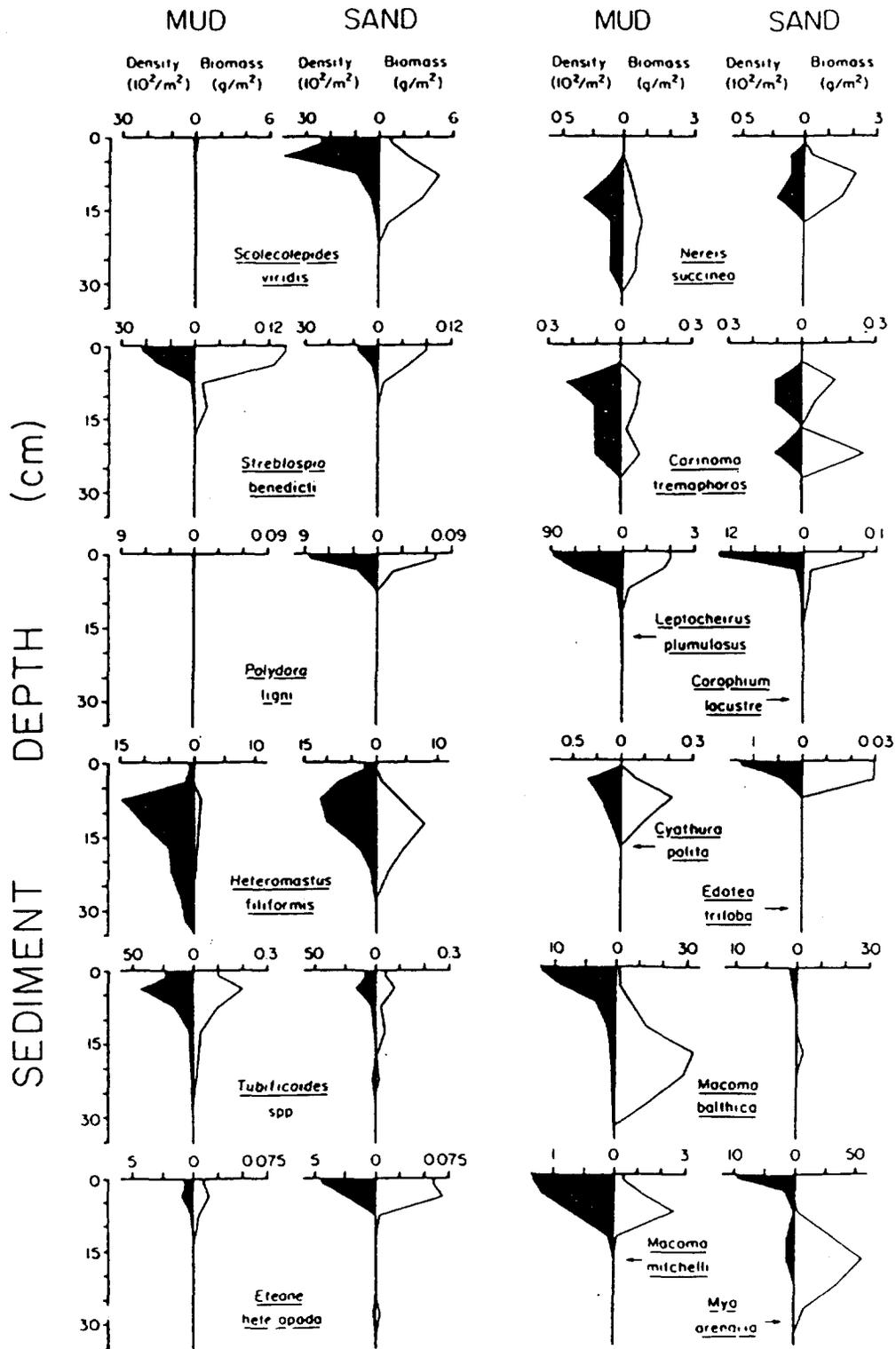


Figure 3. Vertical distribution of common infaunal invertebrates in sand and mud habitats in the Chesapeake Bay (from Hines and Comtis, 1988)

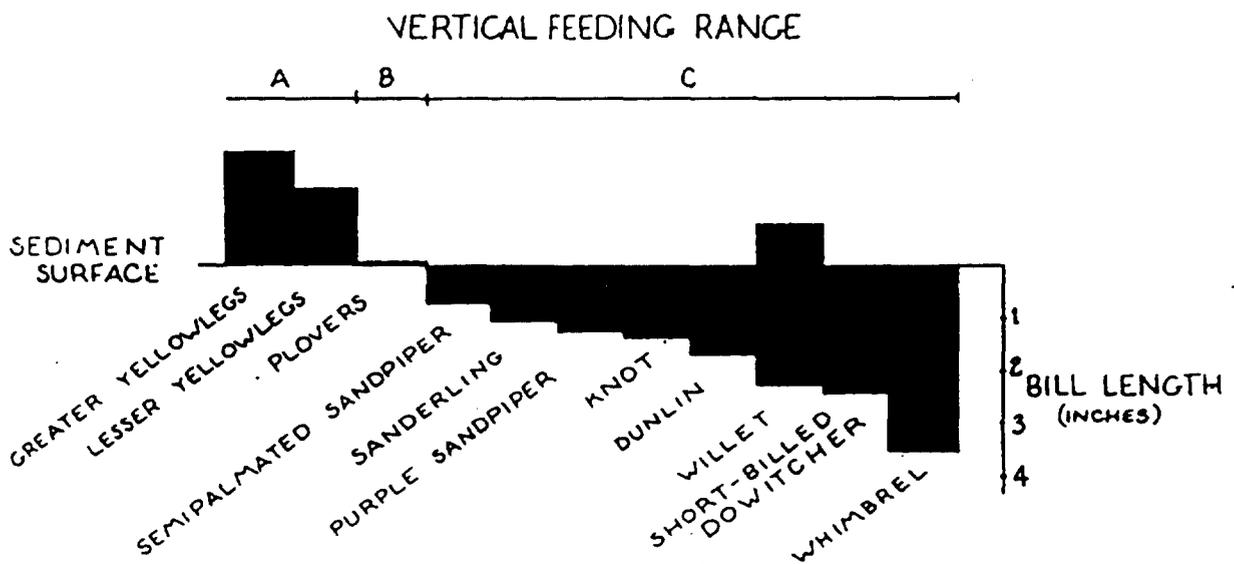


Figure 4. Vertical feeding depths of some common New England shorebirds (modified from Recher 1966). Bill lengths are an average of the ranges given by Palmer (1967). A = species foraging between the water and sediment surface (heights of bars refer to water depths); B = species primarily feeding on the sediment surface; C = species mainly feeding below the sediment-water interface (the willet feeds below the sediment surface as well as in shallow water).

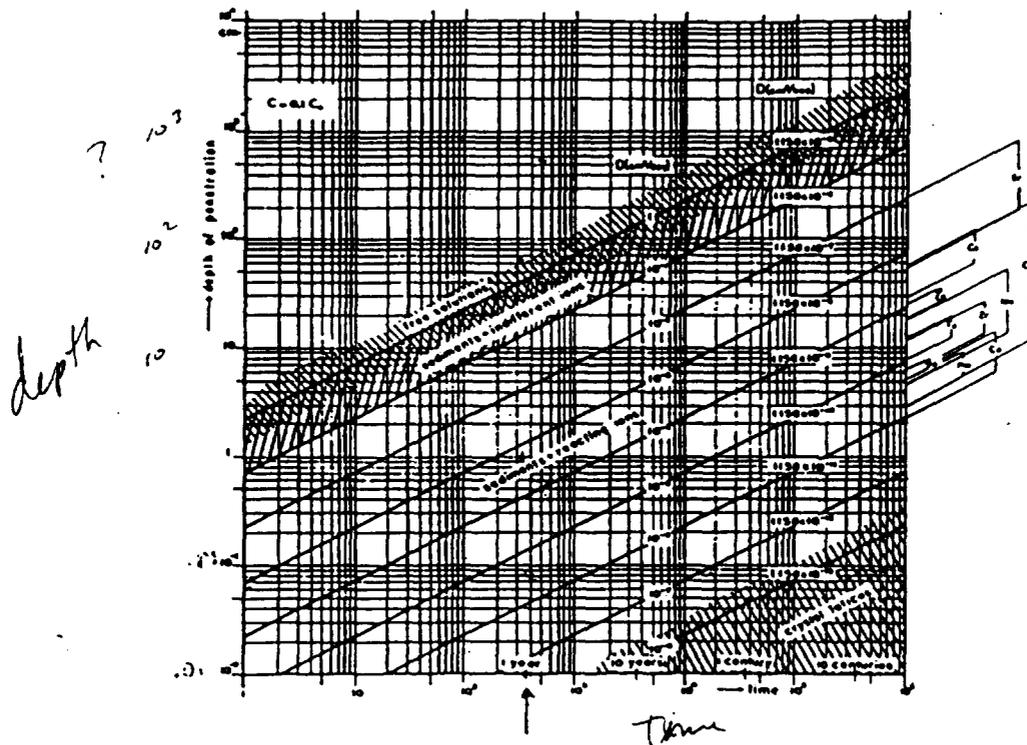


Fig. 5. Depth penetration of a 10% concentration level into a sediment from an overlying water mass with a constant radionuclide concentration, as a function of time, for various diffusion coefficients. The range of diffusion coefficients found for various radionuclides and (marine) sediments is shown on the right (from Duursma & Eisma, 1973, Neth. J. Sea Res. 6: 296, fig. 13).