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Particle bioturbation in Massachusetts Bay: Preliminary results using a new deliberate tracer technique

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ABSTRACT

To better understand temporal and particle size-dependent bioturbation processes, we conducted a study of sediment mixing in Massachusetts Bay using a newly developed deliberate tracer technique. Sediments from a 32-m, fine-grained site were collected and the 38–62 (“silt”) and 63–125 (“sand”) μm fractions isolated. These particle-size fractions were labeled with two different noble metals (Au: silt & Ag: sand) using a thermal diffusion technique. Mixtures of the tracers were spread onto the seafloor in April and July 1992 by divers and were tube-cored (3 replicates) ~ 80 d later in each case. Vertical profiles of the tracers were measured at $\mu\text{g/g}$ (Ag) and ng/g (Au) levels by instrumental neutron activation analysis. During the spring experiment, Au (silt) was mixed to depths > 15 cm and displayed multiple subsurface maxima, whereas Ag (sand) was confined to the upper 5 cm of the bed and showed a near monotonic decrease in concentration with depth. In the fall experiment, the tracers displayed more congruent down-core profiles consisting of near-surface maxima and several subsurface peaks. Two nonlocal bioturbation modes are suggested by the tracer data: reverse conveyor-belt transport and head-down deposit feeding or excavation. A particle caching strategy by an unidentified macrofaunal species is postulated to explain the subsurface peaks, but remains conjectural without better species-level natural history information regarding solid-phase bioturbation.

1. Introduction

Particle bioturbation has important effects on sediment (and contaminant) transport and accumulation processes in the coastal ocean. For example, the incorporation of artificial radionuclides in Irish Sea sediment has been shown to be controlled by biological sediment mixing processes with little contribution from physical sedimentation (Kershaw *et al.*, 1984). Similarly, a causal relationship between the inventory of the naturally occurring, short-lived radionuclide, ^{234}Th , and the magnitude of sediment mixing has been observed in Long Island Sound (Aller and Cochran, 1976; Aller *et al.*, 1980). Whereby at Long Island Sound sites characterized by high mixing rates, excess ^{234}Th was more quickly transported to depths in the sediment where it was no longer available for resuspension and further dispersal.

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Bioturbation processes were implicated to control the incorporation of fine-grained sediment ($< 63 \mu\text{m}$) into sandy sediments of the middle Atlantic Bight (Bacon *et al.*, 1994). It is clear from these and other studies that to better understand and model the dispersal and accumulation of fine-grained sediments and their associated contaminants in the coastal ocean greater attention should be given to sediment bioturbation.

Despite the apparent importance of bioturbation in the coastal ocean, there are many gaps in our understanding. First, only a few studies (e.g., Aller and Cochran, 1976; Martin and Sayles, 1987) have addressed temporal variation in mixing rates and those studies have yielded somewhat disparate results. Whereas both studies measured elevated mixing rates in the warmer months, the yearly maximum in the former study was in early fall, after the temperature maximum, but the yearly maximum in the latter study was in late spring, before the temperature maximum. These results suggest that other underexplored factors, for example, animal abundance or biomass patterns or seasonal changes in carbon flux may be important in determining the temporal variability of mixing rate. Second, particle size-dependent mixing has not been adequately studied in shallow-water sediments. Many laboratory studies, summarized by Taghon (1989), have shown that animals are capable of selecting particles on the basis of size and field evidence for particle-size dependent mixing exists in the form of graded bedding (Rhoads and Stanley, 1965). However, few data exist regarding the relative rates of size-dependent mixing (e.g., Wheatcroft, 1992), therefore it is not possible to incorporate this effect into sediment dispersal models. Third, and most importantly, we do not know what parameters are most important in controlling bioturbation rate (Wheatcroft *et al.*, 1990; Swift, 1993), that is, the biology of bioturbation is still poorly understood. A full answer to this question is a long way off, and certainly not answered in this report. However, a useful step would be to determine the degree to which structural aspects of the benthic community (e.g., numerical abundance, depth distribution within the sediment) can be used to explain observed variations in bioturbation rate and/or mode.

All of these general questions and unknowns are even more acute in Massachusetts Bay where, despite its proximity to metropolitan Boston, very little research has been conducted on soft-bottom benthic processes. There are no published studies of sediment mixing processes in Massachusetts Bay, and previous studies of the benthic fauna have been mainly regional surveys focused on species abundances and diversity (e.g., Blake *et al.*, 1987). Thus, there is little information regarding the natural history, especially sediment reworking capabilities, of Massachusetts Bay soft-bottom fauna. Data pertaining to benthic processes in general and bioturbation in particular are critical as the regional water resources authority has plans to construct a sewage outfall that will extend approximately 15 km into Massachusetts Bay and eventually discharge $\sim 20 \text{ m}^3/\text{s}$ of treated effluent. The fate of particle-

associated contaminants in the effluent will partly depend on sediment mixing processes.

One reason for the fairly low level of understanding regarding the biology of bioturbation has to do with the available tracers. Most previous studies of bioturbation have relied on either sediment-bound radionuclides, exotic particles or painted fluorescent particles ("luminophores"). Both naturally occurring (e.g., ^{234}Th , ^{210}Pb , ^7Be) and artificial (e.g. $^{239,240}\text{Pu}$, ^{137}Cs) radionuclides have been used to study bioturbation on time scales of months to centuries (e.g., Aller and Cochran, 1976; Benninger *et al.*, 1979; Kershaw *et al.*, 1984; Smith and Schafer, 1984; Rice, 1986). Although these radionuclides have yielded many important results regarding sediment accumulation and mixing, they possess at least three shortcomings that limit their utility in studying the biology of bioturbation. First, the input function of radionuclides cannot be controlled, therefore they cannot be used to directly track the mixing of a particular particle size or type. Second, it is not possible to unequivocally distinguish between certain bioturbation modes (e.g., biodiffusion vs. conveyor belt feeding) using naturally occurring radionuclides. Third, it is unlikely that radionuclides (e.g., ^{210}Pb) that integrate processes over a century could be sensitive indicators of bioturbation processes that are driven by organisms with lifetimes measured in months to years. In support of this last statement are the many cases in which recent mixing events have a disproportionate effect on the observed tracer profile (e.g., Smith and Schafer, 1984; Swift and Kershaw, 1986).

Exotic particles also suffer for two reasons. While they are indeed manipulatable, they are also exotic. Thus, there is always some question as to whether the properties that make them exotic, for example, shape (spherical glass beads; Wheatcroft, 1992) or chemistry (fluorescent paint particles; Carey, 1989), might also affect their mixing kinetics. In addition, exotic particles are sometimes difficult to enumerate, often requiring tedious counting under a microscope. The final particle tracer technique consists of coating natural particles with fluorescent paints and enumerating the concentration through visual counting (Mahaut and Graf, 1987; Gerino, 1990). The details of this technique, including areal coverage of individual grains, stability, and chemical treatment of grains during coloration are protected by patent. Therefore, it is difficult to assess the utility of the technique, although encouraging, but limited, results have been reported (e.g., Mahaut and Graf, 1987; Gerino, 1990). A potentially serious drawback to the luminophore technique is that the paint fills in micro-crevices (Mahaut and Graf, 1987), which are important sites of bacterial attachment (Meadows and Anderson, 1966; Weise and Rheinheimer, 1978). A tracer that combined the strengths of radionuclides (i.e., relative ease of enumeration at low concentrations) with those of exotic particles or luminophores (i.e., manipulatability) would be useful.

We have developed such a tracer (Olmez *et al.*, 1994) based on the thermal diffusion of noble metals into the crystalline matrix of natural sediment particles and

enumeration at low concentrations via instrumental neutron activation analysis. This report details results of a preliminary study in Massachusetts Bay in which the new tracer technique was used to study temporal and particle size-dependent mixing at a fine-grained site. An ancillary objective of this research was to obtain structural data (e.g., abundance, depth-distribution) on the macrofauna in order to better interpret the tracer results.

2. Methods

a. Study site. The study site is located in approximately 32-m of water at 42° 24.07'N, 70° 50.05'W in western Massachusetts Bay, in an area of weak acoustic backscatter that has been interpreted to be a depositional locale (Knebel, 1993). Sediment at the site is a poorly sorted sandy-silt, approximately 29% sand, 50% silt and 21% clay (Bothner *et al.*, 1990). Bottom water temperature varies seasonally, with the yearly minimum ($\sim 3^{\circ}\text{C}$) in March and maximum ($\sim 11^{\circ}\text{C}$) in October (Townsend *et al.*, 1991). Seasonal hydrographic surveys that included measurement of nutrient and dissolved oxygen concentrations, as well as phytoplankton community structure and productivity have determined the general water column conditions of the Massachusetts Bay region (Townsend *et al.*, 1991). Late winter conditions are characterized by a well-mixed water column, high nutrient levels and low phytoplankton concentrations. Beginning in March and continuing into April, there is evidence (fluorescence spikes in a profiling fluorometer) for a spring phytoplankton bloom in the absence of vertical stratification (i.e., water depth < critical depth). A thermocline typically begins to develop by June and is well established by August when nutrients are depleted and chlorophyll-*a* concentrations are low. In early October vertical mixing begins, and nutrient and phytoplankton levels are characteristic of a fall phytoplankton bloom (Townsend *et al.*, 1991).

An ongoing field program conducted by the U.S. Geological Survey, Woods Hole (Bothner *et al.*, 1990; Butman *et al.*, 1992; Knebel, 1993) has focused on the geological framework, sediment transport and physical oceanographic regime of the Massachusetts Bay region. Findings to date indicate that the region is spatially and temporally complex. Shallow-water (<40 m) bathymetry is rugged, with many small topographic highs and lows that reflect Pleistocene glaciation processes (Knebel, 1993). Bottom sediment size ranges from boulders to mud and mainly reflects bathymetry, with coarse-grained sediment on topographic highs, and fine-grained sediment typically in broad depressions (e.g., the present study site). Sediment resuspension is controlled by waves (Butman *et al.*, 1992), with only weak residual currents. The probability of wave-resuspension is highest from October to April, with generally quiescent, depositional conditions during the remainder of the year (Butman *et al.*, 1992).

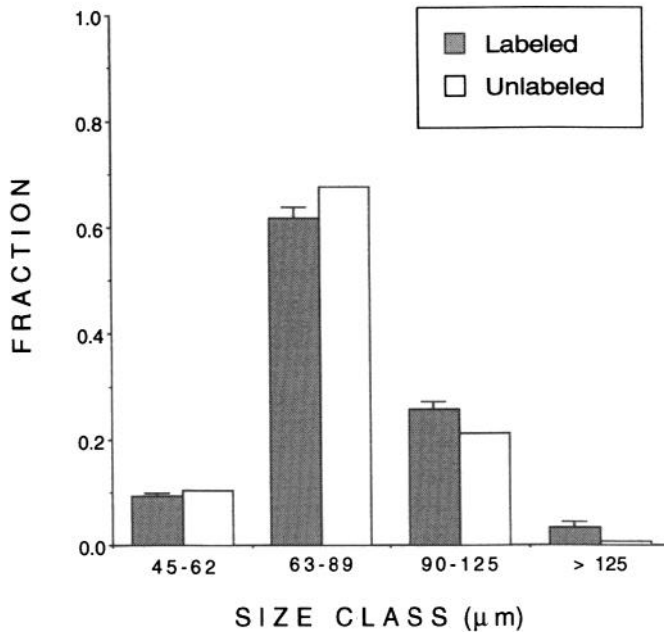


Figure 1. Size-frequency histogram of the nominal "sand" (silver) grain size classes before and after the tracer labeling procedure. Error bars for the labeled sediment are the standard deviation of three replicates taken from the bulk sample.

b. Field and laboratory methods. The location of the study site was selected following a reconnaissance cruise in late February 1992, during which three box cores were collected within the approximately 400 by 400 m area of fine-grained sediment. Grain size, macrofaunal abundance, as well as background metal concentrations were determined from each box core. The two dominant size fractions at the study site: 63–125 μm "sand" and 38–62 μm "silt" were isolated, via wet sieving, and labeled with silver and gold, respectively. The particle labeling technique (Olmez *et al.*, 1994) involves wetting the sediment with solutions containing known concentrations of Ag and Au. This step is followed by drying at elevated temperatures, which reduces the element to a metallic state and, then diffusion by subjecting the sediment/metal mixtures to a temperature of approximately 1100°C. The labeled sediment is then acid etched and washed to remove all unreacted, including surface adsorbed, metal. The labeling technique does not alter the size (Fig. 1), specific gravity or surface properties of the particles (Olmez *et al.*, 1994). Therefore, those properties that are relevant to animals remain unchanged by the labeling technique. Labeled particles were soaked for at least 48 hr in 12°C unfiltered seawater prior to deployment to permit initial development of a biofilm.

Fifty milliliters of labeled sediment (equal amounts of Au and Ag) was spread onto the seafloor by divers using a salt shaker-like device that permits relatively uniform

distribution of the tracers (Wheatcroft, 1992). Three patches spaced approximately 3 m apart were initiated on April 28, 1992 and a fourth patch on July 23, 1992. Currents during the tracer deployments, and at all other times the divers were present at the site, were very weak; thus the majority of tracer was confined to a patch ~ 75 cm in diameter. A variety of navigational aids were used to ensure successful relocation of the patches. Because surface spar buoys were consistently destroyed or removed, LORAN-C fixes were used to locate the approximate dive area (± 50 m). In the center of the dive area a 30-kHz acoustic transponder was moored 2 m above the bottom. The transponder, in concert with a diver-held interrogator/receiver, provided range and bearing information to guide the dive teams to within 5 m of the treatments. Individual patches of tracer were marked with two 7-cm diameter floats on ~ 30 cm of polypropylene line. One of the April patches was cored three times on July 22, 1992 using 7.2-cm internal diameter, 40-cm long polybutyrate tube cores. The cores were separated by ~ 25 cm. The patch that was initiated in July was cored three times on October 8, 1992. Poor visibility during the October dives precluded location of the remaining April patches. Our tracer data are thus limited to two time periods: an 85-d "spring" and a 78-d "fall" deployment.

Within 1 hr of collection all cores were subdivided at 1-cm intervals to 5 cm and at 2-cm intervals down to 25 (spring experiment) and 30 cm (fall experiment). Fall cores were further subdivided at 0.5-cm intervals in the upper centimeter. An outer ring of sediment ~ 2 cm thick was trimmed from each depth interval to discard any tracer that might have been subducted by the leading edge of the core tube. Sediment samples were placed into pre-washed polypropylene jars. All field and laboratory handling of sediments was conducted with nonmetallic utensils. To assess the entire methodology (e.g., spreading, coring, processing and enumeration) a control experiment that consisted of spreading the tracers, followed by immediate coring (3 cores) was conducted during the April dive series. Processing and laboratory analyses for the control cores was identical to the spring and fall samples.

Concentrations of Au (38–62 μm fraction) and Ag (63–125 μm fraction) were determined by instrumental neutron activation analysis (INAA). This high-resolution technique consists of bombarding homogenized aliquots of sediment with neutrons in the MIT Research Reactor, during which nuclei of all elements present (tracers and others) absorb neutrons and hence become radioisotopic. The radionuclides then decay back to their stable states and in the process emit γ -rays of known energies that are measured using solid-state γ -ray detectors (Olmez, 1989). Irradiation time, decay time before counting and counting time were all optimized to increase the signal to noise ratio of a given element. In addition, the entire sample was rinsed several times with distilled water prior to irradiation to remove as much salt as possible which would induce additional activity.

At the beginning and end of each tracer deployment (i.e., April, July and October) a 40 by 40 cm box core was collected within 100 m of the acoustic mooring. Three 10

by 10 cm subcores were randomly selected for identification, abundance and depth-distribution determination of macrofauna (i.e., animals caught on a 500 μm sieve) at 0–2, 2–4, 4–8 and 8–16 cm depth intervals. The macrofaunal samples were processed following standard procedures (e.g., 10% buffered formalin, transfer to ethyl alcohol, Rose Bengal staining). Counts were confined to the fifteen most abundant species at a given time, although to accomplish this all individuals retained on the screen were qualitatively assayed.

3. Results

a. Background and control experiments. Ambient gold and silver concentrations at the study site were measured by INAA prior to the initiation of the experiments (February 1992). Samples were collected at various depth intervals down to 16 cm from three subcores spread between two box cores collected at the study site, as well as from two surface grab samples. The average background concentration of Au was 7.1 ± 0.8 ng/g, while Ag was found at concentrations of 5.9 ± 0.9 $\mu\text{g/g}$ (\pm Std. Error, $N = 25$). Background sediments from an acrylic tube core obtained by a diver in October 1992 at the close of the experiments also showed similar metal concentrations. Various statistical tests (e.g., Mann-Whitney, Kruskal-Wallis, parametric regressions) showed that there were no consistent trends in the ambient concentration data for either metal (i.e., no changes with depth in the sediment or between box or subcores or with time), hence the concentration of gold and silver in the sediments at the site prior to and during the four month period of the experiments was assumed to be low and uniform.

In April a control experiment was conducted approximately 75 m away from the acoustic transponder where the bottom was of similar grain size and microtopography (e.g., tubes, burrow openings) as the experiment locations. Results from the three replicate cores are, in general, good with minimal penetration of tracer (Au or Ag) below the cm-thick surface interval (Fig. 2). Typically the fraction of the total inventory in the uppermost interval exceeded 95%, except for the Au-profile from core 1, where the surface interval contains $\sim 87\%$ of the tracer. Although it is visually distinct, the subsurface gold peak in core 3 represents a concentration of only 18 ng/g. These results suggest that the tracer and sediment handling methodologies are not biased and that tracer concentrations found below the surface centimeter in the spring and fall experimental cores are likely due to natural processes of bioturbation and/or sedimentation.

b. Tracer data. The two particle size components (38–62 μm , “silt,” labeled with Au vs. 63–125 μm , “sand,” labeled with Ag) had very different vertical distributions at the end of the 85-d spring deployment (Fig. 3). In all three spring cores, the silt profiles had multiple subsurface peaks consisting of 10 to 30 percent of the total inventory. The subsurface maxima in cores 1 and 2 were in phase and occurred at

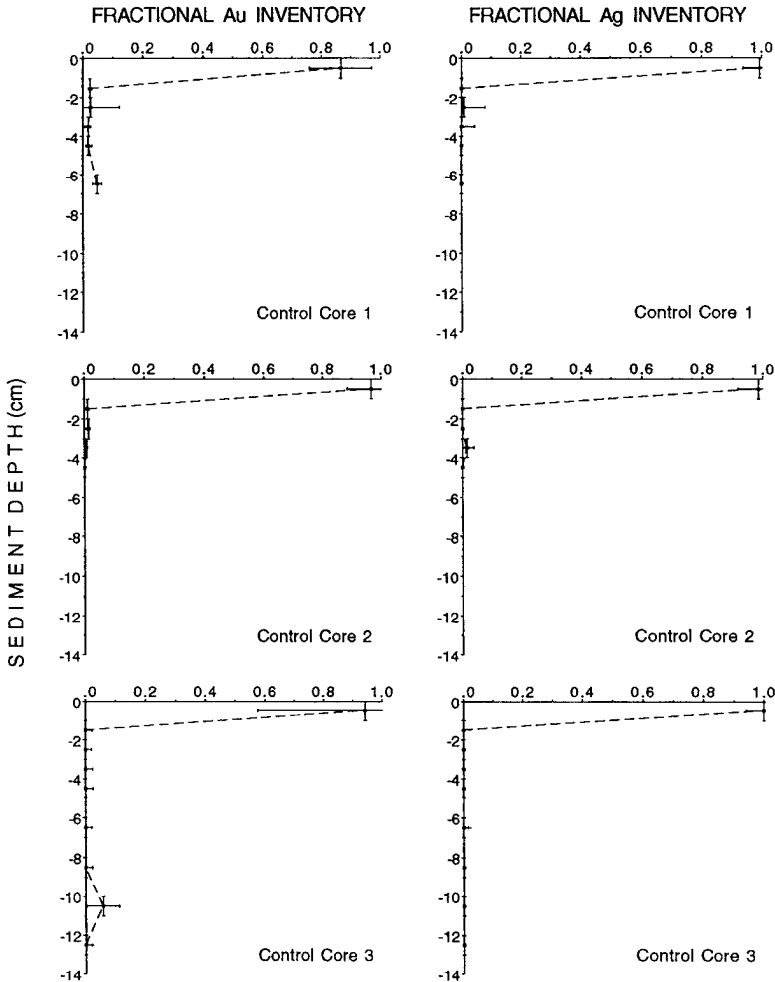


Figure 2. Fractional tracer inventory ($\pm \sigma$ counting errors) for gold (left panels) and silver (right panels) as a function of sediment depth for the control experiment. To obtain the fractional inventory the total amount of tracer observed within a core was divided into the amount observed in a given depth interval. The measured average background concentration of Au and Ag was subtracted from the raw data prior to normalization.

approximately 4–7 cm and 12 cm, while peaks in core 3 were out of phase and occurred at 2–4, 7–9 and 16 cm. The average vertical penetration distance for the silt was 4–6 cm, and maximal penetration distances were > 15 cm (Fig. 4). In contrast, the Ag-labeled very fine sand was restricted to the upper portion of the sediment column (Fig. 3). Average penetration distance was < 2 cm, and maximal penetration distance was 6 cm (Fig. 4). In both cores containing measurable silver (no above background Ag was measured in core 1), the uppermost depth interval was devoid of excess Ag.

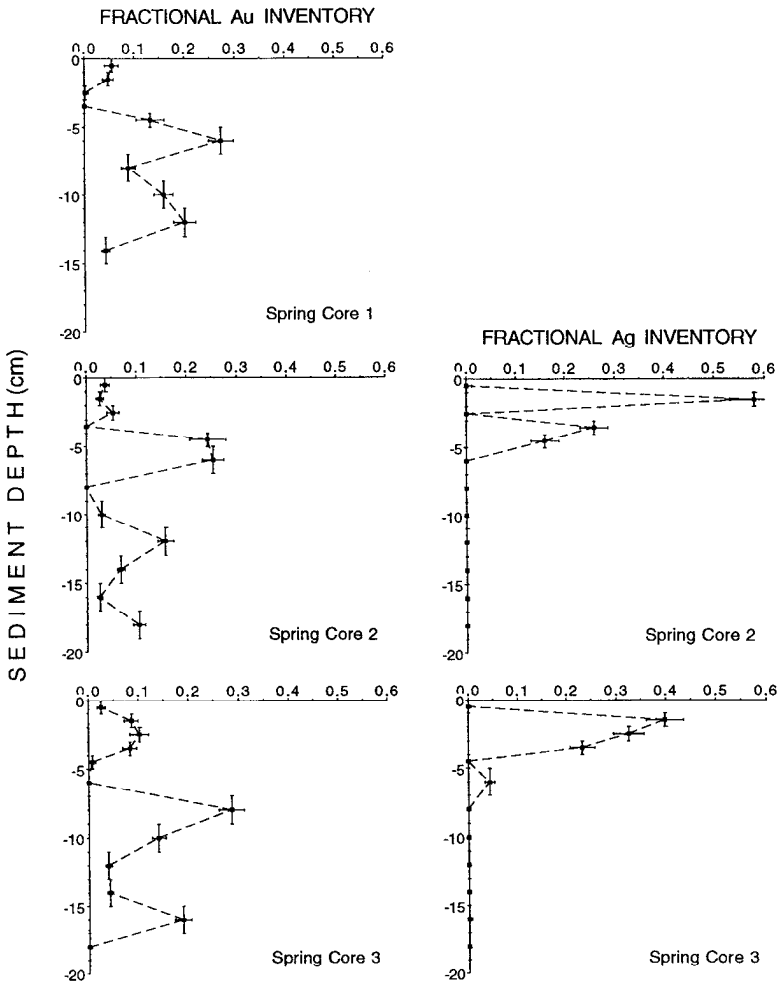


Figure 3. Fractional tracer inventory ($\pm \sigma$ counting errors) for gold (left panels) and silver (right panels) as a function of sediment depth for the spring experiment. Note that no above background Ag was measured in core 1.

In contrast to the results of the spring deployment, the Au and Ag profiles were more congruent in the fall deployment (Fig. 5). Profiles were characterized by relatively high fractional tracer inventories in the upper 4 cm of the bed and near background levels below. In all three cores, however, several subsurface peaks were observed and these were present, in most instances, in both the Au and Ag tracer data for a given core (Fig. 5). Subsurface peaks were measured in core 1 at 7–11 cm and 19–23 cm, in core 2 at 13–17 cm and in core 3 at 19–23 cm. For the most part the amplitude of the peaks is much lower compared to those observed in the spring data, due to the generally larger total inventory of the tracers in the fall cores. The absolute amount of tracer (~ 50 ng/g) at a given depth interval, however, is

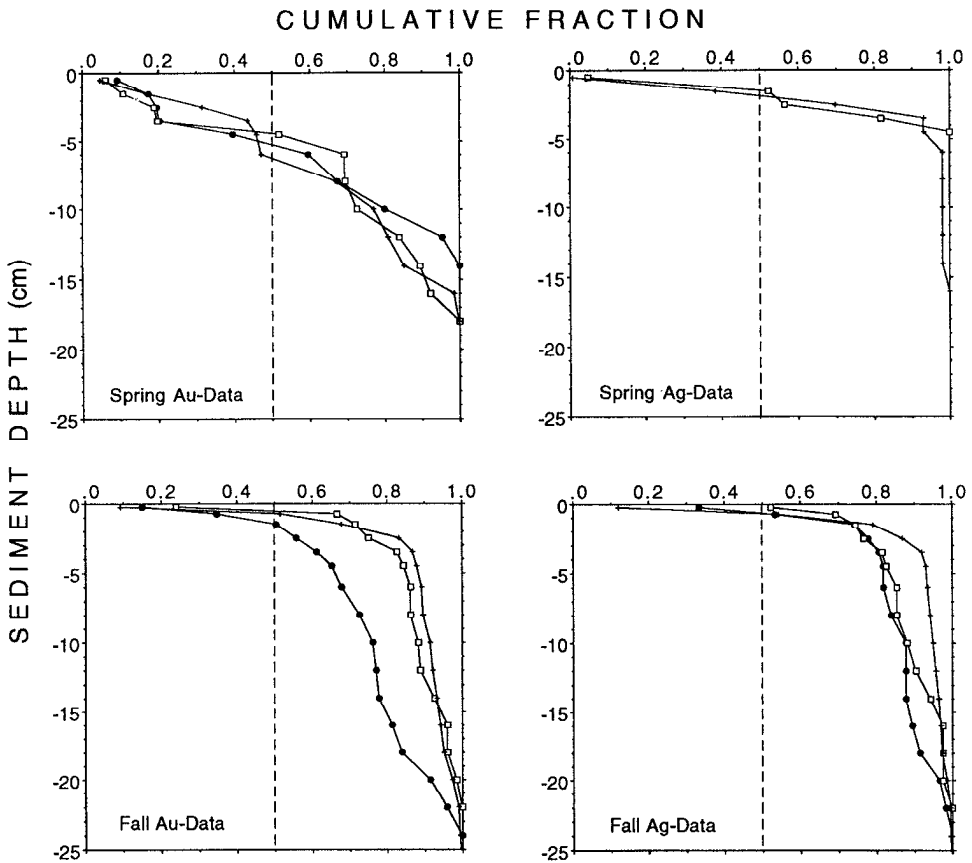


Figure 4. Cumulative fraction of tracer as a function of sediment depth for both experiments. Core 1: solid circles, core 2: open squares and core 3: crosses.

approximately the same for both time periods and is well above ambient metal concentrations. In most cases, profiles of both metals displayed surface minima, similar to that observed in the spring Ag data. Average penetration distances for both tracers was < 1 cm; however, tracers were observed to 23-cm depths.

c. Macrofauna. The fine-grained sediments of the study area support an abundant and diverse community of benthic invertebrates. Except for one subcore, in which there were approximately thirty juveniles of a species of amphipod (*Leptocheirus pinguis*), fifteen species comprised over 90% of the total number of individuals retained on a 500- μ m sieve, and most of the data and discussion focus on those species. Macrofauna abundance follows a seasonal pattern characterized by low numbers of individuals in the winter, a factor of two increase in abundance during the spring and early summer, followed by an $\sim 50\%$ drop in early fall (Fig. 6). Much of this pattern is due to the temporal variation in abundance of two species of sponion

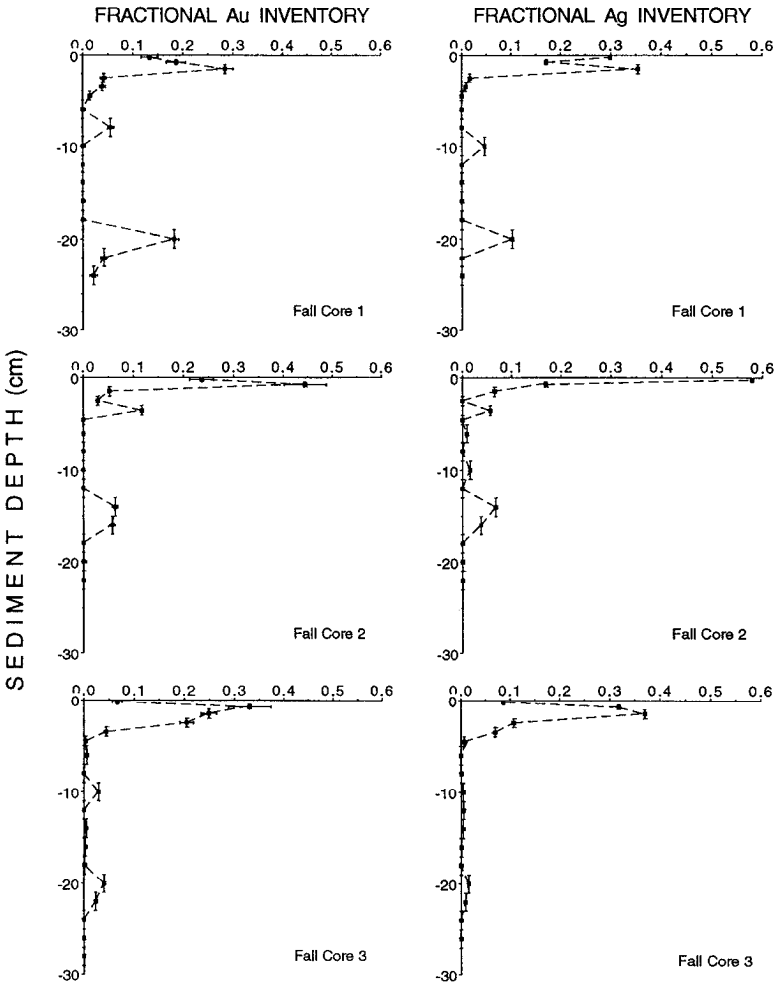


Figure 5. Fractional tracer inventory ($\pm \sigma$ counting errors) for gold (left panels) and silver (right panels) as a function of sediment depth for the fall experiment.

polychaete, *Spio limicola* and *Polydora socialis*. During April these species were present in numbers approaching 200 individuals per 10 by 10 cm subcore (2×10^4 individuals per m^2) (Fig. 6 and Table 1). Abundance of *P. socialis* fell considerably by the July sampling period; however, many of the other species (e.g., *Mediomastus californiensis*, *Tharyx acutus* and *Prionospio steenstrupi*) had their yearly maximum in abundance at this time (Table 1), thus total macrofaunal abundance rose slightly. With few exceptions, abundances of all species dropped by the October sampling period.

The majority of individuals were found in the upper 4 cm of the sediment column (Fig. 7). In April, approximately 80 and 15% of the individuals were located in the 0 to 2 cm and 2 to 4 cm depth intervals, respectively. During the course of the year

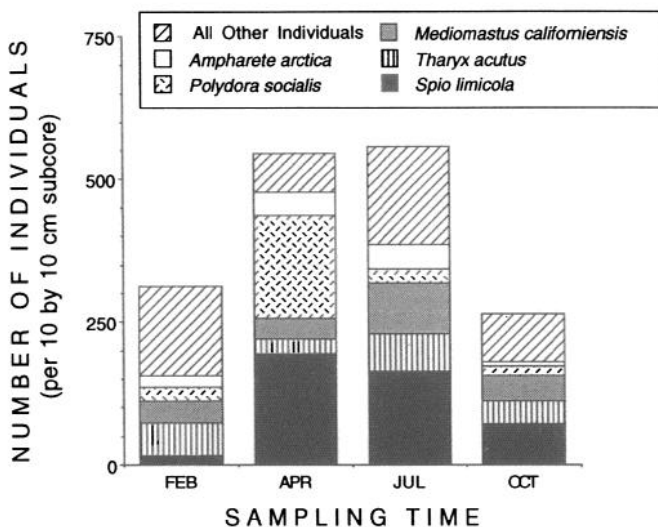


Figure 6. Temporal abundance variation of all macrofauna and five most abundant species in replicate 10 by 10 cm subcores.

there is a progressive shift in the shape of the depth distribution histograms, with an increasing percentage of individuals found at deeper depths. However, as abundances decreased in the upper 2 cm, abundances in the next depth interval (2 to 4 cm) increased; thus the fraction of individuals below 4 cm remained fairly constant

Table 1. Fifteen most abundant species observed during the three sampling periods ordered by overall abundance. Numbers represent mean of individuals observed in three 10 by 10 cm subcores summed over all depth intervals \pm one standard error. In parentheses are species abundance ranks for each sampling period. NP signifies that the species was not present.

Taxon	Sampling Period		
	April	July	October
<i>Spio limicola</i>	194.3 \pm 47.5 (1)	163.0 \pm 38.7 (1)	71.0 \pm 11.8 (1)
<i>Polydora socialis</i>	179.7 \pm 24.1 (2)	25.7 \pm 10.0 (7)	17.7 \pm 8.7 (5)
<i>Mediomastus californiensis</i>	36.3 \pm 5.2 (4)	89.0 \pm 8.7 (2)	44.0 \pm 9.6 (2)
<i>Tharyx acutus</i>	25.7 \pm 2.9 (5)	66.0 \pm 15.7 (3)	40.0 \pm 15.3 (3)
<i>Ampharete arctica</i>	41.0 \pm 5.6 (3)	41.3 \pm 7.4 (4)	7.7 \pm 2.3 (10)
Nemertea spp.	13.3 \pm 2.6 (8)	40.3 \pm 17.0 (5)	24.0 \pm 0.6 (4)
<i>Monticellina baptistae</i>	14.7 \pm 5.9 (6)	23.3 \pm 9.0 (8)	10.7 \pm 6.8 (8)
<i>Prionospio steenstrupi</i>	1.3 \pm 0.7 (13)	36.0 \pm 3.2 (6)	17.7 \pm 3.8 (6)
<i>Levinsenia gracilis</i>	11.7 \pm 2.3 (9)	10.0 \pm 1.2 (13)	12.0 \pm 1.0 (7)
<i>Ninoe nigripes</i>	6.0 \pm 1.2 (11)	18.7 \pm 1.2 (9)	7.3 \pm 1.2 (11)
<i>Leitoscoloplos acutus</i>	NP	13.3 \pm 2.7 (11)	10.0 \pm 2.1 (9)
<i>Nucula delphinodonta</i>	4.7 \pm 0.9 (12)	13.3 \pm 4.1 (12)	3.7 \pm 0.9 (13)
<i>Maldane glebifex</i>	9.0 \pm 2.9 (10)	9.7 \pm 2.2 (14)	2.3 \pm 0.7 (14)
<i>Exogone verugera</i>	NP	14.0 \pm 0.6 (10)	4.7 \pm 1.5 (12)
<i>Phoronis architecta</i>	13.7 \pm 2.7 (7)	2.7 \pm 0.9 (15)	0.3 \pm 0.3 (15)

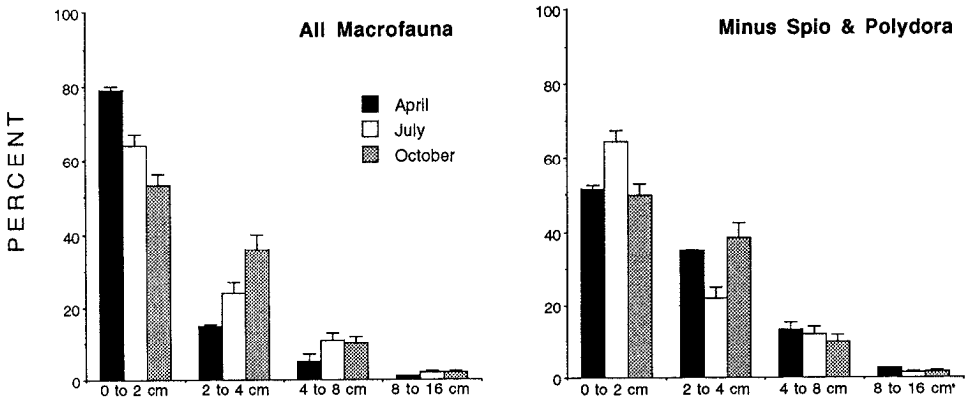


Figure 7. Depth distribution of all macrofauna (left panel) (\pm standard error, $N = 3$) and all macrofauna minus the two common spionid species, *Spio limicola* and *Polydora socialis* (right panel), during the April, July and October sampling periods.

throughout the entire sampling period. A qualitatively different pattern is observed in the depth-distribution data if the two common spionid species (*Spio limicola* and *Polydora socialis*) are neglected. In that case, the greatest percentage of individuals in the 0 to 2 cm depth interval occurs in July, rather than April (Fig. 7).

Individual species exhibited essentially one of three depth distributions (Fig. 8). In the first type of distribution, $> 60\%$ (sometimes $> 80\%$) of the individuals were found in the upper 2 cm of the sediment. Species such as *Ampharete arctica* (an ampharetid polychaete) and *Nucula delphinodonta* (a bivalve) displayed this depth distribution during all sampling periods, whereas other species (e.g., *Spio limicola* and *Polydora socialis*) displayed this pattern only part of the year. The second depth-distribution pattern is one in which the majority of individuals occurred fairly evenly in the upper 4 cm of the bed. Species such as *Tharyx acutus* (a cirratulid polychaete) and *Mediomastus californiensis* (a capitellid polychaete) are characterized by this depth distribution. Finally, two species, *Levinsenia gracilis* (a paraonid polychaete) and *Maldane glebifex* (a maldanid polychaete), display maximal numbers in the 4–8 cm depth range during part of the year (Fig. 8). Few individuals were found below 8 cm during any of the sampling periods.

4. Discussion

Before discussing the tracer data it is necessary to explore potential methodological problems. Spurious results could be obtained in at least three ways: (1) problems in tracer spreading, coring and pre-INAA processing, (2) tracer desorption and mobility within the pore-water, and (3) cross-contamination during INAA. With the exception of poor visibility during the October dive series, no significant problems were encountered during the tracer spreading and coring operations. Cores were returned to the surface in excellent condition. Results from the control experiment

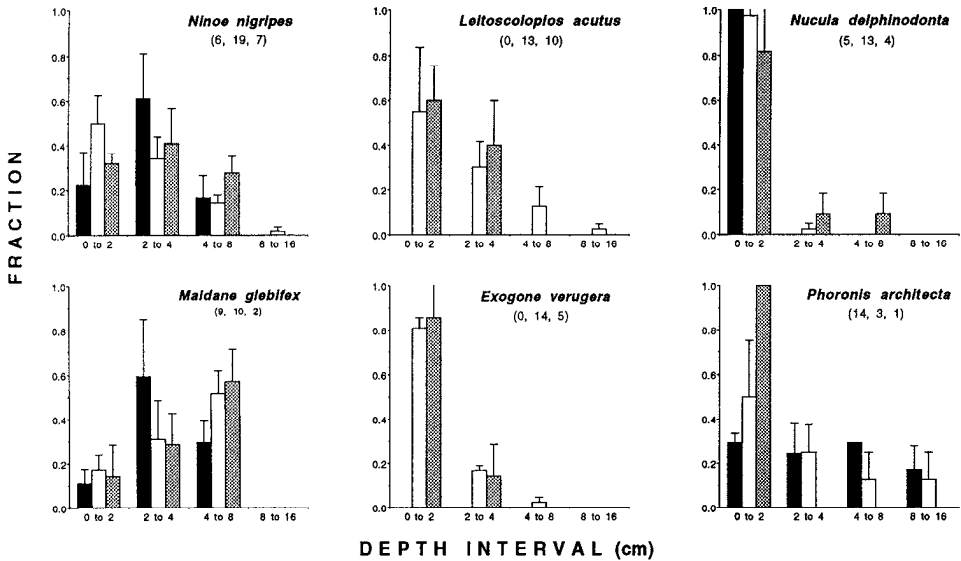


Figure 8. Depth distribution of the fifteen most abundant species (\pm standard error) during the April (black), July (white) and October (stippled) sampling periods. In parentheses are the average number (rounded to the nearest integer) of individuals of each species that were observed during each sampling period.

(Fig. 2) in which only minor amounts of tracer were found below the uppermost centimeter indicate that the methods prior to INAA are sound. The small amount (18 ng/g) of gold that was measured at depth (10–11 cm) in core 3 is approximately a factor of two and a half less than the subsurface peaks observed in the spring and fall experiments. If the Au or Ag was remobilized during the experiments, transported within the pore-water and reabsorbed later, then the utility of this particulate tracer technique would be severely compromised. Metals diffusion into the crystalline matrix of the particles was confirmed by energy dispersive X-ray analysis of individual particles; no free or surface adsorbed or Ag was detected. Furthermore, sequential strong acid leaches did not yield any metals in solution after the initial leach (Olmez *et al.*, 1994). Thus, desorption of tracer elements in the typically more benign marine pore-water environment during the experiments is highly unlikely. Finally, INAA affords virtually no opportunity for sample cross-contamination because samples are physically separated during irradiation and counting (Olmez, 1989). To further insure unbiased tracer data, all samples were counted blindly (i.e., they were not identified until after the results) and in random order. All of these results and precautions strongly suggest that the tracer data are sound.

a. Implied transport modes. Past studies (e.g., Aller and Cochran, 1976; Benninger *et al.*, 1979; Boudreau, 1986; Rice, 1986; Robbins, 1986; Smith *et al.*, 1986; Boudreau

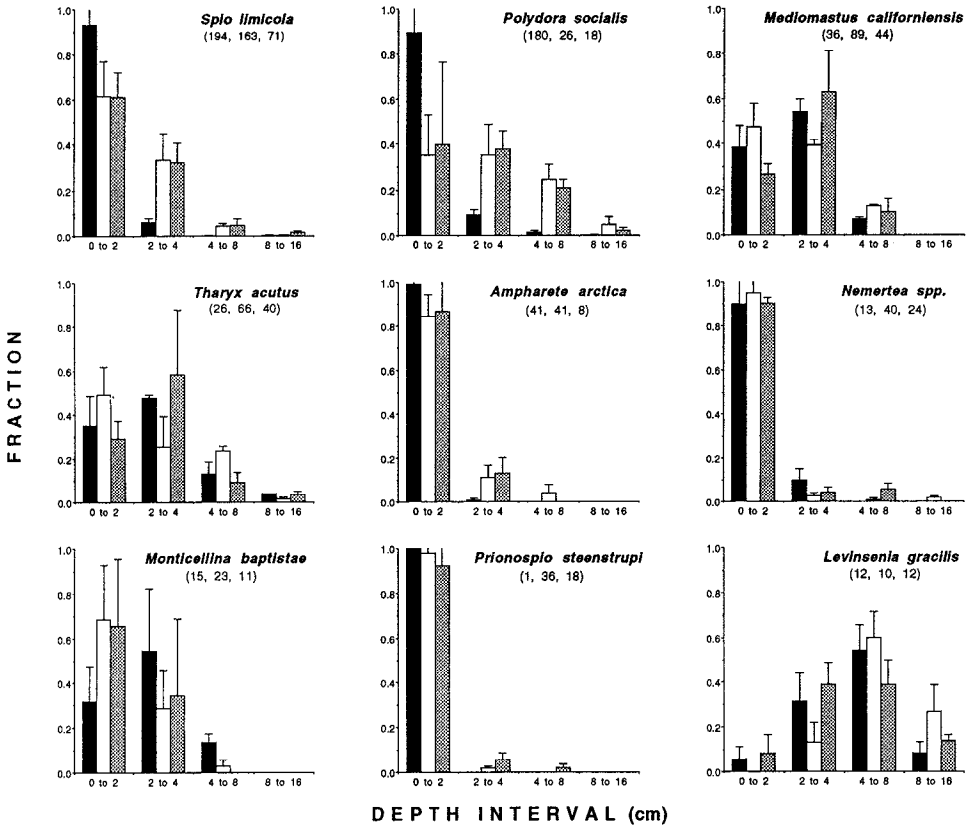


Figure 8. (Continued)

and Imboden, 1987; Wheatcroft *et al.*, 1990; Wheatcroft, 1992) have identified at least three different bioturbation modes: (1) reverse conveyor-belt, (2) head-down deposit feeding or excavation, and (3) biodiffusion. Although by necessity each of these modes is an abstraction of the myriad sediment displacing activities that occur, they are readily incorporated into mathematical models of sediment reworking and appear to have some generality. Each of these transport modes has important ramifications for the redistribution and chemical transformations of various sedimentary components (e.g., Boudreau, 1986). For example, particle subduction rates depend strongly on the bioturbation mode (see below) and therefore it may be just as important to identify the bioturbation mode as it is to measure the bioturbation rate. In this study, the two nonlocal transport modes, reverse conveyor-belt and head-down deposit feeding or excavation are implied by the tracer data.

Reverse conveyor-belt transport is nonlocal movement of sediment from the sediment surface to some depth in the bed. Transport can be active in the sense that it represents a biological activity such as deposit feeding or tube building or it can

represent passive gravitational filling of open burrows or tubes (e.g., Benninger *et al.*, 1979; Boudreau and Imboden, 1987). This bioturbation mode results in subsurface peaks in tracer profiles, and has been previously recognized in tracer data (e.g., Benninger *et al.*, 1979; Smith *et al.*, 1986; Gerino, 1990; Wheatcroft, 1992), and in some instances the responsible organism identified (e.g., sipunculans, Smith *et al.*, 1986). In the present instance, a fairly common species at the study site, the cirratulid polychaete *Tharyx acutus*, has been reported to feed in a reverse conveyor-belt mode (Myers, 1977). Note that Myers' (1977) laboratory observations are atypical in that most previous work on the mechanics of deposit feeding in particular, and the autecology of sediment reworking organisms in general, have focused on species that egest or excavate material onto the sediment surface. This focus is understandable, in that observations in the subsurface are considerably more challenging, but it has potentially led to a bias in our view of sediment displacing activities. The fact that there are many examples (e.g., Benninger *et al.*, 1979; Kershaw *et al.*, 1984; Smith *et al.*, 1986; Gerino, 1990; Wheatcroft, 1992) of tracer data that display subsurface peaks, suggests that reverse conveyor-belt feeding may be more common than previously suspected and worthy of more focused attention.

The surface minima in the spring Ag data and in the fall cores suggest tracer dilution either through deposition from the water column or through biogenic sediment transport from tracer-free sediment. Although published short-term deposition rates are not available for Massachusetts Bay, it is unlikely that they would be high enough (~ 4.5 cm/yr) to deposit at least 1 cm of sediment in the ~ 80 days of the experiments. Moreover, the fact that subsurface minima were not seen in all cores (e.g., fall core 2) suggests that the responsible process was patchy on scales of 10's of cm. Physical deposition is unlikely to be patchy on such small scales, especially on the low relief bottom characteristic of the study site. It is more likely that biological sediment transport, either horizontal or vertical, is responsible for the observed dilutions. The latter is favored in that it is also more likely to yield the small-scale patchiness observed. Head-down deposit feeding or excavation is the nonlocal transport of sediment from some depth within the sediment to the sediment surface (i.e., the opposite of reverse conveyor-belt transport). Many animals are known to feed in this manner (Rhoads, 1974), including various maldanid (Kudenov, 1982), orbinid (Rice, 1986) and capitellid (Fuller *et al.*, 1988) polychaetes (Table 2). Species from all of these groups are present at the study site (Fig. 8, Table 1) and in some instances, for example, the capitellid polychaete, *Mediomastus californiensis*, are quite common.

The ability to identify bioturbation modes based on field-derived, tracer data alone is an important advantage that deliberate tracers introduced as an impulse function have over traditional radiotracers (e.g., ^{210}Pb , ^{234}Th). While reverse conveyor-belt transport can be identified from radiotracer profiles because it produces a subsurface peak in activity (Smith *et al.*, 1986), biodiffusive transport and head-down deposit

Table 2. Feeding modes of polychaetes. Feeding modes of species marked with an asterisk are based on information concerning closely related species (typically congeners). d.f. = deposit feeder

Species	Family	Mode	Reference
<i>Spio limicola</i>	Spionidae	interface feeder*	Dauer <i>et al.</i> (1981) Muschenheim (1987)
<i>Polydora socialis</i>	Spionidae	interface feeder* reverse conveyor-belt*	Dauer <i>et al.</i> (1981) Schäfer (1972)
<i>Mediomastus californiensis</i>	Capitellidae	head-down d.f.	Fuller <i>et al.</i> (1988)
<i>Tharyx acutus</i>	Cirratulidae	reverse conveyor-belt surface d.f.	Myers (1977) Rice (1986)
<i>Ampharete arctica</i>	Ampharetidae	surface d.f.	Mauer & Leathem (1981)
<i>Monticellina baptistae</i>	Cirratulidae	?d.f.*	
<i>Prionospio steenstrupi</i>	Spionidae	interface feeder*	Dauer <i>et al.</i> (1981)
<i>Levinsenia gracilis</i>	Paraonidae	subsurface d.f.*	Risk & Tuncliffe (1978)
<i>Ninoe nigripes</i>	Lumbrineridae	scavenger*	Fauchald & Jumars (1979)
<i>Leitoscoloplos acutus</i>	Orbiniidae	head-down d.f.	Rice (1986) Rice <i>et al.</i> (1986)
<i>Maldane glebifex</i>	Maldanidae	head-down d.f.*	Fauchald & Jumars (1979)
<i>Exogone verugera</i>	Syllidae	scavenger*	Fauchald & Jumars (1979)

feeding or excavation cannot be distinguished from each other solely on the basis of radiotracer data. That is because the latter transport mode acts as an apparent sedimentation rate (Rice, 1986), and sedimentation (physical or biological) and biodiffusion both yield exponentially decreasing radiotracer profiles. Those cases that have modeled conveyor-belt transport (e.g., Rice, 1986; Robbins, 1986) have been motivated by a priori information on the dominant organisms at the sites of interest and/or laboratory experiments using impulse tracers.

b. Variation in transport modes. At the outset of this research project we had intended to compute summary biodiffusivities from each of the tracer profiles and test for temporal and particle-size specific variation (e.g., Wheatcroft, 1992). Differences in the implied transport modes between particle sizes and times (spring vs. fall) and clearly nondiffusive mixing precluded such a simple approach (see below for a different type of comparison). We are nonetheless intrigued by the differences in the tracer distributions, and believe that the most parsimonious explanation for these differences is that shifts in the dominant bioturbation modes (discussed above) occurred. If this is the case, then the question becomes what was different during the spring that caused silt-sized particles to be displaced in a different manner than the sand-sized particles.

An immediately obvious factor is the temporal abundance of macrofauna at the site. Is there a species that is much more abundant during the spring experiment and is that species known to feed in a reverse conveyor-belt mode? There are only two

species that were markedly more abundant during April and July versus July and October: the spionid polychaete *Polydora socialis* and the phoronid, *Phoronis architecta* (Fig. 8, Table 1). Phoronids are suspension feeders with U-shaped digestive tracts (Barnes, 1980), so they probably do not transport sediment to depth. There is no direct particle transport information on *Polydora socialis*, however, and that available for congeners is equivocal (Table 2). Dauer *et al.* (1981) report that *P. ligni* is a facultative surface deposit- and suspension-feeder (an "interface" feeder) that feeds and egests material at the sediment-water interface. In contrast, Schäfer (1972) reports that *P. ciliata* feeds at the sediment surface and frequently stuffs open, subsurface tubes with fecal pellets. This behavior provides a mechanism to produce the observed Au tracer profiles, but remains conjectural without direct natural history observations of *P. socialis*.

There are many reasons to expect functional or behavioral changes in biogenic sediment transport through time. For example, temperature-driven metabolic changes elicit faster deposit feeding rates observed in the laboratory (e.g., Kudenov, 1982), or, similarly, changing redox conditions can alter deposit-feeding rates (e.g., Fuller, 1992). Neither temperature nor redox conditions are known to affect transport mode, however. Another factor that may elicit a shift in the dominant bioturbation mode is the temporal availability of organic carbon due to the spring phytoplankton bloom. The occurrence of a spring bloom in coastal Massachusetts waters was established by the pioneering observations of Bigelow (1926). More recently, Townsend *et al.* (1991) describe a well developed phytoplankton bloom during March and April in western Massachusetts Bay, with high nutrient (e.g., silicate, nitrate) and chlorophyll concentrations throughout the upper water column. They also cite evidence (in the form of fluorescence spikes in a profiling fluorometer) for aggregates of sinking phytodetritus below the thermocline at several of their stations (Townsend *et al.*, 1991). It is not possible to say whether this material reaches the benthos, however, sediment trap (4.25 m above bottom) samples collected by the U.S. Geological Survey (M. Bothner, unpublished data) at a nearby site yielded elevated total organic carbon values in the spring relative to the rest of the year. It thus seems reasonable that a considerable fraction of the yearly organic carbon flux to the bottom occurs during a short interval in early spring, as has been observed in many other shallow temperate environments (e.g., Wassmann, 1984; Christensen and Kannevorf, 1985).

A recently proposed (Jumars *et al.*, 1990) foraging strategy to contend with episodic food inputs is to cache or sequester labile organic matter so that it is unavailable to competitors. Because most macrofauna and microbes, are concentrated near the sediment surface, burying material at depth and periodically returning to "mine" this food source would be a viable strategy. Thus, the subsurface peaks observed in the spring Au profiles may be a byproduct of phytodetritus caching. That similar patterns were not observed in the sand-sized Ag data may reflect a particle-

size limitation of the responsible species(s), that is, sand-sized sediment was either actively avoided or morphologically unmanipulatable.

c. Implications for contaminant accumulation and dispersal. In the absence of bioturbation, fine-particle bound contaminants released at a point source are apt to disperse over large distances and not accumulate at sites that experience critical shear stresses during some time of the year. Bioturbation, by preferentially subducting some particle sizes and types while returning others to the surface where they are available for resuspension and further dispersal, significantly complicates this simple picture (cf. Jumars *et al.*, 1981). Results from the present experiments demonstrate there were differences in particle penetration (or subduction) rates as a function of both time and particle size (Fig. 4). Although the depth of erosion during a given wave resuspension event can vary considerably, a useful reference point is to consider particles transported out of the upper 1-cm thick surface layer to be no longer available for resuspension. During the spring experiment 80% of the silt tracer was transported out of the upper 1 cm, while only ~45% of the sand tracer was removed from the surface interval. In the fall experiment, 25–45% of the silt tracer and 15–25% of the sand tracer were transported below the upper centimeter. Because of the very low currents (<5 cm/s) measured during the experiments, physical resuspension was not a factor. Thus, for both experiments the finer particle size was transported out of the surface layer at approximately a factor of two faster rate. This result suggests that particle-size dependent dispersal rates may vary less than a simple application of physical sediment transport models would suggest, and that contaminants bound to fine-grained particles can accumulate in the near field, even under episodically high-energy conditions.

5. Summary

The biological insight regarding bioturbation that can be obtained using traditional radiotracers (e.g., ^{210}Pb , ^{234}Th) is limited. Deliberate tracers such as those described by Olmez *et al.* (1994) and used herein, provide a more powerful means to better understand mechanisms of bioturbation, especially with respect to particle-size dependent transport rates. In this study we have discussed preliminary data obtained using a deliberate tracer technique that is based on the thermal diffusion of noble metals into the crystalline matrix of natural mineral grains and subsequent enumeration via instrumental neutron activation analysis. During an 85-d (May–July) experiment, silt-sized particles were transported nonlocally to depths as much as 18 cm and formed multiple subsurface peaks. In contrast, during the same period sand-sized particles were not transported below 5 cm. During a similar experiment in the fall (July–October), the two particle sizes were transported more similarly, with the majority of tracer retained in the upper 5 cm of the bed. During both experiments

there was also evidence for head-down deposit feeding or excavation in the form of concentration minima at the sediment surface.

Structural data regarding the macrofauna, including temporal variation in abundance and depth distribution, are only moderately useful in interpreting the tracer results. The main problem lies in the lack of species-level natural history information regarding the foraging and sediment displacement activities of many of the numerically important species at the site. An especially important class of data that are missing is the macrofaunal response to time-varying carbon flux as may occur following a spring phytoplankton bloom.

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