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Conservative tracer study of horizontal sediment mixing rates in a bathyal basin, California borderland

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ABSTRACT

In situ tracer (50–125 μm plastic particles) experiments conducted using the DSV *Alvin* over a two year period in the 1240 m deep Santa Catalina Basin (eastern Pacific) have yielded near-surface (0–1.5 cm) *horizontal* bioturbation rates of order 1–10 cm^2yr^{-1}. Vertical biodiffusivities obtained from the same and similar particulate tracers at the same site are approximately an order of magnitude less. Mixing of near-surface, coarse sediment in Santa Catalina Basin is anisotropic. Deeper within the sediment horizontal bioturbation is not diffusive on a two-year time scale, but would appear to be a form of mixing termed "nonlocal symmetric" by Boudreau and Imboden (1987), whereby particles are moved appreciable distances advectively. The finding that bioturbation in near-surface sediments is anisotropic in Santa Catalina Basin and the likelihood that this phenomenon is widespread in deep-ocean sediments calls into question the present parameterization of the effect sediment mixing has on various early diagenetic processes. Specifically, the contribution of bioturbation to organic carbon remineralization rates via microbial intermediaries may be underestimated. Bioturbation rates represent more than simply vertical mass transfer coefficients and should be incorporated into models of early diagenesis accordingly.

1. Introduction

The displacement of sediment grains by organisms, i.e., *bioturbation,* influences early diagenesis in two important ways. It and sedimentation are the mass transfer mechanisms responsible for the redistribution of solids within a deposit. In the absence of biogenous sediment mixing, particles move downward at the slow sediment accumulation rates typical of the open ocean; bioturbation significantly accelerates this movement for some particles. Historically, it has been the mass transfer facet of sediment displacement that is explicitly treated in models of early diagenesis (Berner, 1980). Because bulk geochemical gradients are steepest in the vertical dimension, and time is uniquely associated with depth into the sediment, previous models of sediment mixing have focused solely on vertical mass transfer rates. Thus, particulate biodiffusion coefficients (D_b), obtained by fitting the coupled

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advection-diffusion-reaction equation to the down-core concentration profiles of a variety of radionuclides or other tracers (Goldberg and Koide, 1962; Guinasso and Schink, 1975), represent the rate of sediment mixing in the vertical dimension *only*.

Bioturbation also influences geochemical processes in a manner that does not depend on the direction of sediment movement, but only on the intensity (e.g., displacements per time). For example, displacement of a particle destabilizes pore-water microgradients surrounding that grain, thereby speeding reactions that might normally be slowed by a build-up of solutes in the immediate region. Persistent destabilization of pore-water microgradients may lead to enhanced bulk $CaCO_3$ or SiO_2 dissolution rates (Reimers, 1989). Similarly, increased rates of particle displacement, regardless of the displacement direction, have been shown to increase microbial activity (Fenchel and Jørgensen, 1977; Yingst and Rhoads, 1980), resulting in enhanced organic-carbon remineralization rates. By emphasizing bioturbation's influence on early diagenesis via vertical mass transfer, this second, *direction-independent* category of effects has been often ignored or poorly parameterized in models of early diagenesis.

A recent mechanistic decomposition of the vertical biodiffusion coefficient (D_b) and survey of animal activities that displace sediment (Wheatcroft *et al.,* 1990), suggests that sediment mixing rates in the deep ocean may be anisotropic, with horizontal rates exceeding vertical ones at the same site. This conjecture is based on the twin observations that: (1) many macrofauna in the deep sea are surface deposit feeders (Jumars and Gallagher, 1982) that transport particles predominantly in the horizontal; and, (2) many near-surface infauna and epifauna must actively forage, thus eliciting high horizontal mixing rates due to their crawling and burrowing activities (Wheatcroft *et al.,* 1990). If the rate of sediment mixing is greater in the horizontal than the vertical, the apparent contribution of bioturbation, scaled by D_b, to various geochemical processes will potentially be underestimated. That is, the direction independent consequences discussed above will be poorly parameterized. To address the potential for anisotropic mixing in deep-ocean sediments a direct comparison of horizontal and vertical mixing rates determined at a single site is needed; such a comparison forms the subject of this communication.

Part of the reason for the lack of previous measurements of horizontal bioturbation rates is that they are not easily made. There are no known sources of natural or artificial tracers (radioisotopic or otherwise) providing bulk horizontal gradients with a known geometry that can be sampled remotely from surface vessels. Thus, an *in situ* experimental approach using a submersible or ROV is required to introduce, relocate and core small-scale treatments on the deep-sea floor (cf. Krezoski, 1989). These goals were realized using the DSV *Alvin,* and the results demonstrate that near-surface (0–1.5 cm) horizontal biodiffusivities are an order of magnitude faster than vertical rates measured at a bathyal site in the eastern Pacific.

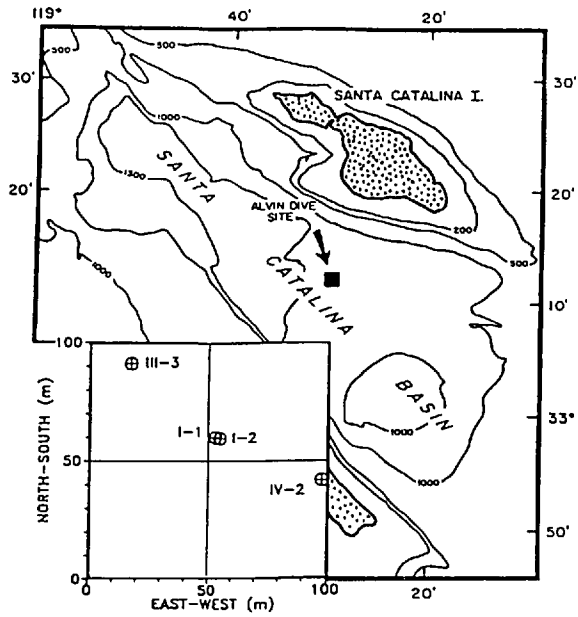

Figure 1. Bathymetric chart of Santa Catalina Basin located approximately 100 km SSW of Los Angeles, California. Inset shows relative location of treatments on the flat (<1 m of local relief) basin floor determined from a combination of dead-reckoning and *Alvin* navigation. Contours in meters.

2. Materials and methods

a. Study site. The study was conducted at a depth of 1240 m at the floor of Santa Catalina Basin (SCB), a bathyal basin in the California borderland tectonic province (Fig. 1). The benthic biology and sediment geochemistry of SCB are particularly well studied, even by shallow-water standards. Organic carbon flux to the bottom (Smith, 1987) and dissolved O_2 levels are sufficient to support an abundant and reasonably diverse benthic community (Jumars, 1976; Smith and Hamilton, 1983; Smith, 1986; Wishner and Gowing, 1987). At the study site, the endobenthic macrofauna is dominated by members of several polychaete-worm families (Paraonidae, Cirratulidae and Cossuridae) (Smith *et al.,* 1986), whereas the epibenthic megafauna is strongly dominated by the brittle star *Ophiophthalmus normani* (Smith and Hamilton, 1983; Wheatcroft *et al.,* 1989).

Sediments in SCB are a poorly sorted mixture of terrigenous and biogenous clayey-silts. The mean disaggregated grain size is 4 μm (Emery, 1960), however, *in situ* the sediment is typically packaged into fecal pellets of varying size. Wet sieving of sediments from SCB reveal that ≈70 percent of the sediment is coarser than 62 μm (C. R. Smith, pers. commun., 1991). The disaggregated coarse fraction (>62 μm) makes up 5–10 percent of the sediments by weight and is composed mainly of

radiolarians, foraminiferans, quartz grains and lithic fragments. Near-bottom currents are tidally driven and generally oriented parallel to the main axis of the basin (NW-SE). Flow velocities at 2 meters above the bottom have been measured with Savonius-type current meters to be in the range 1–5 cm s^{-1} (K. L. Smith, pers. commun., 1991).

A variety of studies, still in progress, of sediment mixing in the basin suggest that there are at least three, concurrently operating, bioturbation regimes (Smith, 1992). On time scales important to this experiment (<2 yr), the majority of sediments in SCB are mixed in a vertically diffusive manner, with D_b's ranging from 0.1 to 40 cm^2yr^{-1} (Smith *et al.,* 1988; Wheatcroft, 1991). Over two-year time-scales, the deposit feeding and burrowing activities of a motile, chirodotid holothuroid result in nonlocal mixing over cm length scales in 10–20 percent (by area) of the SCB sediments (Smith, 1992). Finally, interspersed throughout the basin are areas where sediment is mixed advectively over larger distances, apparently due to the foraging activities of an echiuran worm (C. Smith *et al.,* 1986). These zones of advective mixing are relatively easily delineated, however, by the presence of 10–20 cm high mounds and adjacent feeding depressions on the sediment surface. Because the objective of this experiment was to compare rates of horizontal and vertical *biodiffusive* mixing, treatments were located well away from the mound-depression complexes. Areas subject to mixing by chirodotids could not be excluded from the treatment areas, thus this type of bioturbation may have an impact on the results of this experiment.

b. Field and laboratory procedures. To assess horizontal mixing rates, particulate tracers with known initial and boundary conditions were introduced into the sediment. This task was accomplished using the DSV *Alvin* and specially constructed "bead implanters" (Fig. 2). Functioning as a combined cork screw and syringe, the bead implanters deposit a 15-cm long by 0.48-cm diameter, vertically oriented, rod-shaped plug of tracer particles into the sediments. Laboratory pretests confirmed that when the T handles were maintained in a stable position, tracers were restricted to a vertically oriented cylinder <1 cm in diameter.

The tracers themselves are inert (nontoxic) plastic particles called Microtaggants (3-M Corporation, Minneapolis, MN), typically used in explosives identification. Roughly prismatic in shape, their mean dimensions are 123 × 83 × 74 μm (range: 50–180 μm); specific gravity is 1.4. Their surface texture is rough, similar to that of ambient sediments in SCB. Short term feeding rate experiments demonstrate that several species, including the community dominant, the polychaete, *Levinsinia occulata,* ingest the Microtaggants on 12–48 hr time scales (D. L. Penry, pers. commun., 1991).

Particles were prewashed in fresh water to remove dust created during the production process and soaked in seawater for at least 24 h prior to use. The Microtaggants are colored blue for easy enumeration under a dissecting microscope.

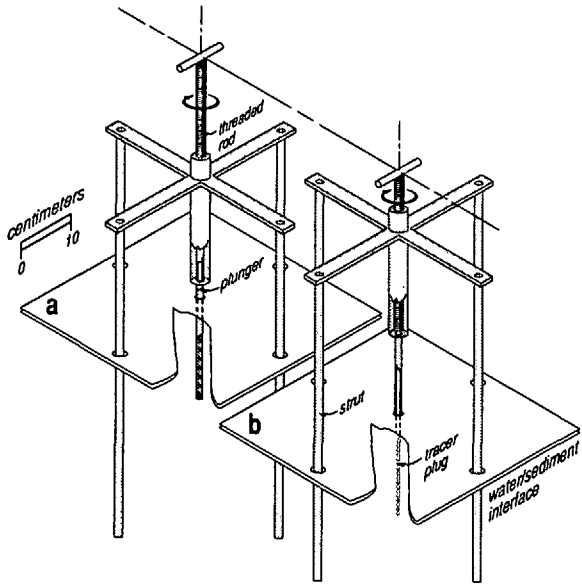

Figure 2. Schematic cartoon of the bead implanters. The device is made up of two pieces: an inner "plunger" and an outer "sleeve." The plunger consists of a T handle welded to a 1 cm diameter threaded rod attached to a 0.48 cm diameter solid plunger. The sleeve comprises a threaded large diameter (3 cm) hollow tube that is welded to a small diameter (0.48 cm i.d.) hollow tube that is open at the bottom. Welded to the central tubes are 4 "spokes" that have vertically oriented struts ≈ 50 cm long. (a) Initially, the instrument is vertically inserted into the sediment to a prescribed level positioning the hollow tube filled with Microtaggants within the sediment and the plunger tip at the water-sediment interface. Clockwise rotation of the T handle produces a torque that is countered by the 4 struts embedded in the sediment. These struts are located 16 cm from the tracer plug. (b) By maintaining the T handle vertically stationary and thus the plunger tip at the water-sediment interface, the sleeve (shaded) portion of the instrument is forced upwards, extruding the Microtaggants out the bottom of the hollow tube. The result is a cylindrical plug of tracers that is approximately 15 cm long and 0.5 cm in diameter.

Prior to a dive, Microtaggants were gently tamped into the implanters, where they were held in place during *Alvin*'s descent by a combination of inert silicon grease and a small cork. An approximately 1.5-cm long plastic toothpick was also inserted in the bottom of the implanter. This marker, located some 15 cm below the sediment surface, and thus out of the sediment mixing layer, was used to locate the plug origin.

A variety of navigation aids were used to ensure a high probability of relocating the pencil-sized treatments on the monotonous sea bottom. Three expendable acoustic transponders with different interrogation frequencies were moored in a triangular pattern at the dive site and surveyed from the RV *Atlantis II*. One of the transponders was chosen as the central marker for the dive site, allowing *Alvin* to consistently land within an approximately 400-m diameter circle. Passive acoustic triplane

Table 1. Summary of treatments.

Treatment	Implanted	Cored	Duration (d)	Problems
I-1	1-18-87 (dive 1790)	11-7-88 (dive 2134)	658	
I-2	"	"	"	
I-3	"	"	"	?implanter failure
II-1	10-28-87 (dive 1935)	11-5-88 (dive 2132)	373	corer missed
II-2	"	"	"	corer missed
II-3	"	"	"	corer missed
III-3	10-31-87 (dive 1938)	11-5-88 (dive 2132)	370	
IV-2	11-10-87 (dive 1949)	11-7-88 (dive 2134)	362	
Control	11-7-88 (dive 2134)	11-7-88 (dive 2134)	0	insert failure

reflectors formed the next level of navigational aid. These numbered markers were carried by the submersible and deployed adjacent to treatment locations. Finally, plastic stakes with numbered face plates were implanted by the submersible within 40 cm of the plug locations. Extensive photographs and verbal descriptions of the adjacent sea floor were made to ensure successful relocation of the treatments.

At intervals of approximately 1 and 1.8 yr the treatments were relocated and cored using *Alvin* (Table 1). The sampling devices are modified 20 × 20 cm Ekman corers (Rowe and Clifford, 1973), with specially machined baffles that subdivided the water column and upper 1–2 cm of the sediment into nine 44-cm^2 (square) compartments. This adaptation, along with fortuitously calm seas during all submersible recoveries, kept lateral swash to a minimum (see discussion below). A control experiment, consisting of a tracer-plug implantation followed by immediate coring was conducted during the last dive series.

On board the *Atlantis II,* after siphoning the supernatant water from each subcompartment, a 7 × 8, regularly spaced array of 1.4-cm internal diameter syringe subcores was taken to approximately 10 cm depth from each Ekman core. The leading edges of the syringes were beveled to minimize tracer subduction. Following removal of the subcores, all mud below 10 cm was passed systematically through a 1-mm sieve, and the approximate (±1 cm) location of the toothpick and hence the origin of the tracer plug was noted.

In the laboratory, syringe subsamples from each core were processed in random order. Processing consisted of vertically subdividing each syringe into increments of 0–0.5, 0.5–1.5, 1.5–3.5 and 3.5–≈ 10 cm. The sediment was then sonified for 90 s using a 250 watt Vibracell ultrasonicator to disaggregate fecal pellets and other aggregates. Pretests confirmed that the Microtaggants themselves were not broken by the

sonifier. Samples were then passed through a 44-μm Nytex sieve, thus removing the majority of the ambient sediment. The >44-μm fraction was then filtered onto ruled filter paper (8 μm nominal pore size) and transferred to a petri dish to await enumeration.

Counts were made using a Wild M-5 dissecting microscope at 12× magnification (15× oculars). By using the filter lines as visual guides, the entire filter (9.6 cm^2) was counted. The contrast between the deep blue Microtaggants and the generally white ambient particles (quartz, lithic fragments, foraminiferans and radiolarians) made counting surprisingly easy and precise. Multiple counts of samples with fewer than 50 Microtaggants were identical, while fractional uncertainties for samples with greater numbers of tracer was <10 percent.

c. Numerical and statistical analyses. Each 7 by 8 array of observed Microtaggants per subsample at the four different vertical levels was tested initially for positive spatial autocorrelation using a modified version of Moran's I (Cliff and Ord, 1981; Ebdon, 1985). The modification consisted of extending Moran's I to situations involving point values. Thus, comparisons are made between all $n(n-1)/2$ possible pairs of points, weighted by the reciprocal of their squared distances. Values of I are used in forming a standard normal deviate which is then used in tests for significance (Cliff and Ord, 1981). The rational behind testing for positive spatial autocorrelation is as follows. Organized transport mechanisms, such as diffusion or radial advection, are likely to result in tracer concentration fields in which similar values are grouped together, and thus display positive autocorrelation (i.e., there will be a large scale concentration gradient). Nonlocal symmetric mixing (Boudreau and Imboden, 1987) or various contamination processes are likely to be negatively autocorrelated or randomly dispersed, and thus have no mean large scale concentration gradient. Further analysis of the tracer data was discontinued if the one-tailed, null hypothesis of random spatial distribution in Microtaggant numbers could not be rejected ($\alpha = 0.05$).

Because there was no *a priori* reason to suspect *horizontal* anisotropy in mixing rates (i.e., the tracer concentration isopleths should be and were roughly circular in plan view), positively autocorrelated concentration fields were analyzed using the 1-dimensional diffusion equation in cylindrical coordinates, whereby tracer concentration (C) is a function of time (t) and radial distance (r) only:

$$\frac{\partial C}{\partial t} = D_{xx}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right)\right], \tag{1}$$

and D_{xx} is the horizontal biodiffusion coefficient. During the relatively short duration of the experiment (<2 yr) sedimentation rate in SCB is too slow ($\leq$10 cm kyr^{-1}) to be an important factor (Schwalbach and Gorsline, 1985).

For an instantaneous source, initially distributed uniformly through a cylinder of

radius a (implanter radius), the solution of Eq. 1 is (Crank, 1975):

$$C = \frac{C_0}{2D_{xx}t} \exp(-r^2/4D_{xx}t) \int_0^a \exp(-r'^2/4D_{xx}t) I_o\left(\frac{rr'}{2D_{xx}t}\right) r'\,dr'. \quad (2)$$

where all variables are as before, r' is a dummy variable from 0 to a, I_o is the modified Bessel function of the first kind of order zero, and C_o is the initial number of Microtaggants per unit of length in the plug cylinder. The integral in Eq. 2 was solved numerically using the Romberg method, and the Bessel function was approximated by a 4th-order even power series (Spiegel, 1968).

Due to the importance of the initial number of Microtaggants (C_o) on the results, some explanation of its computation is required. C_o was obtained by two different methods. First, size-frequency data were used to calculate the average volume of a Microtaggant. By computing the internal volume of the bead implanters per unit of length and using a porosity of 35% (standard for fine sand, Griffiths, 1967), an estimate of the number of Microtaggants per unit of implanter length was made. The second method circumvented errors associated with choosing a porosity by focusing on weights. Five replicate samples (i.e., packed each time) of Microtaggants from a 1-cm length of bead implanter were extruded onto squares of preweighed foil, oven-dried for 24 h (60°C), and weighed on a Cahn microbalance. The average Microtaggant volume and nominal density (1.4 g cm^{-3}) were then used to compute the average Microtaggant weight, thus yielding the number of Microtaggants per unit of length of implanter. Estimates of C_o from both methods were within 8 percent. Given the greater uncertainty in the former method, the value obtained through weighing was used.

The complexity of Eq. 2 precluded linearization and the use of standard parameter estimation techniques based on regression (Ratkowsky, 1990). Thus a more time-consuming yet comparably accurate method of fitting the raw data to theoretical horizontal biodiffusivities was employed. Theoretical radial concentration profiles were first generated using a range of horizontal biodiffusivities (Eq. 2). These profiles were then compared visually to the raw data to provide an initial estimate of the value of D_{xx}. Final selection of the best-fit horizontal mixing coefficient (to one significant figure) was obtained by minimizing the sum of the residuals between the $\log_{10}$-transformed observed and theoretical concentrations. Log transformation removed the disproportionate influence of near-field values on the results.

If one accepts *a priori* that horizontal mass transfer is biodiffusive, then horizontal mixing rates can be approximated in a different manner. This method uses the random-walk model of biodiffusion (Boudreau, 1989; Wheatcroft *et al.,* 1990) to calculate a mixing coefficient from the mean-square-displacement of particles. Conceptually, each Microtaggant is considered to perform a random walk over the duration of the experiment. The Microtaggant's final radial distance from the plug is then measured, squared, and the average of these values provides an estimate of the

mean-square-displacement ($\langle r^2 \rangle$). In this microscopic view of diffusion (Bockris and Reddy, 1970; Berg, 1983), the mean-square-displacement in two dimensions is related to the horizontal biodiffusivity (D_{xx}) and time (t) by

$$\langle r^2 \rangle = 4D_{xx}t. \tag{3}$$

Rearranging Eq. 3 yields

$$D_{xx} = \frac{\langle r^2 \rangle}{4t}, \tag{4}$$

which can be used to estimate the horizontal biodiffusivity.

Finally, to statistically compare horizontal and vertical (obtained from Wheatcroft, 1991) biodiffusivities from SCB, the nonparametric rank-sums test was used (Conover, 1980). In its present configuration this test is analogous to the Jonckheere test for ordered alternatives, since the number of treatments (k) is two (Hollander and Wolfe, 1973).

d. Error analysis. During shipboard and laboratory processing there are several potential sources of systematic and random error that require evaluation before the results can be presented. The first and most critical of these potential errors is horizontal movement of the cored tracers during submersible ascent and recovery. That horizontal swashing did not occur, or at least was minimal, is indicated by the patterns of tracer abundance in the surficial (0–0.5 cm) layer in the syringe subcores within a corer subcompartment. Recall that the Ekman corers had specially machined inserts that partitioned the water column and upper 1–2 cm of sediment into 9 subcompartments. If horizontal swashing was appreciable, it would homogenize the surficial distribution of tracers within a subcompartment. A gradient in Microtaggant numbers was present within most subcompartments (i.e., between adjacent syringe subcores), however, and this gradient matched the overall, core-wide trend. It is difficult to believe that swashing would have produced such patterns.

Another potential source of error is downward subduction of Microtaggants during syringe subcoring. Although the leading edges of the syringes were beveled, some subduction is inevitable. To address the magnitude of this error, laboratory tests were performed using sediments from SCB. Because the sediment fabric and shear strength could not be maintained at *in situ* conditions, sediments of two contrasting shear strengths (stiff and soupy) that bracketed SCB conditions were used. Microtaggants were settled onto the sediment surface, the supernatant water removed, and multiple syringe cores were then taken. The cores were then vertically subdivided and enumerated as previously described. Results show that 2–3 percent of the number of Microtaggants on the surface are subducted to the 0.5–3.5 cm levels, while $\leq$6.5 percent of the surface tracers were subducted to $>$3.5 cm. Thus, small numbers of Microtaggants ($\approx$5) at depth could be artifacts of syringe subcoring.

The final source of error occurred during separation of the Microtaggants from ambient sediments. Due to the extreme hydrophobicity of the Microtaggants (which also foiled attempts at magnetic separation), tracers often were caught in the 44-μm Nytex sieves or on the sieve sides. This problem was minimized by thorough cleaning between processing subcores, but some contamination was inevitable. Because the subcores were processed in random order, this problem should not have affected observed trends. It does, however, impose a lower bound on the resolution of the enumeration technique. Thus, subsamples with ≤ 5 Microtaggants were excluded from regressions.

3. Results

Four of the eight successfully implanted treatments were relocated and cored (Table 1), thus providing two long-term (658 d) and two short-term (≈ 365 d) cores for analysis and discussion. The other treatments were either missed during coring or were compromised in some other manner (Table 1). Particularly unfortunate was the fate of the control core. It was successfully implanted and cored, but the corer inserts did not reach the sediment surface. Thus, greater swashing was possible; but more damaging still, the supernatant water drained out the edges of the corer before processing started, thus spreading Microtaggants over a large portion of the sediment surface. These problems rendered the control results equivocal. As will shortly be shown, however, the patterns of tracers in the control were sufficiently unlike the treatments to lend confidence in the latter.

a. Spatial autocorrelation. Data were initially tested for two-dimensional, positive autocorrelation using Moran's I modified for point data. Results (Table 2) indicate that a random distribution of Microtaggants could be rejected confidently in nearly all of the upper two levels (0–0.5 and 0.5–1.5 cm) of the treatment cores (the 0.5–1.5 cm level in Core I-2 is the exception). Positive (or negative) spatial autocorrelation was not the case for the control core or for most of the deeper (> 1.5 cm) intervals of the treatment cores. In some instances (cores I-1, 1.5–3.5 cm and III-3, 1.5–3.5 cm) positive spatial autocorrelation was due to the inclusion of a large number of adjacent zero values (i.e., the absence of tracer). If Moran's I was computed using only non-zero data, then the null hypothesis of a random distribution of Microtaggants could not be rejected in those cores as well.

This screening procedure indicates that the Microtaggant concentration fields in the upper (0–0.5 and 0.5–1.5 cm) depth intervals of the treatment cores are positively autocorrelated, while the lower levels (> 1.5 cm) are either not autocorrelated or devoid of significant numbers of Microtaggants. Randomness in the control data, which underwent significant swashing, could not be rejected. Because the tracer data are not randomly distributed, it is unlikely that physical swashing was responsible for their dispersal. Instead, the likely cause for the observed positive autocorrelation in the near-surface tracer data is horizontal, biogenous mixing of sediment.

Table 2. Results of modified Moran's I test for spatial autocorrelation for point data using an inverse-squared weighting function. Test is one tailed for positive autocorrelation ($\alpha = 0.05$).

Treatment	Depth interval (cm)	Moran's I	p-level
Control	0–0.5	0.046	NS
	0.5–1.5	0.057	NS
	1.5–3.5	0.028	NS
	>3.5	0.015	NS
I-1	0–0.5	0.251	<0.001
	0.5–1.5	0.075	<0.01
	1.5–3.5	0.216	<0.001
	>3.5	−0.054	NS
I-2	0–0.5	0.127	<0.005
	0.5–1.5	−0.026	NS
III-3	0–0.5	0.162	<0.001
	0.5–1.5	0.142	<0.001
	1.5–3.5	0.004	NS
	>3.5	0.072	<0.05
IV-2	0–0.5	0.133	<0.001
	0.5–1.5	0.110	<0.005
	1.5–3.5	0.125	<0.001
	>3.5	0.047	NS

b. Horizontal biodiffusion coefficients. Illustrated in Figures 3–6 are the number of observed Microtaggants per subcore plotted as a function of radial distance from the plug center. As the patterns in spatial autocorrelation suggested, the upper two depth intervals typically revealed significant gradients in tracer numbers as a function of radial distance. The data are rather noisy, especially in the far-field, requiring an explanation as to the source of the curves in the figures. In those cores and depth intervals that could be fitted with a horizontal biodiffusivity, the solid curve is the D_{xx} that yields the lowest sum of the residuals. The dotted curves are theoretical concentration profiles for D_{xx}'s an order of magnitude smaller (fine dotted lines) and larger (coarse dotted lines) than the best-fit D_{xx}. For example, in Core I-1 (0–0.5 cm) the data best match a D_{xx} of 2 cm^2yr^{-1}, and thus the dotted curves correspond to horizontal biodiffusivities of 0.2 and 20 cm^2yr^{-1} (Fig. 3). These latter curves are included to illustrate that the best-fit D_{xx}'s are good to an order of magnitude. Thus, overall, the results indicate that horizontal bioturbation rates in the near-surface sediments calculated by fitting gradients to the data are of order 1 cm^2yr^{-1} and range from 0.4 to 10 cm^2yr^{-1}.

Transport below 1.5 cm depth in the sediment is not horizontally diffusive in character (Figs. 3–6). In the lowest two depth intervals, there is either a complete lack of Microtaggants in the far field (e.g., Core I-2) or the number of Microtaggants per subcore is "lumpy" with significant amounts (more than subduction due to the syringe subcoring could explain) of tracer occurring in isolation far from the plug

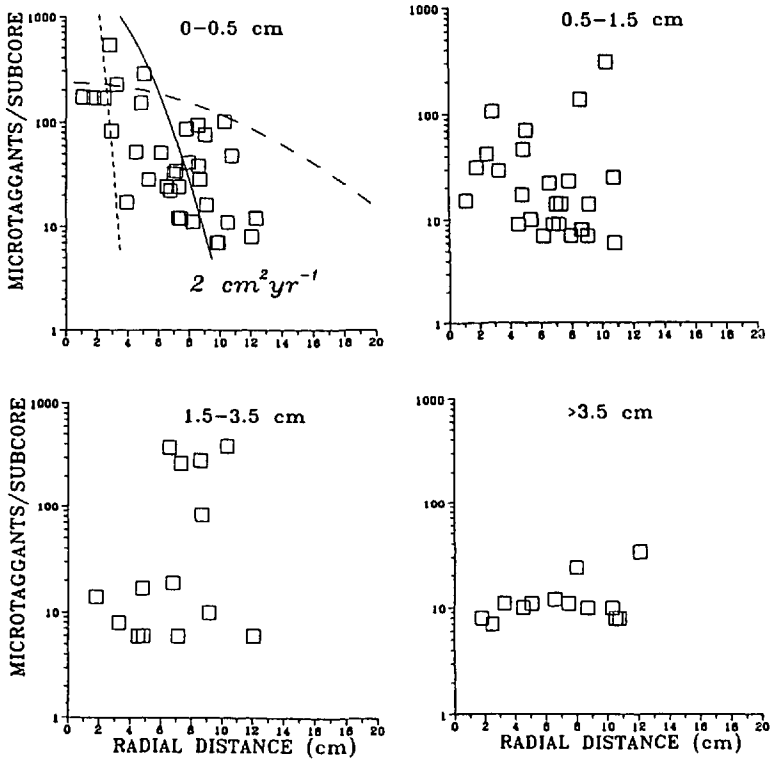

Figure 3. Core I-1 (658 d): Observed Microtaggant numbers per subcore plotted as a function of radial distance from the plug. Solid curve in depth interval 0–0.5 cm (upper left) represents a theoretical horizontal biodiffusivity of 2 cm^2yr^{-1}, dashed curves depict D_{xx}'s an order of magnitude smaller (short dashes) and larger (long dashes).

(e.g., Core IV-2, Fig. 6). There are at least two mechanisms by which significant numbers of Microtaggants can be transported into the far field. The first, is "nonlocal symmetric" (Boudreau and Imboden, 1987) horizontal transport of tracers within a given depth interval. The other is horizontal transport of tracers at the sediment surface followed by vertical transport to depth, via either passive burrow filling or reverse conveyor-belt deposit feeding (Wheatcroft *et al.,* 1990). Given the present experimental setup, it is not possible to distinguish between these two mechanisms, and both appear equally plausible.

An alternative to the gradient approach of computing biodiffusivities is to focus on the mean-square-distance, $\langle r^2 \rangle$, that the Microtaggants have traveled. Conceptually, this method treats each Microtaggant as if it had completed a 2-dimensional random walk. The radial distance from the plug is then measured and the mean-square-distance computed by averaging over the total number of Microtaggants observed at each depth interval in each core. Knowing the total elapsed time allows computation of D_{xx}, via equation 4 (Table 3). The resultant horizontal biodiffusivities are compara-

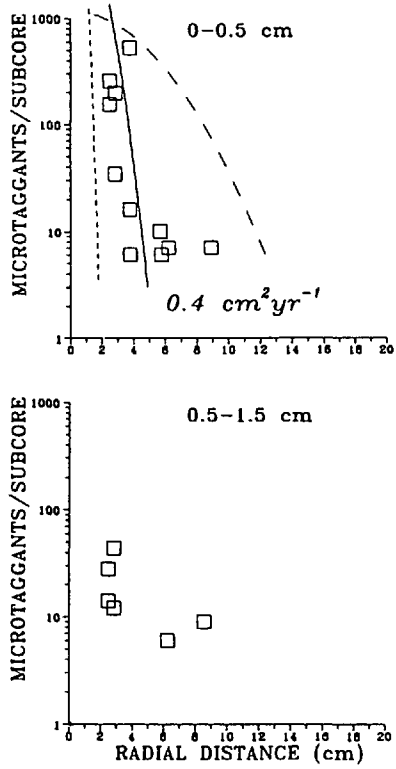

Figure 4. Core I-2 (658 d): Observed Microtaggant numbers per subcore plotted as a function of radial distance from the plug. Curves are as in Figure 3. No tracers were observed in the lower depth intervals (i.e., > 1.5 cm).

ble to those obtained via the gradient approach, but slightly higher. The overall result remains unchanged, however: horizontal mixing rates in the near-surface sediments of SCB are of order 1–10 cm^2yr^{-1}.

4. Discussion

To assess the importance of the initial findings reported herein, comparison must be made with vertical biodiffusivities estimated at the same site. Although radionuclide-(^{210}Pb, ^{228}Th and ^{234}Th) derived D_b's are available from SCB (Smith *et al.*, 1988), they are not used as a comparison to the horizontal biodiffusivities due to probable biases associated with their different decay rates and their association with finer particles (Smith *et al.*, 1988). Instead comparisons are made with D_b's determined from other conservative, particulate tracers: Microtaggants and spherical glass beads of similar size (62–420 μm) (Wheatcroft, 1991). Both types of tracer were spread onto the SCB seafloor and cored at intervals from 0.8 to 2.7 yr using *Alvin* [see Wheatcroft (1991) for greater detail]. Vertical biodiffusivities were computed using

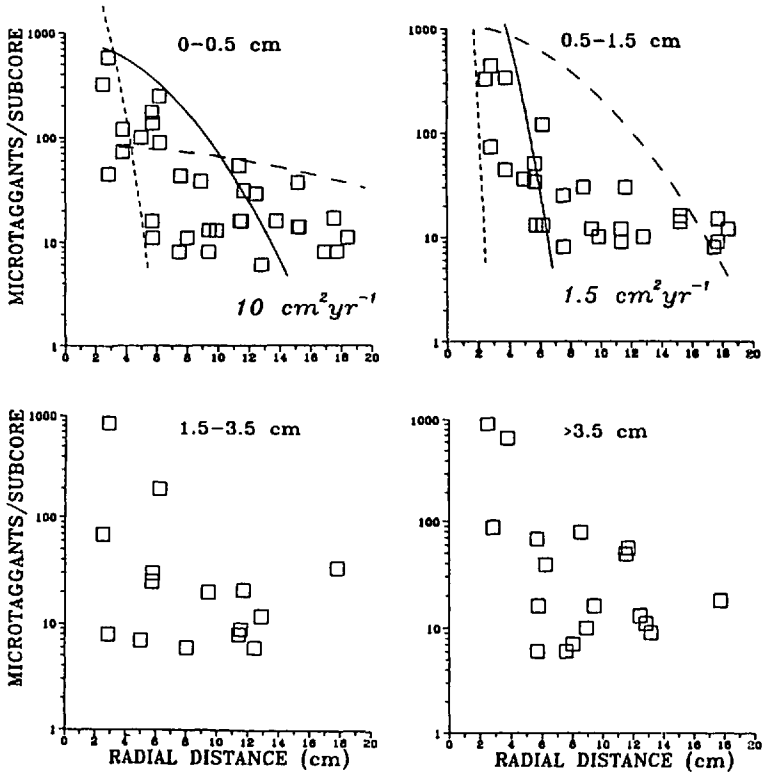

Figure 5. Core III-3 (370 d): Observed Microtaggant numbers per subcore plotted as a function of radial distance from the plug. Curves are as in Figure 3.

the gradient and the mean-square-displacement methods, both of which yield nearly identical results. Although the vertical biodiffusivities are derived from three different types of tracer: Microtaggants (raw data courtesy of C. R. Smith, University of Hawaii), 62–125 μm glass beads and 126–420 μm glass beads (Wheatcroft, 1991), there is no detectable difference among them.

To make an overall comparison between horizontal and vertical rates, all of the vertical D_b's were pooled into one category and compared, using the one-tailed rank-sums test, to the measured horizontal mixing rates (D_x's). In its present configuration, with $k = 2$ treatments (horizontal and vertical biodiffusivities), this test is identical to the Jonckheere test for ordered alternatives (Hollander and Wolfe, 1973). The results (Table 4) indicate that the null hypothesis, that vertical mixing rates are greater than or equal to horizontal mixing rates, can be rejected with a high level of confidence ($p = 0.004$). The mean horizontal mixing rate (±1 standard error) from Table 3 is 5 cm^2yr^{-1} ± 1.5 cm^2yr^{-1} compared to the mean vertical mixing rate of 0.5 cm^2yr^{-1} ± 0.25 cm^2yr^{-1}.

Elaboration on two points is required before discussing the implications of these

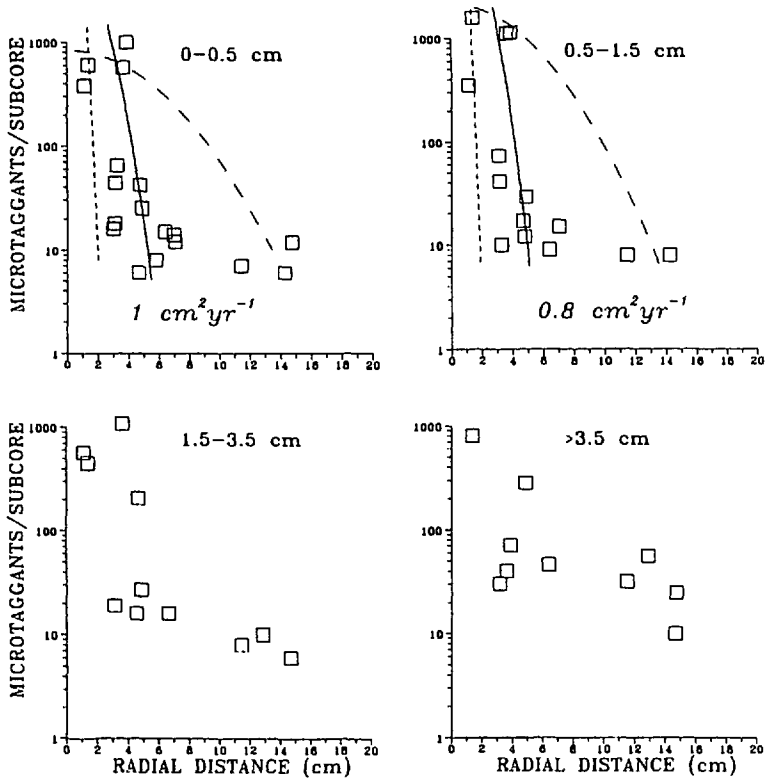

Figure 6. Core IV-2 (362 d): Observed Microtaggant numbers per subcore plotted as a function of radial distance from the plug. Curves are as in Figure 3.

data. First, an issue of some importance in this particular study, and in bioturbation research in general, is how faithfully a tracer represents the transport kinetics of the "bulk" sediments. In some respects, an ideal tracer does not exist for sedimentary systems, because they are nearly always a complex mixture of different mineralogies, grain sizes, organic and microbial coatings, etc. Animals respond in complex and incompletely understood ways to these attributes (Wheatcroft and Jumars, 1987;

Table 3. Summary of microscopic transport parameters and the resultant horizontal biodiffusivities [see text and Wheatcroft *et al.* (1990) for greater detail].

Core	Depth interval	$\langle r^2 \rangle$ (cm^2)	Time (yr)	D_{xx} (cm^{2}yr^{-1})
I-1	0–0.5	30.6	1.80	4.2
I-2	0–0.5	11.2	1.80	1.5
III-3	0–0.5	42.6	1.01	10.5
	0.5–1.5	33.7	1.01	8.3
IV-2	0–0.5	12.0	0.99	3.0
	0.5–1.5	9.4	0.99	2.4

Table 4. Summary of horizontal (D_{xx}) and vertical (D_b) biodiffusivities calculated from the mean-square-displacement (microscopic) method. In parentheses are ranks used in the one-tailed rank-sums test (Conover, 1980) to compare the magnitude of the different biodiffusivities. The raw data for cores denoted by an asterisk are courtesy of Craig Smith, University of Hawaii.

D_{xx} source	D_{xx} (cm^2yr^{-1})	D_b (cm^2yr^{-1})	D_b source
Core I-1 (0–0.5 cm)	4.2(10)	0.05(1)	Core 1937-2 (126-420 μm)
Core I-2 (0–0.5 cm)	1.5 (6)	0.43(5)	Core 1937-3 (62-125 μm)
Core III-3 (0–0.5 cm)	10.5(12)	0.17(3)	Core C-1934-1*
Core III-3 (0.5–1.5 cm)	8.3(11)	1.7 (7)	Core C-1934-2*
Core IV-2 (0–0.5 cm)	3.0 (9)	0.37(4)	Core 1937-1 (62–125 μm)
Core IV-2 (0.5–1.5 cm)	2.4 (8)	0.16(2)	Core 1937-1 (126–420 μm)

Smith *et al.*, 1988; Wheatcroft, 1991). Thus, an integrative measure such as a vertical or horizontal biodiffusivity should be considered with a measure of caution, and the tracer from which it was derived must always be kept in mind.

In this context, the tracer used in this study is by no means ideal. The Microtaggants differ in size, specific gravity, shape, composition, and surface characteristics from some proportion of the ambient sediments. In some instances, these differences are large and probably important. For example, the average Microtaggant is approximately an order of magnitude larger than the mean disaggregated grain size in SCB (see Methods section). Wheatcroft (1991) has presented evidence that vertical mixing rates are size-dependent in SCB, with vertical biodiffusivities for the 8–16 μm fraction an order of magnitude larger than the 125–420 μm fraction. Therefore, it is likely that the *absolute* horizontal and vertical rates measured in this study are less than the bulk sediment mixing rates in SCB. The important point is that the rates derived from the Microtaggants are anisotropic, with near-surface horizontal rates greater by an order of magnitude. Furthermore, there is no reason not to believe that horizontal mixing rates are size-dependent also, although there is no evidence yet available to support this conjecture. The more crucial question for this study is whether the direction (i.e., dominance in vertical or horizontal) and degree of anisotropy of mixing rates differs between the Microtaggants and the ambient sediments. At present there is no *a priori* reason to suspect such an effect.

The second issue is the potential for physical transport of the Microtaggants. Movement of tracers in SCB in both horizontal and vertical directions is likely due solely to biological processes. This assertion is based on conservative calculations of the critical shear velocity (U^*_{cr}) (Raudkivi, 1976) required to move the smallest (50 μm) Microtaggants that yield $U^*_{cr} \approx 0.5\ cm\ s^{-1}$. Assuming smooth turbulent flow and a logarithmic velocity profile, this shear velocity translates to flow velocities of $\approx 15\ cm\ s^{-1}$ at a height of 2 meters above the bottom. The tidally driven, bidirectional current velocities measured in SCB at the same vertical height are in the range of $1–5\ cm\ s^{-1}$ (K. L. Smith, pers. commun., 1991), at least a factor of three less than that

required to physically transport the Microtaggants. Moreover, the tracer data themselves are not indicative of physical transport, because the concentration isopleths are roughly circular, not markedly elongated as one would expect from bidirectional flows.

The finding that near-surface (0–1.5 cm) horizontal bioturbation rates in SCB are an order of magnitude greater than vertical rates is not entirely surprising given the composition of the SCB benthic community (Jumars, 1976; Smith and Hamilton, 1983; Smith, 1986; Smith *et al.,* 1986; Wheatcroft *et al.,* 1989) and their likely mechanisms of sediment displacement (Wheatcroft *et al.,* 1990). The epibenthic megafauna of SCB is strongly ($\approx 99\%$) dominated by the brittle star *Ophiophthalmus normani,* which occurs at densities of approximately 16 m^{-2} (Smith and Hamilton, 1983; Wheatcroft *et al.,* 1989). This brittle star is an active forager, often moving at high rates (≈ 50 cm min^{-1}; pers. obs.) across the sediment surface in response to a variety of cues (see Smith and Hamilton, 1983). Locomotion in nearly all ophiuroids consists of a rowing-like action, in which pairs of arms are alternately moved forward and the body drawn up behind (see Fig. 117 in Schäfer, 1972). Thus, *O. normani* is likely to move sediment grains horizontally over small step lengths at high frequencies (short rest periods) (Wheatcroft *et al.,* 1990), yielding appreciable horizontal biodiffusive transport rates.

Other epibenthic and near-surface megafauna (see Smith and Hamilton, 1983; Wheatcroft *et al.,* 1989) will further contribute to horizontal mass transfer rates via their locomotory activities. A noteworthy animal, because its abundance is likely to be underestimated in photographic surveys, is the chirodotid holothuroid, *Chirodota* cf. *pacifica* (Wheatcroft *et al.,* 1989). This animal (≈ 5 cm long) burrows horizontally 1–3 cm below the sediment surface (Smith, 1992; pers. obs.), where it probably deposit feeds. Because step lengths due to deposit feeding normally scale with body length (Wheatcroft *et al.,* 1990), it most likely transports particles horizontally and vertically (Smith, 1992) in a nonlocal fashion and may be responsible for the isolated patches of tracers observed in the far field in some of the cores.

Given the complexities involved in measuring horizontal mixing rates, it is not surprising that there are few previous studies having results germane to this study. Smith and Schafer (1984) measured excess ^{210}Pb activity on 1 cm intervals in the vertical and horizontal dimensions in two subcores of a box core raised from the middle slope off Newfoundland. Vertically, most of their profiles are consistent with simple biodiffusive mass transfer (i.e. display negative exponential gradients), but there are cases in which the ^{210}Pb activity in the upper 4 cm is uniform. This type of mixing corresponds to an instantaneously mixed box model (cf. Berger and Heath, 1968). In another case there is a subsurface peak in ^{210}Pb activity at about 10–11 cm which may be due to reverse conveyor-belt mixing (J. Smith *et al.,* 1986; Wheatcroft, 1991). The vertical data demonstrates forcefully the small-scale heterogeneity characteristic of deep-sea bioturbation. The meaning of Smith and Schafer's (1984)

horizontal data is less easy to interpret. There are no systematic horizontal gradients in ^{210}Pb activity, but this finding is equivocal, since it could mean that horizontal mixing rates are high enough to destroy any gradients or that there never were any gradients. Computation of the coefficient of variation (a measure of variance when means are different) of the ^{210}Pb activities within a given depth interval shows that the surface values are slightly less than subjacent levels. This could be taken as evidence for higher horizontal mixing in the surficial sediments, a result compatible with the present study, but the differences are slight.

The only other study that has addressed horizontal mixing of sediments, focused on bioturbation in profundal Lake Superior using a novel tracer technique. Krezoski (1989) used a submersible to deploy pellets of sediment that were spiked with the rare earth element samarium. He returned 23 d later, tube cored around his treatment and quantified the amount of samarium. Two problems make his results inappropriate for bioturbation studies: (1) the size of this pellet (20 cm diameter) was such that it likely had a negative impact on the benthic fauna, and (2) there is strong evidence that physical transport occurred (Krezoski, 1989). Despite these problems, his approach is a promising one as it solves many of the problems of using exotic particles that were encountered in this study.

Anisotropy in sediment mixing rates, whereby particles are displaced more frequently and dispersed over greater distances per unit of time in the horizontal than vertical, has many important biological and geochemical consequences. For the purpose of further discussion, the ramifications of anisotropic mixing are subdivided into those that depend on the directionality of movement and those that depend solely on the intensity of particle motion. The most obvious *directionally* dependent consequence of greater horizontal mixing rates is that surface traces will have shorter residence times than models based on vertical D_b's would predict (Wheatcroft *et al.*, 1989). Thus, trace residence times are likely to be on the order of days to weeks, rather than months to years as previously postulated (Heezen and Hollister, 1971; Mauviel and Sibuet, 1985). Time-lapse photographic studies of the ocean floor from a variety of locations (Rowe *et al.*, 1974; Paul *et al.*, 1978; Thorndike *et al.*, 1982; Gardner *et al.*, 1984; Lampitt, 1985; Wheatcroft *et al.*, 1989) appear to support this assertion.

Because the spatial distribution of bottom stress, the ultimate determinant of where a particle stops, is markedly influenced by bottom roughness, rapid and continual smoothing of microrelief on the deep-sea floor will also influence the distribution of newly arriving particulate material. Recently, several workers have observed that low-density aggregates collect within negative relief features (e.g., pits and open burrows, Aller and Aller, 1986; Mauviel *et al.*, 1987) or in the lee of positive relief features (e.g., mounds and trails, Lampitt, 1985; Reimers and Wakefield, 1989), both of which are areas of locally reduced bottom stress. In fact, some animals build pits that function as bedload traps to exploit this resource (Nowell *et al.*, 1984;

Jumars *et al.,* 1990). If not quickly consumed by heterotrophs, these localized concentrations of labile organic matter will materially affect local remineralization rates (Aller and Aller, 1986; Reimers, 1989), as well as influence microbial and meiofaunal distributions and abundances (Aller and Aller, 1986). The longevity of some of these biogeochemical "hot spots" (e.g., open burrows) cannot be disputed, as evidence of them is frequently preserved in the sedimentary record. It is likely, however, that high horizontal mixing rates continuously destroys and creates microrelief at rates that precludes the buildup of significant quantities of labile material and hence localized changes in reactivities.

High horizontal mixing rates also preclude the maintenance of bulk horizontal gradients of a variety of chemical species (e.g., various radionuclides or alkalinity). Thus, the widespread implicit assumption that surficial radionuclide activities are laterally uniform (Stordal *et al.,* 1985) appears to be safe, although persistent negative relief features (open burrows) discussed above may be exceptions. Homogenization of surficial sediment also has important implications for the foraging ecology of both subsurface and surface deposit feeders (Jumars *et al.,* 1990). Subsurface deposit feeders, especially head-down, conveyor-belt species (Rhoads, 1974; Wheatcroft *et al.,* 1990) will obtain particles of average surficial sediment composition rather than locally determined food sources. That is, vertical particle motions within their convective cells will be decorrelated by horizontal mixing (Wheatcroft *et al.,* 1990).

Enhanced biogenous horizontal transport of particles also effectively increases the foraging area of sessile, surface deposit feeders, in a manner analogous to physical sediment transport (Miller *et al.,* 1984; Miller and Sternberg, 1988). Stated in a different way, more particles pass within a surface deposit feeder's foraging area per unit of time, increasing potential food resources. Or do they? The effect may not be as important as a simple application of horizontal biodiffusivities might imply, because in many cases deposit feeders are causing the elevated horizontal transport rates. Thus, increases in particle and hence nutrient transport rates are only obtained at the expense of greater utilization of nutrients by deposit feeders. This same situation is often over looked in models of organic matter diagenesis. In these models, an increase in vertical mixing rate is postulated to result in increased preservation of organic carbon, because elevated D_b's ostensibly transport more carbon deeper, where anaerobic degradation rates are slower (Emerson *et al.,* 1985; Emerson and Hedges, 1988). The cost of increased vertical or horizontal biodiffusivities, however, must be paid by increased assimilation of organic material by deposit feeders. Thus, enhanced vertical mixing rates may not have the postulated affects on carbon preservation, or at least these influences will be less than predicted (cf. Aller, 1990). Future studies that address organic carbon preservation must strive to isolate the effects of mass transfer due to bioturbation *per se* from assimilation due to

Table 5. Directionally dependent rest periods (Ω) computed from the observed horizontal and vertical biodiffusivities using a step length of 0.25 cm.

D_x (cm^2yr^{-1})	Ω_x (d)	D_b (cm^2yr^{-1})	Ω_z (d)
4.2	1.4	0.17	67
1.5	3.8	1.7	6.7
10.5	0.5	0.37	31
8.3	0.7	0.16	71
3.0	1.9	0.05	228
2.4	2.4	0.43	27
	$\langle\Omega_x\rangle = 1.8\,d \pm 0.5\,d$		$\langle\Omega_z\rangle = 72\,d \pm 33\,d$

deposit feeding. Studies such as Kristensen and Blackburn's (1987), with more realistic mixing regimes, are a first step in this direction.

I now turn to the other category of potential anisotropic mixing effects, namely those that are independent of the direction of sediment movement, and depend only on the intensity of motion. Greater horizontal mixing rates of near-surface sediments imply that those sediments are moved more frequently (i.e., have shorter rest periods) than vertical biodiffusivities would suggest. To gain some appreciation for the magnitude of this effect, Table 5 lists directionally-dependent rest periods based on the horizontal and vertical biodiffusivities obtained in this study. An arbitrary step length (Wheatcroft *et al.,* 1990) of 0.25 cm was chosen for both horizontal and vertical motion. Thus, large, near-surface particles are horizontally displaced, on average, every 1.8 d, while vertical displacements occur much less frequently, occurring every 72 d (Table 5). This difference in rest periods of some 40-fold is due not only to the higher biodiffusivities in the horizontal, but also to the added dimension in horizontal (2-D) versus vertical (1-D) mixing. A biodiffusion coefficient is made of a squared step length divided by an integer multiple of the rest period (Wheatcroft *et al.,* 1990), the value of which depends on the number of dimensions in the problem (i.e., $D_b = \delta^2/N\Omega$, where $N = 2$, 4 or 6, for one, two and three-dimensional diffusion, respectively). Thus, equivalent biodiffusivities in one and two-dimensional systems yield horizontal rest periods one half the value of vertical rest periods, since to fill the greater space in 2 dimensions requires more frequent steps (Ghez, 1988). As stated earlier, this exercise is purely illustrative, since the value used for the step length and their dimensional equivalence is not known. It is likely, however, that horizontal step lengths are less than vertical ones (Wheatcroft *et al.,* 1990); thus the difference in rest periods may be even more significant.

Greater frequency of particle displacements has potentially important implications for calcareous and siliceous microfossil dissolution rates. For example, Aller (1982) has shown that dissolution of $CaCO_3$ in Long Island Sound is most extensive in highly bioturbated areas where alkalinity build-up is prevented by enhanced pore-water irrigation and the oxidation of solid-phase sulfides during particle reworking. Although horizontal mixing will not likely bring iron sulfide-rich sediment

to the surface where it oxidizes releasing sulfuric acid, a process required in Aller's (1982) model, enhanced solid-phase mixing, regardless of its directionality, does lead to enhanced pore-water movement. It is impossible to move solids through a fluid without disrupting the fluid to some degree. Thus, pore-water microgradients (i.e., those approaching the scale of individual particles) will be kept in a state of disequilibrium, increasing benthic exchange rates of solutes involved in reactions normally slowed by stable pore-water concentrations (Reimers, 1989). This disequilibrium is apt to lead to greater $CaCO_3$ (Aller, 1982), as well as SiO_2 dissolution rates (Schink *et al.,* 1975).

Finally, enhanced displacement frequency of sediments due to horizontal mixing will affect organic carbon degradation rates via microbial intermediaries (Plante *et al.,* 1990). It has been known for some time that elevated rates of deposit feeding in particular, and bioturbation in general, lead to enhanced microbial activity (Fenchel and Jørgensen, 1977; Yingst and Rhoads, 1980; Valiela, 1984; Kristensen and Blackburn, 1987). Metazoans increase microbial remineralization rates by both digesting and respiring bacterially assimilated organic matter and by making room for more active, faster growing (and respiring) microbes. In addition, waste products are removed more effectively due to enhanced particle motion and in some instances particle size is reduced, thus increasing the surface area available to microbes. These relationships underscore the problem of decoupling organic carbon degradation rates from bioturbation rates as is commonly done in models of organic matter diagenesis (Emerson *et al.,* 1985; Murray and Kuivila, 1990). Models that explicitly couple the effects of metazoan mixing rates with microbial response and hence organic carbon decay rates are a logical, but challenging next step.

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