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EFFECT OF DEPOSIT FEEDERS ON MIGRATION OF ^{137}Cs IN LAKE SEDIMENTS

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Illite clay particles with adsorbed ^{137}Cs were added as a submillimeter layer to the surface of silt-clay sediments contained in rectangular Plexiglas cells stored in a temperature-regulated aquarium, in order to trace the effect of the oligochaete, *Tubifex tubifex*, and the amphipod, *Pontoporeia hoyi*, on mass redistribution near the sediment-water interface. A well-collimated NaI gamma detector scanned each sediment column (~10 cm deep) at daily or weekly intervals for six months, depicting the time evolution of radioactivity with and without added benthos. In a cell with tubificids ($\sim 5 \times 10^4$ m^{-2}), which feed below 3 cm and defecate on surface sediments, the labeled layer was buried at a rate of 0.052 ± 0.007 cm/day (20°C). When labeled particles entered the feeding zone, ^{137}Cs reappeared in surface sediments creating a bimodal activity profile. In time, the activity tended toward a uniform distribution over the upper 6 cm, decreasing exponentially below to undetectable levels by 9 cm. In a cell with amphipods ($\sim 1.6 \times 10^4$ m^{-2}) uniform activity developed rapidly (~17 days) down to a well-defined depth (1.5 cm). The mixing of sediments by *Pontoporeia* is described by a simple quantitative model of eddy diffusive mixing of sediment solids. The value of the diffusion coefficient, 4.4 cm^2/yr (7°C) was computed from a least squares fit of theoretical to observed profile broadening over time. In a cell without benthos, small but measurable migration of ^{137}Cs indicated an effective molecular diffusion coefficient of 0.02 cm^2/yr.

1. Introduction

Both marine and freshwater macrobenthos have considerable influence on the sediments in which they dwell. Through their life activities, such as feeding, defecation, respiration, and movement, these organisms affect the physical and chemical nature of sediments [1–8], and can have a profound effect on the stratigraphic record [9–14].

The deposit feeding macrobenthos are particularly important substratum modifiers. "Conveyor-belt" species [6] feed below the oxidation-reduction discontinuity and defecate at the sediment-water interface, providing a direct link between two distinctly different biogeochemical regimes. Tubificid oligochaete worms possess this life mode and are abundant in many lakes and rivers. Other burrowing deposit feeders, such as crustacean amphipods, feed on near-surface sediment and move through surficial sediments in a plow-like manner [33]. Both of these organisms occur in abundance in the Great Lakes [15–18].

Experimental work on the role of macrobenthos in the mixing and redistribution of sediment solids and interstitial water in freshwater sediments has centered almost exclusively on the oligochaetes, and has been concerned with the determination of fecal pellet evolution rates under various environmental conditions. Two approaches have been used: either evolved fecal pellets are collected for volumetric and/or mass determination, or the burial and redistribution of a distinctive marker horizon is measured. In fecal pellet collection methods, tubificids are manipulated so that the evolved feces may be easily distinguished from the sediment substratum and removed for analysis. Segregation of feces from the substratum has been accomplished either by removing the tubificids from the

sediment [19] or by inverting a stramin capped vial containing sediment and tubificids over a collection vessel [20,21]. In marker horizon studies, a layer distinguishable in some way from the sediment matrix is placed at or below the surface of the substratum. Then its rate of burial and redistribution under the influence of an introduced macrobenthos population is monitored. A variety of marker horizon types have been used including colored particles [22–24], pollen grains [11], and radioactively labeled materials [25].

These methods have substantial shortcomings. The effects of organism movement through the sediment, compaction, and diagenesis of the fecal pellets are completely neglected in fecal pellet collection studies. Marker horizon experiments address the problem of compaction and diagenesis of fecal pellets, and may be conducted in the field [23,26]. However, the progress of a marker horizon composed of colored particles can be followed only as it falls to the zone of maximum tubificid feeding. Thereafter, colored particle concentration becomes too low to follow details of the mixing process. Attempts to quantitatively describe sediment redistribution by tubificids have either required that the experimental cell be destroyed for analysis [11], or involved considerable guesswork by the investigator [23]. In order to understand in detail the effects of bioturbation it is necessary to devise a method whereby the experimental cell may be monitored frequently, non-destructively, and with high resolution. Ideally, the organisms should not be able to differentiate between marker horizon material and the surrounding sediment matrix. Here we report on the development of a suitable method and on initial results using both tubificid worms and the amphipod, *Pontoporeia hoyi* (= *Pontoporeia affinis*, see Segerstråle [27]).

TABLE 1

Bulk density and fractional dry weight of sediments in experimental cells

Depth interval (cm)	Control		Tubificids		Amphipods	
	ρ_b	F_d	ρ_b	F_d	ρ_b	F_d
0–0.5	1.17	0.35	1.32	0.21	1.19	0.26
0.5–1.0	1.39	0.34	1.41	0.33	1.25	0.34
1.0–1.5	1.71	0.44	1.33	0.34	1.54	0.38
1.5–2.0	1.64	0.57	1.45	0.36	1.39	0.38
2.0–2.5	1.41	0.47	1.46	0.39	1.60	0.38
2.5–3.0			1.33	0.41	1.65	0.38
3.0–3.5	1.44	0.48	1.67	0.45	1.54	0.38
3.5–4.0			1.76	0.47	1.46	0.42
4.0–5.0	1.66	0.48	1.47	0.50	1.30	0.37
5.0–6.0	1.71	0.49	1.42	0.53	1.63	0.37
6.0–7.0	1.56	0.48	1.32	0.52	1.43	0.42
7.0–8.0	–	–	1.44	0.52	–	–

ρ_b in g wet weight/cm^3; F_d in g dry sediment/g wet sediment

2. Methods

2.1. Labeled clay particles

The gamma-emitting radionuclide ^{137}Cs is ideally suited for high-resolution non-destructive radiotracer studies because of its long half-life (~30 years), its gamma energy (661 keV) which is sufficient to practically eliminate sediment self-absorption effects, and its high affinity for certain clay minerals (illite) which occur naturally in sediments of the Great Lakes [28, 29]. ^{137}Cs is not only strongly adsorbed to the surface of illite, but is apparently incorporated into mineral lattice sites where it is effectively immobilized [30, 31]. Thus the nuclide, incorporated on or into illite clay particles, can be expected to trace the movement of sediment solids. Labeled clay was prepared by adding about 70 μCi of carrier-free ^{137}Cs to a distilled water suspension of sieved (<62 μm) illite-rich sediment (~10 g) derived from the Chagrin Shale member of the Ohio Shale. The suspension of activated clay was kept at an elevated temperature (~100°C) for several weeks on the untested assumption that prolonged exposure to increased temperatures would accelerate the migration of ^{137}Cs into mineral lattice sites and therefore enhance the extent of fixation. Following the procedure, the labeled illite was isolated by decanting and then resuspended in 250 ml of 1 M non-radioactive CsCl (~20°C) to remove easily exchangeable radioactive cesium ions. Very little ^{137}Cs (<1%) was desorbed from the illite during the four days of this treatment. After about six months, the distribution coefficient for desorption was measured by suspending 0.1 g (dry weight) of the labeled illite in 100 ml of filtered interstitial water and after an elapsed time of one month determining the activity of the filtered water (with appropriate corrections

for filter uptake, etc.) relative to that remaining on the illite.

2.2. Experimental cells

Plexiglas cells (25.40 cm × 5.08 cm × 1.27 cm) with 0.16-cm-thick walls were loaded with fine-grained sediment (sieved to ≤250 μm) collected from either Lake Erie near Ashtabula, Ohio (tubificid experiment) or from Saginaw Bay, Lake Huron (amphipod experiment). The sediment was allowed to compact and additional sediment was added until a stable 15-cm-high column was established. The bulk density and fractional dry weight of the sediments given in Table 1 are comparable to values found in undisturbed sediments from the collection sites. A submillimeter layer of labeled illite (~1 μCi ^{137}Cs) then was added with a Pasteur pipet. Completed cells were transferred to a temperature-controlled (20° ± 1°C) 40-liter (tap water) aquarium equipped with activated charcoal filters and several bubblers for adequate aeration. Each cell was itself equipped with a small bubbler to insure complete exchange of water in the cells with the aquarium. In-situ light conditions were not simulated in the laboratory.

2.3. Detector system

The activity of ^{137}Cs was determined by means of a 2 × 2 NaI detector coupled to a single-channel analyzer-counter-timer system. The NaI detector was shielded from all incident radiation except that which passed through a pair of 4-mm slits extending the full width of the experimental cells (5.08 cm). The slits were machined out of solid lead cylinders 8.8 cm long by 8 cm diameter. The shielded detector assembly, weighing about 140 kg, rested on a 2-cm-thick aluminum plate supported by a 5-ton hydraulic jack as shown in Fig. 1. Precise and reproducible positioning (≤0.5 mm) and smooth movement of the assembly was possibly because of the careful alignment of the four vertical rods serving as tracks for the aluminum plate, the use of brass bushings to prevent the skewing of the plate, and the small displacement of the assembly (~1.3 mm) per stroke of the jack piston. The distribution of ^{137}Cs activity was typically determined by scanning, in millimeter intervals, the length of each cell placed in a standard reproducible position flat against the inner wall of the aquarium. A cell being scanned was isolated from other active cells within the aquarium by an interposed lead brick

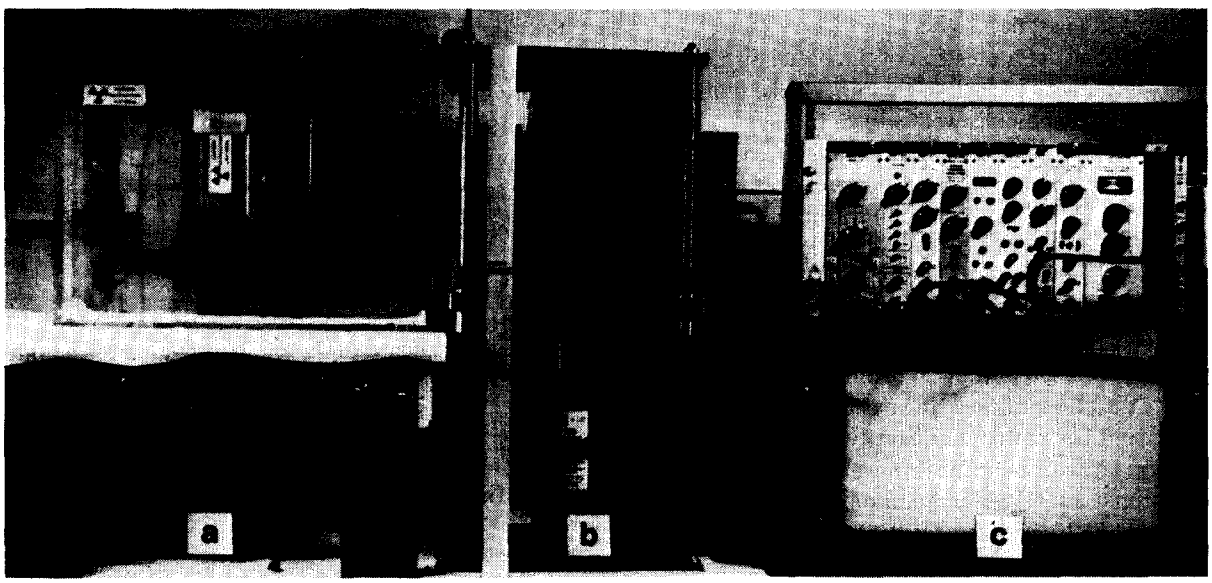

Fig. 1. The experimental setup: (a) aquarium with experimental cells; (b) shielded detector and frame; (c) counting system.

suitably wrapped in polyethylene to prevent contamination of the water with lead. For most positions of the detector, sufficient counts were accumulated within 100 seconds counting time. An entire profile could usually be obtained in one hour for the particular combination of slits and activities used.

A significant disadvantage of the present system is that ^{137}Cs activity is integrated over the full width of the cell. Consequently, lateral heterogeneity in fecal pellet deposition or mixing over a lateral distance of less than 5 cm cannot be inferred by this system. In fact, significant heterogeneities over this distance in tubificid density and pellet production were noted in some cells. A detector system which viewed only a small fraction of the cell width and which could traverse horizontally as well as vertically would remove this shortcoming and could be made by modification of the present system.

2.4. Initial experiments

Activity profiles were measured in three different cells: (1) a control cell with labeled sediment but without organisms, (2) a cell with tubificid worms, and (3) a cell with amphipods. Since it contained a submillimeter surface layer of labeled illite, the control cell served to monitor long-term changes in detector system efficiency as well as to provide a measure of the mobility of ^{137}Cs ascribable to diffusional migration.

Following determination of the initial distribution of ^{137}Cs activity in each of the other cells, tubificid worms and amphipods were added. Initially 32 *Tubifex tubifex* (~50,000 m^{-2}) were added to one cell, while 10 amphipods (*Pontoporeia hoyi*) of varying size (~16,000 m^{-2}) were added to another cell. These initial densities are at the highest end of the range which occurs naturally in sediments of the Great Lakes [32]. In each case, additional organisms were eventually introduced to accelerate the reworking process inasmuch as the aim of this study was to depict the effect of these organisms on radiotracer movement rather than to quantify fecal pellet production rates or sediment turnover on an individual organism basis. However, additions of organisms did not occur until relatively late (>1 month) in the history of profile evolution, so initial displacements may be related to the activities of individual organisms. All oligochaetes used in the experiments were from a population collected in the harbor at Cleveland, Ohio, and kept in laboratory culture (15°C; ambient room light). The amphipods were collected from Lake Michigan sediments (near Grand Haven, Mich.) and kept at nearly in-situ temperatures (7 ± 1°C) for only a few days prior to use. Because amphipods are adversely affected by prolonged exposure to elevated temperatures [33], the cell containing them was kept in a separate dark refrigerated aquarium and transferred to the larger unit only for brief periods of gamma scanning. Because amphipods are able to swim, their cell was covered with nylon screen (1-mm mesh) to prevent their loss. No attempt was made to determine mortality of either tubificids or amphipods in the experimental cells.

3. Results and discussion

3.1. Line broadening effects: detector response and diffusional mobility

The response of the detector to a submillimeter radioactivity layer (control cell) is illustrated in Fig. 2a. Data points for each of the first four days of measurement are shown. The shaded area represents the actual distribution of ^{137}Cs activity which is confined to a surface layer approximately 0.05 cm thick. Because the aperture of the detector system is 0.4 cm wide, the observed profile is considerably broader but is very nearly Gaussian in shape with a full width at half maximum (FWHM, see Fig. 2) of 0.43 ± 0.02 cm. This profile is a measure of the efficiency with which a line source at depth z' will be detected when the detector is at depth z:

$$f(z - z') = e^{-(z-z')^2/2\sigma^2} \quad (1)$$

where the standard deviation, σ, is related to the full width at half maximum (FWHM) by:

$$\text{FWHM} = 2.35\sigma = 0.40 \text{ cm} . \quad (2)$$

When the line source and detector are aligned:

$$f(z - z') = f(0) = 1 . \quad (3)$$

For an arbitrary profile, $A(z)$, the observed activity

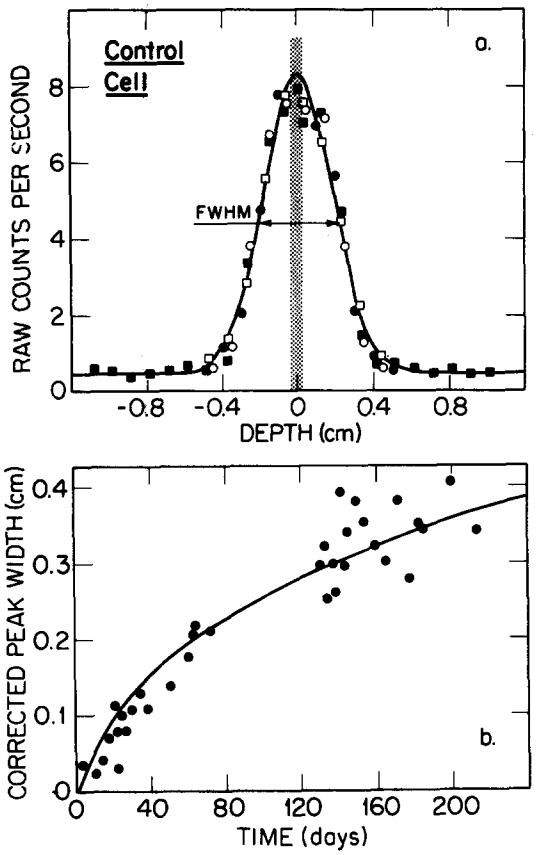

Fig. 2. (a) The actual and measured distribution of activity from an initial submillimeter line source. The nearly Gaussian profile of measured activity mainly reflects collimator geometry and is used to correct all profiles for system optics. (b) The limited broadening of the line source over time in the control cell is presumably due to molecular diffusion. The solid line indicates the expected time dependence of the corrected width (FWHM) for $D_e = 5.8 \times 10^{-5}$ cm^2/day.

versus depth is then:

$$A_{obs}(z) = \int_0^\infty A(z') f(z - z')\, dz' \qquad (4)$$

The function $A_{obs}(z)$ is measured experimentally and the actual distribution, $A(z)$, is determined from equations (1) and (4) using conventional iterative deconvolution methods [34]. The necessity for such corrections can be minimized by using narrower collimator slits (~0.1–0.2 cm). However, this would require an increase in the amount of ^{137}Cs activity introduced to achieve comparable counting accuracy for fixed counting times and increase the background counting rate.

There is a small but measurable increase in the width of the control cell profile over a 200-day period as shown in Fig. 2b. As this cell did not contain macrobenthos, the profile broadening may be ascribed to the desorption of ^{137}Cs from the sediments (illite) and migration through pore water via molecular diffusion. It can be shown [35] that in an infinite isotropic medium the profile resulting from an initial plane source (at $z = 0$) is:

$$A(z, t) = \frac{M}{2\sqrt{\pi D_e t}} e^{-z^2/4D_e t} \qquad (5)$$

where $A(z, t)$ is the activity profile at elapsed time t, and M is a constant. Although the medium is not in fact isotropic in the present experiment, equation (5) provides an approximate measure of the effective molecular diffusion coefficient, D_e. From comparison of equations (5) and (1) using equation (2), the expected peak broadening is given by:

$$\text{FWHM} = 3.3\sqrt{D_e t}. \qquad (6)$$

A least squares fit of equation (6) to experimental data, shown in Fig. 2b, yields a value of 5.8×10^{-5} cm^2/day (0.02 cm^2/yr) for D_e. Although an accurate determination of D_e is not needed in the present study, it is clear that under proper experimental conditions (i.e. isotropic medium, elimination of temperature gradients, etc.) the gamma scan method is an excellent way to measure effective molecular diffusion coefficients in sediments. When exchange of a radiotracer between sediment solids and pore water is reversible and first order (cf. [36]) the effective molecular diffusion coefficient is given by (cf. [37]):

$$D_e \approx \frac{\alpha}{\theta^2} \cdot \frac{1}{1 + K} \cdot D_0 \qquad (7)$$

where the term, α/θ^2, is nearly unity for these sediments, K is the dimensionless distribution coefficient and D_0 is the molecular diffusion coefficient for ions in free solution. Taking D_0 to be about 5×10^{-6} cm^2/sec (4.3×10^{-1} cm^2/day, cf. [37]) and using the above value for D_e, the apparent distribution coefficient is 7400. The desorption experiment yields a value of 5000. The similarity of these values argues against significant irreversible uptake of ^{137}Cs by the illite under present experimental conditions. However, it is clear that unless the presence of organisms some-

how enhances the exchange of ^{137}Cs between sediments and pore water, the mobility of this radioactive species via molecular diffusion should be very small. Over the observation period (>200 days) the broadening ascribable to molecular diffusion is less than 3 mm.

3.2. Experiment with tubificid worms

The evolution of the ^{137}Cs activity profile over a six-month period is illustrated in Fig. 3. The shaded areas represent the profile corrected for the effects of finite-detector resolution. Differences between observed profiles (individual points) and corrected profiles are most pronounced for strongly peaked distributions which occur toward the onset of the experiment. The vertical line associated with each profile indicates the location of the sediment-water interface.

The initial effect of the tubificids on the distribution of radioactivity is one of burial plus some degree of broadening in peak activity. Prior to introducing

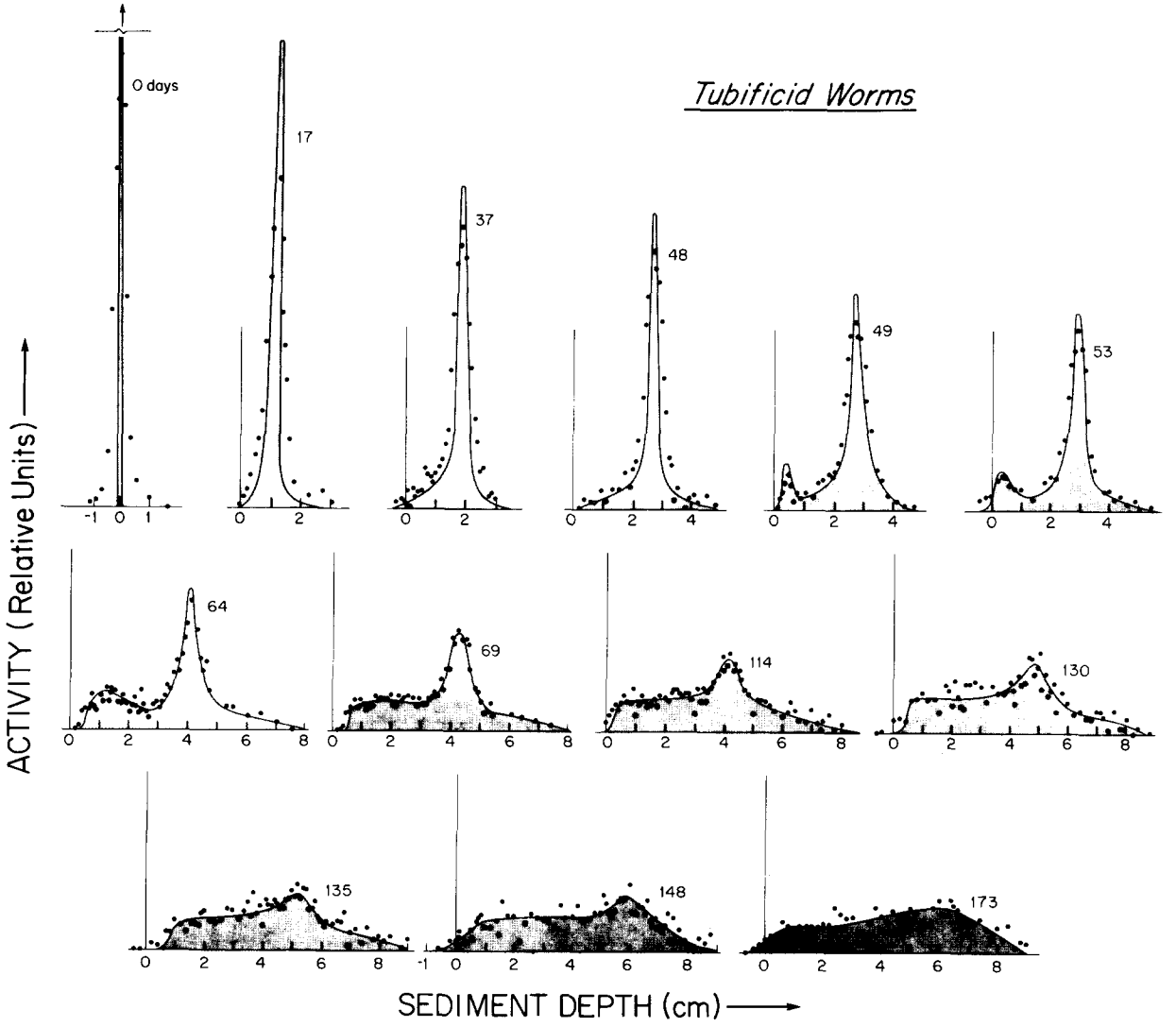

Fig. 3. Effect of tubificids on the distribution of ^{137}Cs. Shaded areas are the activity profiles corrected for system optics. Vertical lines indicate the location of the sediment-water interface.

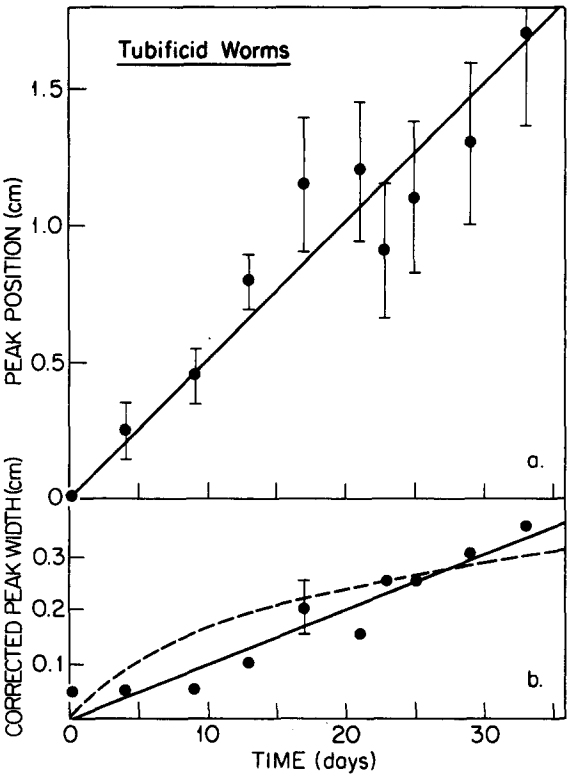

Fig. 4. (a) Location of the peak activity versus time. The rate of burial is essentially constant (0.05 cm/day) during the first month. Error bars primarily reflect uncertainty in specifying the interface due to irregular pile-up of fecal mounds. (b) Peak width corrected for system optics versus time. The linear fit (solid line) indicates a rate of broadening of 0.01 cm (FWHM)/day. The time dependence is not well-described in terms of simple eddy diffusional mixing (dashed line, see text).

additional worms, the burial rate is apparently constant, as seen in Fig. 4a, and equal to 0.052 ± 0.007 cm/day or to 0.59 cm year^{-1} worm^{-1} at 20.0°C. This rate corresponds to 3.8 ml of wet sediment per year per worm (or ~1 g dry sediment year^{-1} worm^{-1}) and is within the range of values reported by Davis [11] for *T. tubifex* at approximately the same temperature. The uncertainties in locating the peak position, indicated by error bars in Fig. 4a, are variable and arise largely from the irregular pile up of fecal material on surface sediments. This ambiguity in the location of the sediment-water interface is ≤0.3 cm.

The line broadening which occurs during the initial period of burial could be the combined result of several processes such as the burrowing motions of worms which penetrate through the labeled layer or variable reworking rates across the cell. The broadening is probably not due to feeding within the labeled layer because during this period there is no return of activity to surface sediments. The width (FWHM) of the activity peak increases over time at a rate of 0.010 ± 0.001 cm/day (Fig. 4b). If this broadening were due entirely to the random motions of the worms above the zone of feeding, then it could be described in terms of the eddy diffusion of sediment solids. Provided the rate of eddy diffusive mixing is constant above the feeding zone and the activity peak is sufficiently isolated from boundary layer effects, the rate of broadening is given by (cf. equation (6)):

$$\text{FWHM} = 3.3\sqrt{K_b t}\,. \tag{8}$$

The value of K_b which gives the best fit to the data is 2.4×10^{-4} cm^2/day (0.1 cm^2/yr) and the resulting regression curve is shown as the dashed line in Fig. 4b. The statistical uncertainties in individual data points are such that this theoretical description is not ruled out; nevertheless a linear dependence is favored by the experimental data. Line broadening appears to be initially slower but subsequently more rapid than expected on the basis of constant eddy diffusivity. Only by additional experiments will it be possible to decide on the applicability of the eddy diffusion concept to tubificid reworking above the feeding zone.

The reappearance of radioactive material in surface sediments occurs dramatically on the 49th day of the experiment. As the labeled sediment passes further into the feeding zone, additional activity is transported to the surface, resulting in a broad secondary maximum in activity near the sediment-water interface. Thus tubificids ingest the radiolabeled particles and probably little if any ^{137}Cs is desorbed during their passage through the gut. Whether some selective avoidance of tracer particles occurs cannot be determined from these experiments. In time this maximum disappears and the profile tends toward a uniform distribution over the upper 6 cm or so, decreasing below this depth to undetectable levels by 9 cm. The maximum displacement of the peak activity is about 6.5 cm. The tail on the distribution is presumably due to a rapid decline in the number of worms feeding below 6.5 cm. Accurate definition of oligochaete

feeding zones must await further experiments. Because there was no sedimentation in this laboratory experiment, the distribution of ^{137}Cs should eventually become uniform over a depth which reflects the maximum range of penetration of this particular tubificid population. When the sedimentation rate is not zero, the shape of the profile below the range of penetration will be preserved indefinitely [12,38]. Profiles of ^{137}Cs observed in the Great Lakes [13,14] and elsewhere [39] have features very similar to those occurring at various stages during this experiment. This suggests that profiles encountered in some lake sediments may be artifacts of biological reworking and that sedimentation rate information derived from analysis of such profiles may be subject to considerable inaccuracy. Robbins et al. [40] have reported finding profiles of ^{210}Pb, ^{137}Cs and Ambrosia pollen in a core from Lake Erie which are self-consistent if interpreted as arising from eddy diffusional mixing. This study supports the speculation [40] that certain benthic invertebrates found in the Great Lakes can provide the mechanism for downward migration of radioactive species.

3.3. Experiment with Pontoporeia hoyi

The action of amphipods on sediments appears to be very different from that of "conveyor-belt" species like tubificid worms [41]. Unlike tubificids, the amphipods appear to transport mass without apparent directionality by their random excursions, feeding, and defecation in near-surface sediments. The changes in the radioactivity profile in the presence of amphipods are shown in Fig. 5 for selected times. Corrected activity profiles evolve from a nearly Gaussian shape into an approximately uniform distribution over the upper 1.5 cm within about 17–20 days. Amphipods interact with sediments over a far more limited and well-defined range. Very little activity appears below the 1.5-cm boundary even several months after the start of the experiment.

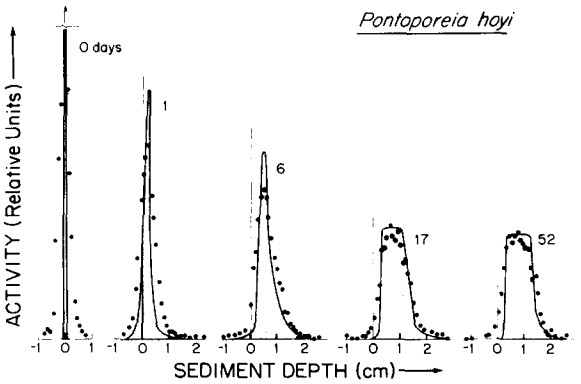

Fig. 5. Effect of amphipods (*Pontoporeia hoyi*) on the distribution of ^{137}Cs. The apparent burial of activity slightly below the sediment-water interface is probably an artifact resulting from parallax errors in locating the sediment interface and to surface irregularities introduced by amphipod activities.

Because of the way in which amphipods interact with sediments, their effect would seem to be amenable to treatment in terms of eddy diffusive mixing. Redistribution of solid phases then can be described by a one-dimensional non-steady state diffusion equation:

$$\frac{\partial A}{\partial t} = \frac{\partial}{\partial z}\left(K_b \frac{\partial A}{\partial z}\right) \tag{9}$$

where A is the activity of labeled particles and z is the depth below the sediment-water interface. Here the effects of sediment compaction are ignored and it is further assumed that the value of the coefficient of eddy diffusion, K_b, is constant over the well-defined zone of mixing of thickness l, and zero below it. Thus equation (9) reduces to:

$$\frac{\partial A}{\partial t} = K_b \frac{\partial^2 A}{\partial z^2} \tag{10}$$

Guinasso and Schink [12] have provided an extensive discussion of the eddy diffusion model and solved a diffusion equation similar to equation (10) but with differing boundary conditions and with allowance made for effects of sedimentation. As no active material passes through surfaces at $z = 0$ or $z = l$ (because $K_b = 0$ for $z \geqslant l$), the boundary conditions are:

$$K_b \left.\frac{\partial A}{\partial z}\right|_{z=0} = K_b \left.\frac{\partial A}{\partial z}\right|_{z=l} = 0 \tag{11}$$

for all $t \geqslant 0$, and:

$$A(z, t) = A_0(z) \tag{12}$$

for $t = 0$. $A_0(z)$ then is the initial distribution of activity. Crank [35] has given an explicit solution to equation (10) with the above boundary conditions. In the present experiment, the initial activity distribution

is given approximately by:

$$A_0(z) = A_0 \quad 0 < z < h$$
$$A_0(z) = 0 \quad h < z < l \tag{13}$$

where h is the initial width of the activity profile (~0.05 cm). The solution given by Crank then reduces to:

$$A(z, t) = \frac{A_0 h}{l}\left[1 + 2\sum_{n=1}^{\infty} \exp(-K_b n^2 \pi^2 t/l^2) \cos\frac{n\pi z}{l}\right]. \tag{14}$$

From this relation, values of the full width at half maximum (depth such that $A(z)/A(0) = 1/2$) versus time were computed for various choices of K_b. The value giving the best least squares fit to the observed time dependence of the corrected peak width for all profiles is 0.014 ± 0.002 cm²/day (4.4 cm²/yr). Comparison of this value with that for effective molecular diffusion (0.02 cm²/yr), indicates that this latter process is insignificant in the presence of amphipods. As can be seen in Fig. 6, the calculated time variation of the width provides a very satisfactory representation of experimental results. Evidently the way in which amphipods mix surface sediments is consistent with eddy diffusional mixing. The value of 4.4 cm²/yr (~7°C) is comparable to that inferred from analysis of ^{210}Pb profiles previously reported [14] for a core from Lake Huron where *Pontoporeia hoyi* is the principal macrofaunal species. Robbins et al. [14] inferred a lower limit of 3.3 cm²/yr for densities of 2700 amphipods (plus 630 tubificids) m^{-2} (~6°C). It must be borne in mind that the organism densities as well as their depths of penetration are not comparable, however.

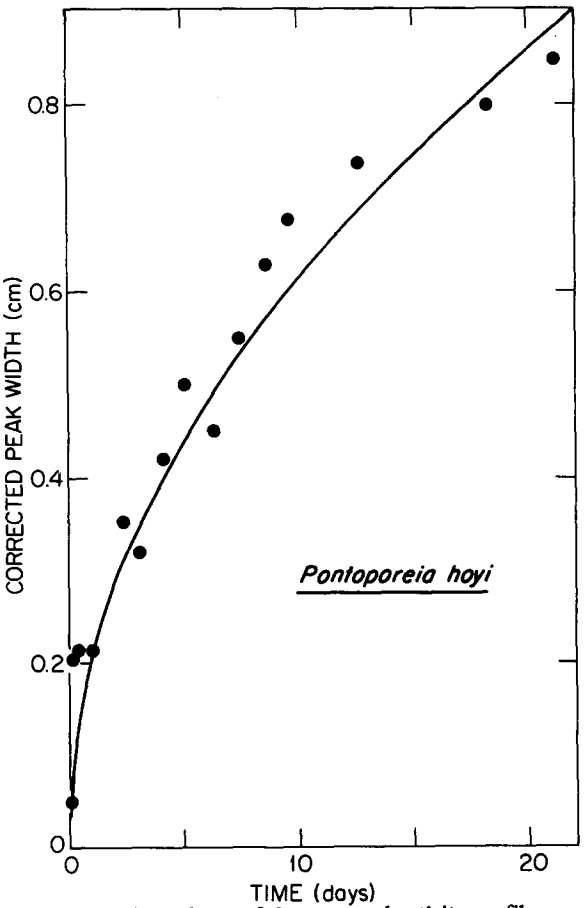

Fig. 6. Time-dependence of the corrected activity profile width (FWHM). The solid line is the expected dependence if mixing occurs by eddy diffusion of sediment solids down to about 1.5 cm depth. The value of K_b giving the best fit is 0.014 cm²/day.

The eddy diffusion model provides a satisfactory representation not only of the time dependence of the width of the activity distribution but also gives a satisfactory account of each profile corrected for detector geometry. Illustrated in Fig. 7 is the theoretical profile for selected times computed using the above values of K_b and l, and compared with corrected experimental values. These results appear to be the first laboratory demonstration of eddy diffusive mixing by an infaunal organism.

The gamma scan method described here provides a simple, high-resolution, non-destructive, and highly quantitative means of studying the reworking of sediments by infaunal macrobenthos. This initial study of tubificid oligochaetes provides an estimate of their reworking rates, yields a new measure of the extent of smearing of material above the feeding zone, illustrates their "conveyor-like", strongly advective action in transporting sediment particles to the sediment-water interface and gives an indication of the downward extent of their particle transport. Experiments with amphipods indicate that they have a well-defined and shallow range of penetration into sediments and that their mode of mixing sediment solids may be described in terms of an eddy diffusion model.

Because of the rapid acquisition of data by the gamma scan system, the time evolution of radioactivity profiles may be determined with considerable

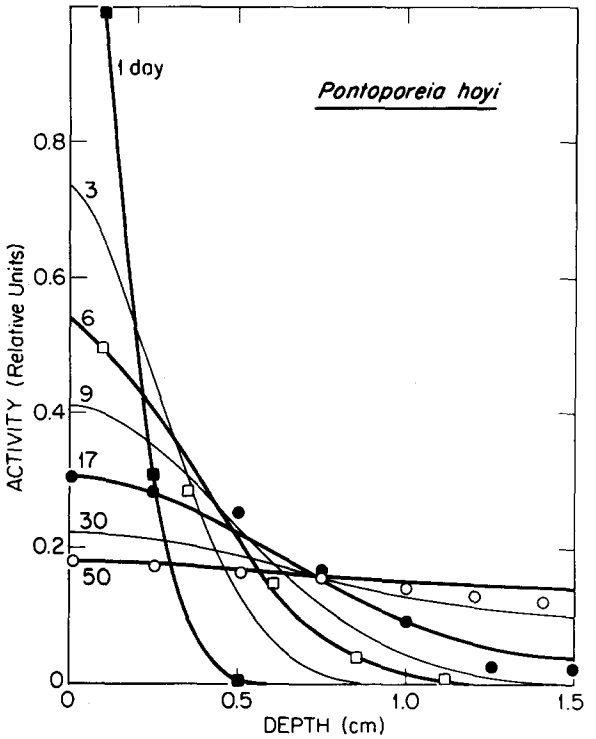

Fig. 7. Time evolution of the theoretical activity profile. For selected times, corrected experimental values are shown for comparison.

accuracy. This method provides the necessary information for quantitative modeling of mass transport near the sediment-water interface. In the case of tubificid worms, their action on sediments cannot be described solely in terms of eddy diffusional models. Fisher [42] models sediment mixing by tubificids in terms of a combination of diffusion and advection of sediment solids. Alternatively, convolution methods [43] possibly used in combination with an eddy diffusion model may be required to treat the effects of tubificids. The gamma scan method is ideally suited to study the effects of finite sedimentation (moving boundary problem) on mixing, species interaction effects, and the influence of sediment geochemistry or toxic substances on reworking rates. Moreover, the method described can be extended to the study of other gamma-emitting nuclides such as ^{54}Mn or ^{59}Fe whose chemical and physical forms are sensitive to local geochemical conditions. Moreover, through the use of a nuclide such as ^{22}Na, which is weakly coupled to sediment solids, relationships between eddy diffusive mixing or non-random particle reworking and interstitial transport may be investigated quantitatively. This problem is presently of particular importance for understanding the geochemistry of recent sediments and exchange of solutes across the benthic boundary layer [44].

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