

BIOTURBATION AND REDISTRIBUTION OF SEDIMENT RADIONUCLIDES IN ENEWETAK ATOLL LAGOON BY CALLIANASSID SHRIMP: BIOLOGICAL ASPECTS

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ABSTRACT

Callianassid ghost shrimp are abundant in both shallow and deep regions of Enewetak Atoll lagoon. They cause extensive bioturbation of lagoon sediments and contribute significantly to both lateral and vertical sediment mixing, often burrowing to depths of over 2.0 m. In addition, their burrows often intersect and disrupt layers of highly radioactive sediments that have resulted from nuclear weapons testing at Enewetak during the 1950's. Some of the highest activity levels of radionuclides are those associated with very fine-grained sediments (<38 μm). Callianassids tend to preferentially store coarse-grained particles (>ca. 1.0 mm) in sub-surface refuse galleries. However, fine-grained sediments are normally either used in tunnel wall construction or pumped to the sediment/water interface and accumulate as mounds. Therefore, callianassid shrimp provide a mechanism by which entrained radionuclides can be redistributed both laterally and vertically to the surface of lagoon sediments.

Enewetak Atoll is the most studied and best understood of any tropical atoll system. Although over a thousand investigators have visited there since 1954 and hundreds of papers have been published on biological and ecological research, nearly all have concentrated on either coral reefs, other hard substrata, pelagic fish or plankton. With the lagoon comprising 92% of the area of the entire atoll, it is surprising that only four authors are known to have published on ecological studies of the soft benthos. Gilmartin (1960; 1966) and Hillis-Colinvaux (1980) reported on algae in the deep lagoon, and Wenner (1977) conducted an ecological study on hippid crabs from wave-swept beaches. Finally, Colin (1986) describes the general distribution of benthic communities in the deep lagoon from remote-controlled photographic surveys, a research submersible and SCUBA dives. To date, we know of no published reports on subtidal infauna from the lagoon.

Below 10 m depth most sandy substrata in Enewetak Atoll lagoon are dominated by large (to 20 cm height) volcano-shaped mounds created by callianassid ghost shrimp and by fecal castings of hemichordate worms. Previously the presence of these biologically derived features has been noted only as anecdotal references by Emery et al. (1954) in a physical description of the lagoon bottom and by Gilmartin (1960) in descriptions of algal sampling stations. However, no one has identified their origins, or attempted any process-oriented studies on this community. Roberts et al. (1982) and Suchanek (1983) have reported on the dynamics of similar communities in tropical lagoons in the Caribbean (U.S. Virgin Islands), but this report represents the first detailed account of bioturbation in Enewetak Atoll lagoon.

Large amounts of several radionuclides, produced from nuclear testing on the atoll from 1948-1958, reside in the marine environment at Enewetak Atoll with the lagoon sediments acting as the largest reservoir of such radioactive elements (U.S.A.E.C., 1973). The long-lived isotopes of plutonium and other radionuclides that still exist in large abundance (e.g., Cobalt) pose the greatest contamination problems. Radioactive materials complexed with carbonate particles as well as soluble and particulate transuranium oxides were introduced into sediments by

the detonation of nuclear devices. Noshkin (1980) presents an overview of those conditions and events which led to the distribution of such transuranic radionuclides both on and within sediments in the lagoon. Noshkin (1980) also takes special care to note that the behavior of these transuranics is similar to that found on other aquatic fallout pathways, making this type of study valuable in predicting processes associated with transuranics on a global aquatic scale. Due to the difficulty in obtaining deep cores in carbonate sediments Noshkin (1980) reports mostly on transuranics from the upper 16 cm of the sediment column. However, from a few 60-cm cores from crater areas he notes that complex areal and vertical patterns emerge but concludes that mixing by burrowing organisms is unlikely to move specific components down through the sediment column.

We believe, however, that bioturbation in Enewetak lagoon has a significant impact on redistributing these radionuclides both vertically and horizontally within the sediment column. Here, we describe some processes by which callianassids can recycle radioactive particles from deep within the sediments to the sediment/water interface and discuss the potential ecological significance of such an event.

In three other closely related papers in this volume we report on (1) the concentration of these radionuclides at 1–2 m depths within sediments (McMurtry et al., 1986), (2) a diverse invertebrate and fish fauna capable of utilizing, processing and/or disrupting these sediments (Suchanek and Colin, 1986) and (3) the redistribution of some of these entrained radioactive isotopes as suspended particulate matter in the water column by callianassid shrimp (Colin et al., 1986a).

METHODS

Bioturbation studies were conducted from June 1980 through December 1982. Density surveys for callianassid mounds and individuals were performed using a variety of methods. The DSRV MAKALI'I was used in the central and southern portions of the deep lagoon (50–80 m) below practical SCUBA range. Colin et al. (1986b) described the atoll, lagoon and the operation of the DSRV MAKALI'I. Visual counts as well as photographs (color transparencies) and b&w video tapes were used in conjunction with a 1.0 × 1.0-m aluminum quadrat held in the mechanical arm of the submarine to obtain density estimates. Counts were taken in regions of obvious low and high density callianassid mound regions and at regularly spaced intervals by stopping the submersible after motoring for about 30 sec and recording densities at the end of each of these hops.

Three types of SCUBA-oriented mound density surveys were performed. In the first, 21 locations were surveyed to 17 m depth by placing 10-m transect lines at pre-determined depth contours. A 2-m swath on either side of each transect line was then surveyed for mounds. Normally, data on two to five depth contours were collected at each site. A second SCUBA-oriented method performed off Enewetak Island involved the use of fixed 10 × 10-m quadrats in which callianassid mounds and other bioturbational features were flagged and monitored every 2 days. A third method involved leveling all the sediment within fixed replicate 1.85 × 1.85-m quadrats and monitoring on a daily basis the number of mounds and depressions produced by callianassids and other bioturbators. These leveling experiments normally ran for 24–96 h.

Alterations in grain size and organic content of sediments by callianassids were analysed in detail. Sediment grain size determinations were made using the methods of Folk (1974). The organic content of sediments (before and after being processed by callianassids) was determined in the following manner. Sediments were dried, finely ground by hand with mortar and pestle and CHN ratios were analyzed using a Hewlett Packard Model 185-B Elemental Analyzer.

Burrow morphology and depth were studied by two methods. The first involved the use of high density fiberglass resin (Fiberglass Hawaii® polyester laminating resin) using the techniques of Suchanek (1983). Resin was poured underwater with the aid of SCUBA into the intake opening of each burrow complex, allowed to harden for 24–48 h and the resulting positive cast was retrieved using air-lifting equipment. The second technique, which produced valuable data on pumping frequencies and lateral extent of burrow complexes, involved seeding burrow openings with fluorescent red painted sediments of various pre-sorted grain sizes (0.13–0.25, 0.25–0.50, 1.0–2.0, 2.0–4.0 and >4.0 mm). Burrow openings were flagged with ID numbers and monitored on a daily basis, recording distances from the original seeded intake opening to mounds producing colored sediment and the frequency of such events.

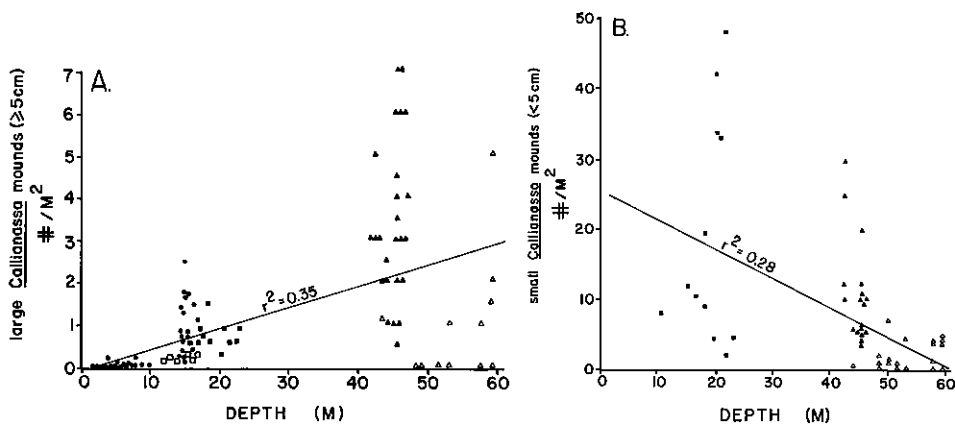


Figure 1. (Left) Depth distribution for abundance of large callianassid mounds (≥ 5 cm high). Symbols refer to method of data collection. (●) = 10-m transect lines, (□) = 10×10 -m survey, (■) = leveling-squares experiment, (▲) = MAKALI'I dive #81-32, (△) = MAKALI'I dive #81-36. Regression line fit mathematically.

Figure 2. (Right) Depth distribution for abundance of small callianassid mounds (< 5 cm high). Regression line fit mathematically. See Figure 1 for symbol explanations.

Cores for radionuclide analyses were collected to depths of 2.0 m using 8 cm diameter plastic core tubes driven by hand into the sediment. See McMurtry et al. (1985; 1986) for details of radiological analyses.

RESULTS

Densities of callianassid mounds found throughout the lagoon using both SCUBA and the DSRV MAKALI'I are given in Figures 1 and 2. Figure 1 represents all mounds > 5 cm in height. These larger mounds increase in abundance as one proceeds into the deeper lagoon, whereas smaller mounds (< 5 cm in height, Fig. 2) tend to decline in abundance along that same gradient. The regression lines are fitted mathematically. The reasons behind these gradients in abundance remain obscure at this time. However, this distribution clearly indicates significantly greater rates of sediment bioturbation in the deep lagoon. The arbitrary cut-off height of 5 cm serves not necessarily to distinguish between distinct species, but rather to more accurately evaluate bioturbational effects by presumed large versus small callianassids. We have found several species of callianassids of varying sizes, and we feel that we may not, as yet, have captured the species that forms large mounds. Suchanek and Colin (1986) give some tentative ID's for some of those species collected.

Rates of sediment processed and pumped to the surface (per m^2) from large and small callianassid mounds were estimated from the leveling experiment. Both absolute volumes and percent contribution to total processing rates for large and small callianassids are given in Table 1 (condensed from Suchanek and Colin, 1986). Processing rates for large and small enteropneusts are also given for comparison. From these results it is clear that callianassids, and specifically large callianassids, make the greatest contribution to bioturbation within the lagoon. Since these experiments were conducted in the shallow portion of the lagoon (15–20 m depth), their absolute contribution would logically only increase with increasing densities in the deep lagoon (Figs. 1 and 2).

Callianassid shrimp also dramatically influence grain size characteristics. Figure 3A and C shows the grain size distribution of sediments at 22 m and 40 m depth,

Table 1. Results of leveled squares experiment. Values represent standardized figures on a per m² basis for *populations* of callianassids and enteropneusts, not individuals

Population	Sediment processing rate cc/m ² /day (range)	% Contribution to total sediment processed (maximum contribution)
Large callianassids (Mounds \geq 5 cm high)	240.1 \pm 206.7 (0-820)	59.6 \pm 35.1 (100)
Small callianassids (Mounds < 5 cm high)	56.0 \pm 52.9 (0-172)	23.9 \pm 30.6 (100)
Large enteropneusts (Castings \geq 5 cm high)	48.0 \pm 125.8 (0-576)	9.9 \pm 23.1 (78)
Small enteropneusts (Castings < 5 cm high)	13.6 \pm 23.3 (0-87)	6.3 \pm 14.9 (69)

respectively, from areas within the lagoon with no callianassids present. The calcareous green alga *Halimeda* dominates the bottom in these regions and the sediment is characterized by a large proportion of *Halimeda* flakes 1-4 mm in size (Fig. 3A, C). An area immediately adjacent to the *Halimeda* flat shown in Figure 3A has abundant callianassids and has a dramatically different grain size distribution (Fig. 3B). Specifically, the large *Halimeda* flakes are absent (noted by small arrows) and the sediment is dominated by grain sizes in the mid-range of about 0.09-0.13 mm. Another area off Inedral Island with typical abundant callianassid mounds was also sampled (Fig. 3D). These results similarly demonstrate that callianassids modify the grain size distribution of surface sediments, eliminating the very fine and very coarse grains, and favoring an intermediate size (in this case about 0.25-0.35 mm), which corresponds quite closely to the size-selective sorting activities of Caribbean *Callianassa* (Suchanek, 1983). Figure 3E and F represents grain size analyses on recently pumped sediment collected in traps placed over active mounds, once again verifying the precise nature of sediment sorting by callianassids at Enewetak.

Larger grains such as *Halimeda* flakes, coral fragments and shell debris are eliminated from surface sediments by storing them in subsurface refuse galleries (Suchanek, 1983). This has been confirmed by introducing painted sediment, largely *Halimeda* flakes, of 4-5.8 mm diameter into callianassid systems and subsequently (from 24 h to 6 months later) excavating the system to identify where the material has been located. Within 24 h this coarse material was found in filled storage galleries with other coarse debris over 50 cm below the sediment surface and also incorporated into the burrow lining. Coarse sediment introduced more than 6 months previously was not as easily located since considerable burrowing activity had occurred in the intervening time, but on several occasions small pockets of this material were encountered, all well buried (40 cm or more) below the sediment surface.

Callianassids also appear to alter the organic content of sediments. Because tropical sediments are typically so nutrient poor, callianassid shrimp appear to construct their burrow complexes in such a way as to maximize the capture of detrital material drifting across the sediment/water interface. In so doing they increase the organic load of sediments pulled into the burrow. Their intake holes (or more accurately, pits) are funnel-shaped and thus act as sinks for drifting material such as algae or other organic detritus. Results of CHN analyses on sediments from intake pits (i.e., before being processed by the shrimp) and from mounds (i.e., after being processed) are given in Table 2. Organic carbon is reduced

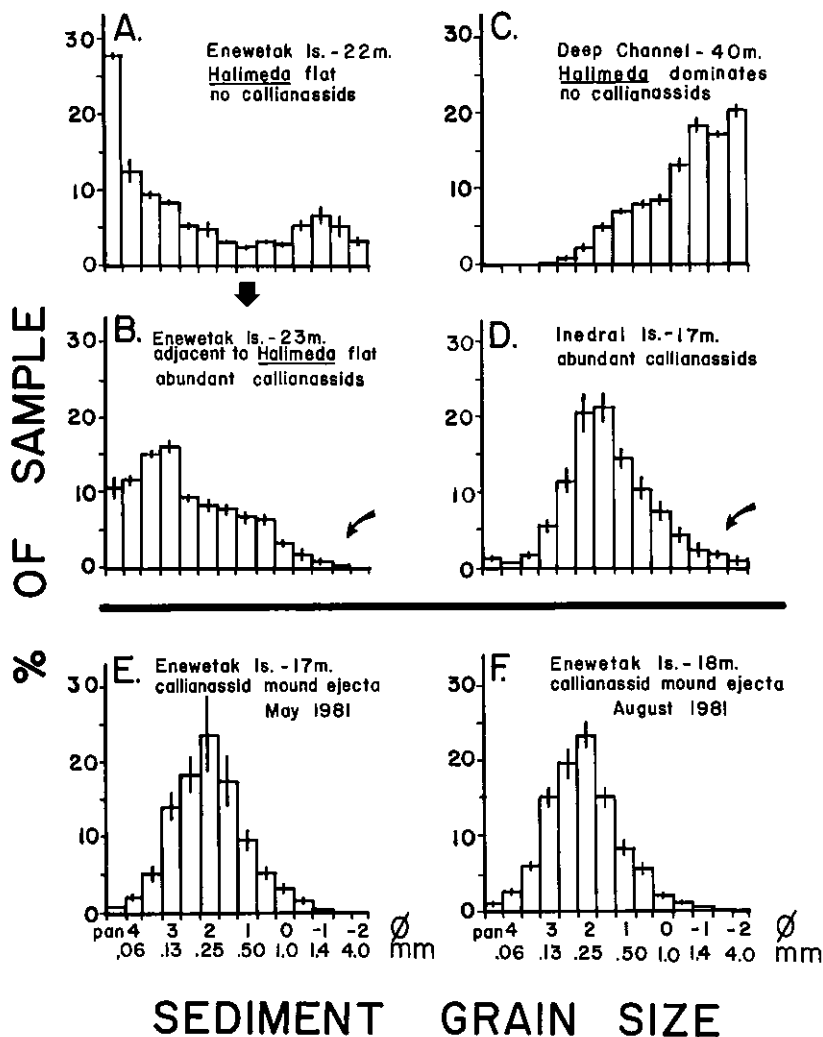


Figure 3. Sediment grain size distribution for various locations in Enewetak Atoll lagoon from regions with and without abundant callianassids. Arrows indicate coarse-grained sediment removal by callianassid sorting.

by more than half of the original levels. Sediment from regions between mounds (and not from intake pits) showed slightly less organic carbon than sediments from mounds, but the variance is high and these values are not significantly different from mound sediments at $P = 0.05$ (t -test).

Table 2. Results of CHN analyses on sediments near Medren Island

Sediment source	Total % carbon	% Inorganic C	% Organic C	% Nitrogen
Mounds	11.15 ± 0.54	11.11 ± 0.19	0.28 ± 0.33	0.02 ± 0.02
Intake holes	11.00 ± 0.45	10.46 ± 0.38	0.61 ± 0.43	0.04 ± 0.03
Between mounds	10.92 ± 0.45	10.85 ± 0.34	0.20 ± 0.37	0.04 ± 0.02

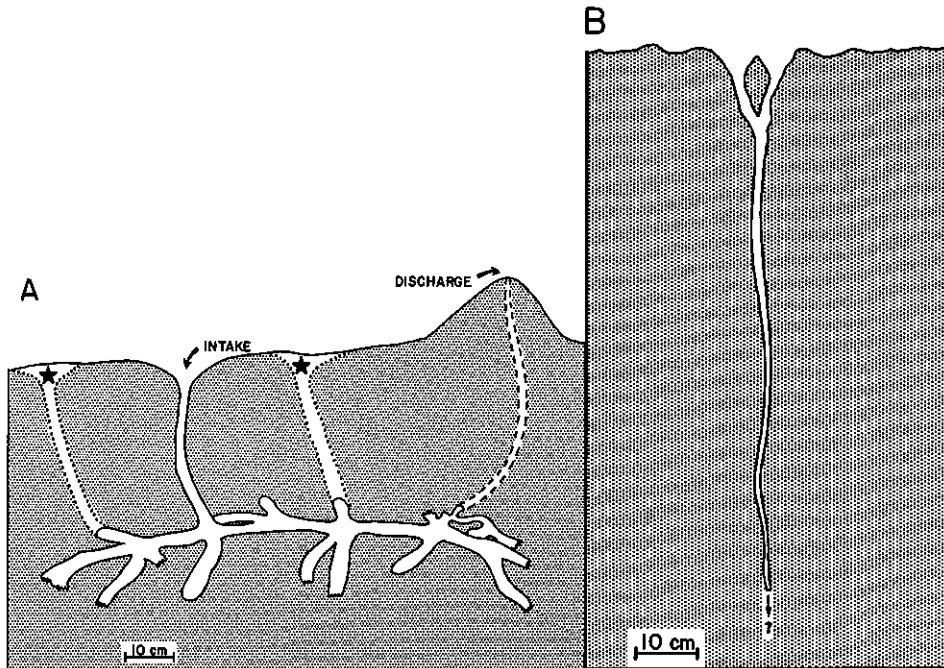


Figure 4. A. Diagram created from a resin-casted burrow from sediments near Enewetak Island. Actual burrow extended further laterally in both directions, but resin did not fill those regions. Solid lines of burrow indicate actual resin cast. Dashed lines indicate speculated connection to mound (note: mound burrow linings are often too flimsy to remain open and therefore do not receive resin). Dotted lines indicate speculated burrow openings to surface (at stars) that lead off of main arms of tunnel. B. Diagram of an alternate form of callianassid burrow from resin-casted sample near Enewetak Island.

Burrow morphologies of callianassids are complex, and methods to investigate them are difficult at best. From Suchanek (1983; in press) and other personal observations (THS) it appears that each species of callianassid shrimp creates an architecturally unique burrow plan. Through the use of numerous resin castings, the depth and lateral extent of burrow complexes have been analyzed. Figure 4A and B shows diagrams of burrows revealed by two such castings from Enewetak lagoon. How the burrow complex is connected to the associated mounds for these particular species remains unclear. Many chambers form blind ends. However, because the resin often solidified before being able to reach the full extent of side passages, the arm(s) leading to the mound(s) on the surface in this case may have been some distance further than the resin reached. The distances between callianassid intake pits and their associated erupting mounds ranged from 8–95 cm with a mean value of 49.5 ± 16.8 cm, $N = 66$ (see below, Fig. 5 and Table 3). Therefore, for a resin cast with a lateral extent of only 60 cm (Fig. 4A) and many of the side arms incompletely filled, mound connections could emanate from any of the incompletely formed side branches. In Figure 4A a speculated shaft leading to a mound has been added with dashed lines to indicate the typical condition.

Intake openings are not permanent features. Flagged openings monitored for long periods of time showed an irregular schedule of opening and closing. Because of the low nutrient content of these sediments, and the relatively regular intervals between burrow side arms, we speculate that callianassids can cover a broader

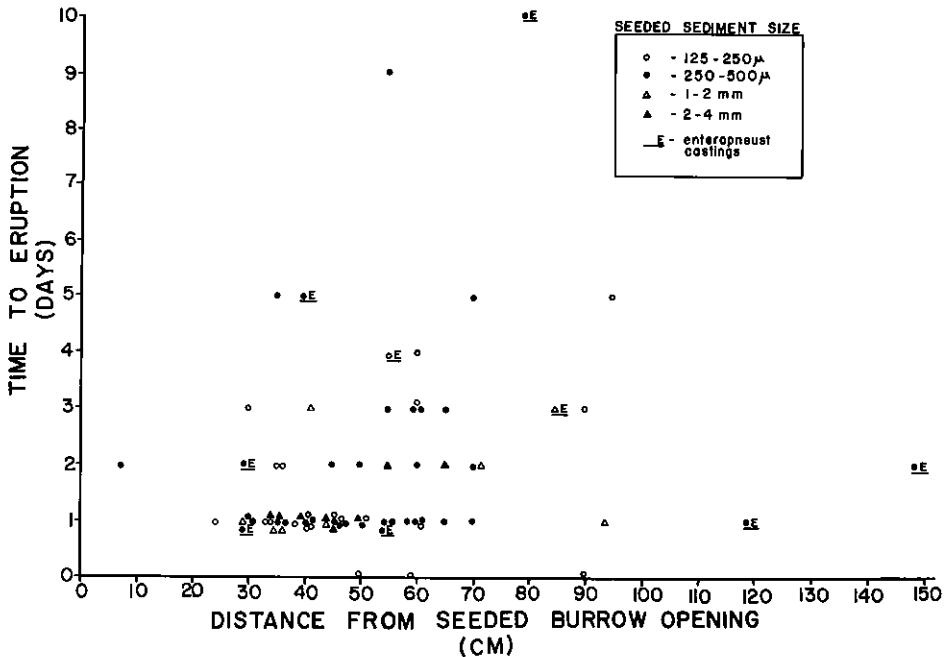


Figure 5. Plot of eruption time versus lateral distances that callianassids pumped introduced, colored sediments of various grain sizes. In some cases the colored sediments erupted in entero-pneust castings as well as from callianassid mounds. Those cases are designated by $\underline{x}E$, where x = the seeded experimental grain size.

area and therefore are able to gather more detritus and extract more organic material from sediments by intermittently opening intake shafts to the surface at various lengths along the burrow. We feel it is extremely likely that these blind ends in the burrow complex may represent turn-around sites and/or potential routes to open such intake shafts to the surface. These speculated shafts have been designated by dotted lines in Figure 4A, with stars at the intake openings. Figure 4B represents a diagram of a much thinner, but deeper, resin casted burrow. Most likely created by a different and smaller species, this burrow extended more than 2 m below the sediment/water interface. Full extraction and knowledge of the burrow below 2 m was unattainable because of the fragile nature of the thin cast at that depth; it broke off at 2 m.

Experimental seeding of various sized colored sediments into intake openings showed that callianassids often process sediment relatively rapidly and can move it considerable distances (Fig. 5). After 30 days, no seeded sediments >4.0 mm in size ($N = 10$ trials) were pumped back out of mounds. Table 3 shows that for sediments <4.0 mm, the number of seeding trials producing colored sediment from associated mounds and the number of mounds per trial producing such seeded sediments was highest for sediments 0.13–0.50 mm. This corresponds well with the results of grain size analyses on selectively sorted and pumped sediments gathered from collection buckets (Fig. 3). Both the average distance from a seeded intake opening to an erupting mound and the time to initial eruption after seeding showed no significant differences between sediment size categories.

Sediments can be cycled through such a system surprisingly fast. We have noted

Table 3. Results of colored sediment seeding experiment

	Grain size of seeded sediments (mm)				
	0.13-0.25 N = 20	0.25-0.50 N = 20	1.00-2.00 N = 20	2.00-4.00 N = 10	>4.00 N = 10
% of trials resulting in pumped sediment	95	100	70	80	0
# of mounds erupted per seeding	1.2 ± 0.5	1.6 ± 0.7	1.1 ± 0.3	1.0 ± 0.0	0
Mean lateral distance sediment was pumped from seeded pit	47.9 ± 18.0	49.9 ± 14.6	55.6 ± 25.4	46.3 ± 10.3	—
Processing time (days)	1.8 ± 1.3	2.1 ± 1.8	1.6 ± 0.9	1.3 ± 0.5	—

that some labeled sediments can pass from the initial seeded intake opening, out a nearby associated mound and slump back down to the original seeded intake opening in 1–5 days ($\bar{x} = 2.7 \pm 1.3$, $N = 14$). A similar phenomenon has been noted by Suchanek (1983) for Caribbean *Callianassa*. This rapid turnover time may reflect a need for callianassids to process a larger volume of sediment because of the generally low nutrient content.

Sediment cores to 2 m depth at Enewetak reveal active callianassid burrowing associated with regions of high radionuclide activity. The most radioactive sediments at Enewetak are those associated with the finest grain sizes ($<38 \mu\text{m}$) (McMurtry et al., 1985; 1986), and, as shown above, callianassid shrimp preferentially pump the fine-grained material to the sediment/water interface forming mounds. Of 11 deep cores from a region near Runit Island, several show callianassid burrows directly associated with the radiologically most active layers (Colin et al., 1986b for location map and McMurtry et al., 1986 for methods of radioactivity analyses). Figure 6A shows a photograph and gamma activity levels from core 5C-1 from about 20 m water depth off Runit Island. The highest levels of radioactivity for this core (ca. 40 times the level of background radiation) are found associated with the fine-grained sediments at core depths of 50–80 cm. In the close-up photograph of the core, callianassid burrow tracks can be seen penetrating this region of highest gamma activity. Figure 6B is a similar representation for core 5D-3, taken some 60 m distant from 5C-1; both cores are from a large region of high density callianassid mounds. In this core, evidence of callianassid burrowing can again be seen in the level of highest gamma activity at a core depth of 60–80 cm, which in this case is about 100 times that of background radiation. In addition, further burrowing and redistribution of this dark-colored, fine-grained, highly radioactive material can be seen in burrows that penetrate the adjacent coarser layer immediately above this level at about 35–45 cm core depth. This layer is composed mostly of coarse sand and *Halimeda* flakes (see close-up photograph of 6B). Beta autoradiographs taken of this same core show that (1) where callianassid burrows intersect the highly radioactive layer, radiation levels are reduced by the removal of those fine-grained particles, and (2) where callianassid burrows penetrate the coarse sediment layer above, more highly radioactive sediments become redistributed and introduced into these layers (McMurtry et al., 1986). We present the details of grain sizes and radionuclide activity levels versus depth for these and nine other cores (20–200 cm in length) from the region near Runit Island in McMurtry et al. (1985; 1986).

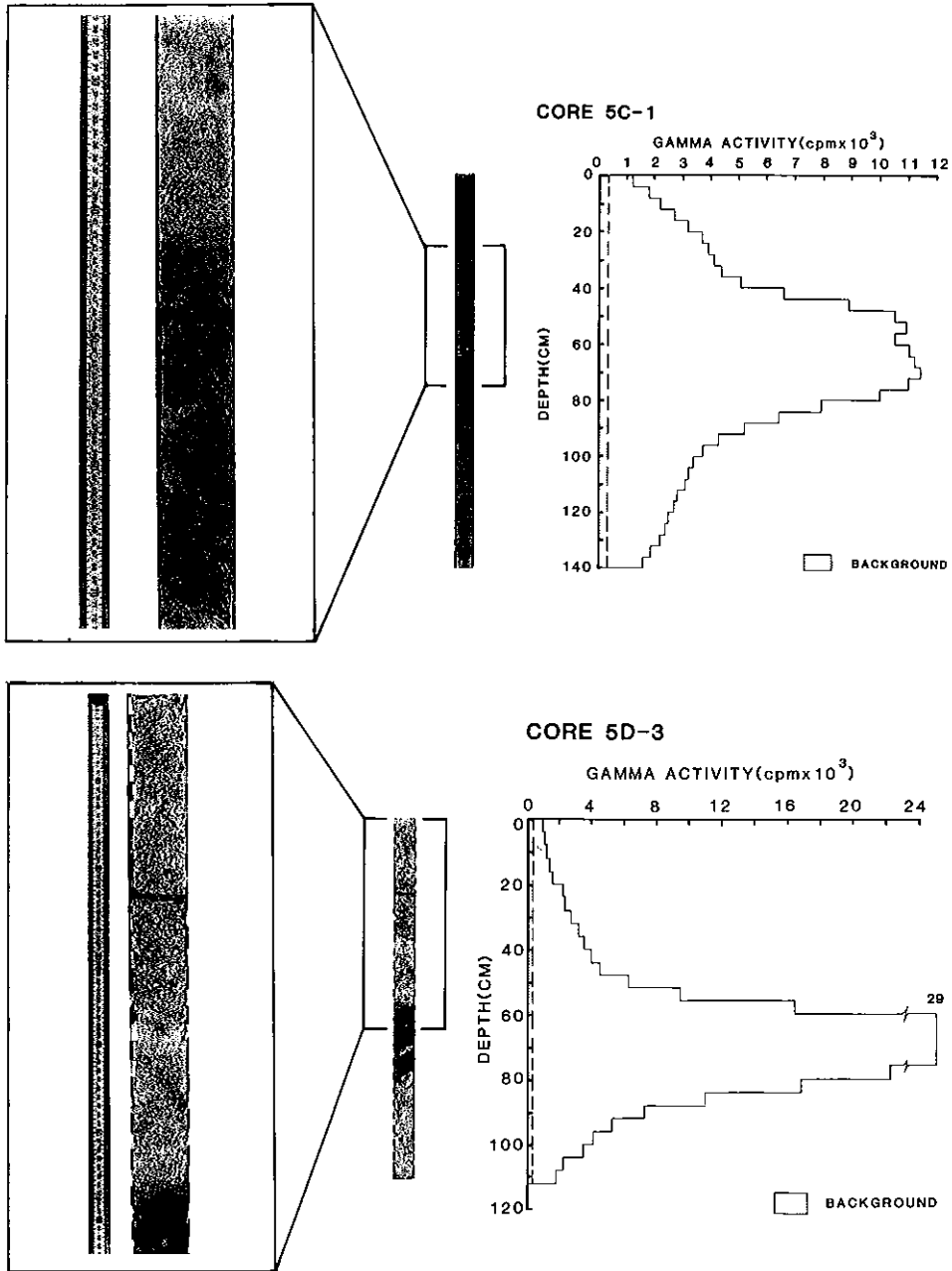


Figure 6. A. Distribution of total gamma activity in relation to core 5C-1 lithology. Note evidence of burrowing into and below the highly radioactive layer. Close-up photo shows burrow in radioactive layer filled with less-radioactive, coarser sediment from an adjacent layer. B. Distribution of total gamma activity in relation to core 5D-3 lithology. Here, note evidence of burrowing into the dark, highly radioactive layer as well as into the upper adjacent layer which contains dark-colored, fine-grained radioactive sediment from below.

DISCUSSION

Callianassid shrimp are not only abundant in the shallow and deep lagoon at Enewetak, but they also substantially alter the physical and chemical nature of entrained carbonate sediments. With burrows penetrating to at least 2 m depth within sediments, substantial mixing of deep and shallow sediments occurs on a continual basis. The sediment processing rates given in Table 1 are conservative estimates since these experiments were conducted in shallow regions of the lagoon (ca. 20 m depth) where the densities of large callianassid mounds average about 0.5–1.0/m². Data collected from the MAKALI'I show that deeper regions have an average density 2–6 times higher than do shallow areas and sometimes reach 7 mounds/m² (Fig. 1). With callianassids performing about 60–100% of the bioturbation within the lagoon and processing up to 820 cc/m²/day of carbonate sediment (Table 1), potentially from sources deep within the sediments, we need to evaluate how such activity may affect other physical/chemical processes within the lagoon.

Cores penetrating over 2 m sediment depth show high concentrations of transuranic radionuclides at depths of over 1.0–1.5 m. We present evidence here that callianassid shrimp actively burrow through these depths and can modify these layers of elevated radioactivity levels (Fig. 6), often processing and mixing substantial quantities of carbonate sediment by selectively storing some sediments at depth and pumping other deeper sediments to the surface. During lateral or vertical burrow construction, callianassids must excavate and eliminate sediments from depth. When such burrowing occurs in sediments high in radionuclides, these are pumped to the surface just like any other sediments, and are either suspended as fine particulate matter (Colin et al., 1986) or accumulate on the sediment/water interface as mounds, eventually being incorporated into other surface sediments.

Because of the well-known difficulty in capturing callianassids (Shinn, 1968; Suchanek, 1983; in press) virtually no research has been done on their predators or organisms which might link them to other trophic levels. However, at Enewetak Atoll, J. E. Randall (noted in Suchanek, 1983) has found at least one natural predator on callianassids, the bone fish *Albula glossodonta* (Forsskål). Exactly how many other predators exist on callianassid shrimp and how many other invertebrates and/or fishes may be utilizing these sediments high in radionuclides remains unknown. Suchanek and Colin (1986) present an overview of sediment bioturbators at Enewetak, but the trophic interrelationships of these fauna and/or their links to the human food chain have not been studied.

In summary, we show that callianassid ghost shrimp are abundant within sediments from the shallow and deep lagoon at Enewetak Atoll. They are active burrowers and process substantial quantities of carbonate sediment each day, pumping some sediments from deep within the sediment column to the surface and selectively storing others at depth. Callianassids alter the organic content and grain size of sediments and they have been found to burrow actively through sediments high in radionuclides. Contrary to previous reports, biological activity within the sediments at Enewetak Atoll lagoon does substantially redistribute transuranic radionuclides and may facilitate their entrance to invertebrate and/or vertebrate food chains. Because we have only skimmed the surface in terms of understanding the mechanisms involved in such processes, we recommend further studies in general on the mobilization and redistribution of radionuclides in the lagoons at Enewetak and Bikini Atolls, and specifically on those processes that appear to have the greatest influence on facilitating these events, namely bioturbation by callianassids and other sub-sediment invertebrates.

ACKNOWLEDGMENTS

Special thanks go to C. Suchanek, J. T. Harrison, L. Bell, S. Johnson and L. Boucher for their help with field and laboratory work. Analyses of CHN were performed by Analytical Services, University of Hawaii. Use of the DSRV MAKALI'I was provided by NOAA, National Undersea Research Program Office, through the Hawaii Undersea Research Laboratory. We also thank the entire staff of HURL, the crew of the R/V LIKTANUR II, K. Coberly (Captain), and W. J. Stanley and H. U. Brown of U.S.D.O.E. This research was supported in part by contract no. DE-AC08-76EV00703 from the U.S. Department of Energy for operation of the Mid-Pacific Research Laboratory and in part by funds from the West Indies Laboratory (Fairleigh Dickinson University). Hawaii Institute of Geophysics contribution No. 1679.

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DATE ACCEPTED: August 12, 1985.

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