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Authors

Druffel, ERM
Williams, PM
Livingston, HD
[et al.](#)

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Variability of natural and bomb-produced radionuclide distributions in abyssal red clay sediments

E.R.M. Druffel¹, P.M. Williams², H.D. Livingston¹ and M. Koide²

¹ Woods Hole Oceanographic Institution, Woods Hole, MA 02543 (U.S.A.)

² Scripps Institution of Oceanography, La Jolla, CA 92093 (U.S.A.)

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The nature of sedimentation and mixing are examined in abyssal red clay sediments from the North Central Pacific using three types of indicators: $^{230}\text{Th}/^{232}\text{Th}$, organic ^{14}C , and ^{137}Cs and $^{239,240}\text{Pu}$. $^{230}\text{Th}/^{232}\text{Th}$ analysed revealed that the clay sedimentation rate in three box cores collected within a 50 km radius was less than $1.0\text{ mm}/10^3\text{ yr}$. However, analyses of the organic carbon in thin layers of sediment revealed that radiocarbon was present much deeper in the cores (down to 20 cm) than was expected from the $^{230}\text{Th}/^{232}\text{Th}$ distribution. In addition, both the stratigraphy and inventory of radiocarbon was significantly different between box cores. The distributions and inventories of ^{137}Cs and $^{239,240}\text{Pu}$ were similar to that found for radiocarbon, further illustrating the spatial variability of radionuclides in oligotrophic North Pacific red clays. These data suggest that bioturbational processes are important for transporting organic carbon down into the sediment column.

1. Introduction

Sedimentation rates determined using the $^{230}\text{Th}/^{232}\text{Th}$ method were reported by Goldberg and Koide [1] for several locations in the Pacific. Significant variations were found in these red clay sediments ($0.4\text{--}1.6\text{ mm}/10^3\text{ yr}$), and appeared to be a function of distance from the continents.

Williams et al. [2] reported a study of cores from the North Pacific that included long-lived (Th) as well as short-lived (^{14}C) radioisotopes and other chemical parameters (organic C, $^{239,240}\text{Pu}$, $\delta^{13}\text{C}$). They observed that radiocarbon was present below the mixed layer and concluded that of the two feasible mechanisms, bioturbation was more important for pumping ^{14}C down into the sediments than was diffusion. These data were corroborated by $^{239,240}\text{Pu}$ measurements in box cores collected in the central North Pacific, which

showed that mud was actively being moved [3], probably by benthic macrofauna [4]. Hessler and Jumars [4] conducted an extensive study of the benthic macrofauna in the North Pacific. One of these cores (BC-33) was studied by Williams et al. [2] and the data are included in this report for comparison.

It was not discernible from the data [2] whether the ^{14}C present below the mixed layer was truly of bomb origin. Thus, detailed stratigraphies of isotopes with known temporal origin and input rate to the ocean (i.e. $^{239,240}\text{Pu}$ and ^{137}Cs) must be examined in order to define the short-term processes taking place within the red clay sediments.

One of the most useful aspects of the present study is that several sediment cores from the same location are examined. It is concluded here that significantly different profiles and inventories for even short-term tracers exist from core to core. It is of utmost importance that this variability be

defined before a broad brush approach is used for predicting the fate of nuclear waste, fossil fuel CO₂ or other contaminants introduced to the oceans.

2. Sampling locations

The study area was in the extensive abyssal plain underlying the mid-Pacific gyre (MPG-1, 29°N, 156°W), approximately 700 km north of Hawaii. The overlying waters are oligotrophic; net primary productivity is low ($\sim 40 \text{ g C m}^{-2} \text{ yr}^{-1}$), in comparison with coastal or equatorial zones [5,6]. Sediments were collected at a depth of 6 km and consisted mainly of oxic red clays (85% red clay and 15% silt). Manganese nodules were plentiful on top of the sediment, with a general abundance of 40–700 nodules m⁻¹ [4]. Bottom waters at this location had a temperature of 1.6°C, salinity of 34.71‰, oxygen content of 3.7 ml l⁻¹ and phosphate was 2.3 μM [4].

3. Samples

The box cores described here were collected using a modified USNEL (United States Naval Electronics Laboratory) box corer described by Hessler and Jumars [4]. The cores had a surface area of 0.25 m², and a length of about 30–40 cm.

Three box cores were collected from the MPG-1 locality. Two of the cores (33 and 638) were the subject of a previous study [2]. The first core was collected by R.R. Hessler on the Seven-Tow cruise in July 1970 (BC-33) at 6040 m (30°0.9'N, 156°12.5'W). Two other box cores were collected by G.D. Wilson on cruise INDOPAC-15 about 100 km SSE of the first core in June 1977 (box core 638 [H-222], 28°34.4'N, 155°30.3'W at 5780 m; box core 3 [H-236], 28°35.45'N, 155°30.39'W at 5584 m).

The presence of undisturbed Mn nodules on top of two of the cores (33 and 3) assured us that the sediment/water interface had been sampled with minimal disturbance. Even though core 638 had no Mn nodules, the top of the core looked relatively similar in appearance to the other cores. Subsurface levels of Pu in core 638 were reduced in proportion to those in eighteen other cores

(Casso and Livingston, in preparation); therefore we are convinced that minimal loss (< 1 cm) of surface sediment occurred.

Each core was sectioned immediately after recovery of the coring apparatus. For radiocarbon and thorium analyses, an inner sub-core with dimensions of 10–20 cm on each side and 30 cm in depth was used. The sediment/seawater slurry (equivalent to a 2-mm vertical section) was sucked up from the undisturbed center (25 cm × 25 cm area) of core 33 and sieved through a 65-μm mesh stainless-steel screen. The solid upper 3 cm of this core was then sectioned into five layers. The upper 3 cm of cores 638 and 3 were sliced into 1-cm sections. The remainder of each core was sampled in 2-cm increments down to 30 cm leaving about 5 cm of sediment at the bottom. There were no visible macrofauna present in any of the samples. The samples were then frozen at -20°C for subsequent analysis. Elaborate precautions were taken to prevent contamination of the samples with ¹⁴C or dead (¹⁴C-free) carbon. For the plutonium and cesium analyses, a sub-core of 10 cm × 10 cm was taken from each core. These were sectioned into 1-cm increments to 10 cm, 2-cm increments from 10 to 20 cm and 4 cm sections thereafter.

4. Methods

The ²³⁰Th/²³²Th ratios were determined at the Scripps Institution of Oceanography on dried sediment samples using standard methods [1]. Percent sedimentary organic carbon (SOC) was determined on dried sediment using a Hewlett-Packard CHN Analyser. Using this methodology, no measurable differences were found in SOC between acidified and non-acidified sediment samples, indicating that the carbonate content was < 0.03%. Percent carbonate was independently determined on core 3 by measuring CO₂ released upon acidification using a Beckman non-dispersive infrared CO₂ analyser.

The thawed sediment samples used for ¹⁴C activity determinations were acidified to pH 3–4 with distilled 6 N HCl, and all samples were dried to constant weight at 80°C. Thereafter, the sediment samples (100–120 g) were burned in a stream

of prepurified oxygen at 600°C for 2–3 hours. Conventional vacuum line techniques were used to obtain CO₂ of high purity necessary for gas-proportional counting. Each CO₂ sample was aged for 4 weeks before counting to ensure decay of any ²²²Rn (3.8-day half-life). The ¹⁴C activity was measured at the La Jolla Radiocarbon Laboratory using a 200-ml copper gas proportional counter filled to a pressure corresponding to 90 cm CO₂ at 25°C. A minimum of 10,000 counts was accumulated for each sample, normally over two separate counting periods. Two blanks were run; one using no sediment and the other using the oxidized portion of an original sample. No CO₂ was evolved by either procedure. The measurable CO₂ recoveries were 70–90% based on the total SOC contents. The $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ values and ages quoted in Table 2 have been calculated in the standard manner [7].

Plutonium and cesium determinations on cores 3 and 638 were performed at the Woods Hole Oceanographic Institution using standard procedures [3]. Core 33 was analyzed for Pu at the Scripps Institution of Oceanography [8]. Results are reported as disintegrations per minute per kg of dry sediment.

TABLE 1

²³⁰Th/²³²Th activity ratios for three cores examined in this study^a

Core	Depth (cm)	²³⁰ Th/ ²³² Th
33	0–3	27.3 ± 0.1
33	9–11	26.0 ± 1.3
33	15–17	13.2 ± 0.4
33	28–30	4.9 ± 0.2
638	0–1	27.8 ± 2.2
638	3–5	23.0 ± 1.8
638	9–11	17.6 ± 0.7
638	15–17	10.2 ± 0.2
638	23–25	5.6 ± 0.3
3	1–2	32.3 ± 2
3	4–5	29.5 ± 1.8
3	7–8	20.3 ± 0.8
3	9–10	18.9 ± 0.8
3	12–13	10.5 ± 0.4
3	14–15	8.2 ± 0.3
3	19–20	5.9 ± 0.2

^a Measurements made at the Scripps Institution of Oceanography.

5. Isotopic profiles

An estimate of the sedimentation rate is determined using the ²³⁰Th/²³²Th ratios (Table 1) as displayed in Fig. 1. As the half-life of ²³⁰Th (75,200 years) is extremely short compared to that of ²³²Th (14.1 × 10⁹ years), the rate of accumulation of sediment is calculated from the slope of the ratios below the mixed layer. Even though the depth of the mixed layer is difficult to determine due to limitations in data frequency there appears to be a break between 5 and 10 cm for all cores. The sedimentation rates calculated from data below 5–10 cm vary among the cores from 0.75 mm/10³ yr in core 3 to 1.05 mm/10³ yr in core 638. Considering the amount of scatter in these data, it appears that the difference in sedimentation rates between cores 33 and 638 is not significant, but that core 3 does show a slightly lower sedimentation rate than the other two cores. The average of these values (0.95 mm/10³ yr) is in agreement with the average value of 1.0 mm/10³ yr found by

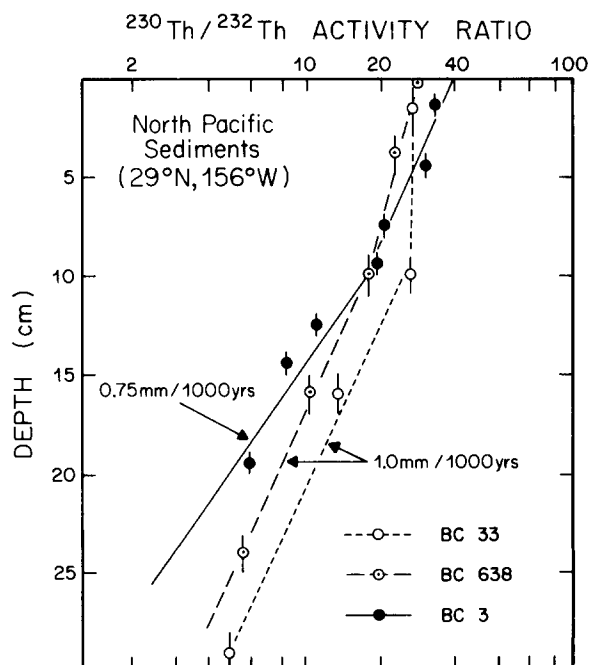


Fig. 1. ²³⁰Th/²³²Th activity ratios in cores 33, 638 and 3. The sedimentation rates, determined from the slope of each set of points below the mixed layer (10 cm), are 0.75–1.05 mm/1000 years.

Goldberg and Koide [1] for sediments in the North Pacific (19°N, 178°W). However, it is likely that bioturbation extends down to depths as great as 20 cm in this region, according to Bowen et al. [9]. If this is the case, then the slope of values between 10 and 20 cm is artificially steep due to mixing and the sedimentation rate calculated above ($1 \text{ mm}/10^3 \text{ yr}$) is an overestimate, perhaps by even an order of magnitude, of the actual accumulation rate. Without additional data from below the 20-cm horizon, we can only conclude that bioturbation is more intense in the top 5–10 cm of these sediments, than it is at depths between 10 and 20 cm. As a result, only a maximum estimate for the sedimentation rate ($\leq 1 \text{ mm}/10^3 \text{ yr}$) can be calculated.

Results of organic analyses performed on these cores are shown in Fig. 2. Percent SOC in dry sediment from cores 638 and 3 (Fig. 2A) range from 0.3 at the top of the cores to 0.1% below 20 cm. The abundance of SOC in core 33 appears lower (0.2%) in the surface slurry than in the top 3 cm of sediment. This low value may reflect screening out of large ($> 65 \mu\text{m}$ diameter) organic particles. The SOC profiles from cores 638 and 3 are slightly different in that core 638 has slightly lower values than core 3 in the mixed layer, and slightly higher values than core 3 below this horizon.

Inorganic carbon in core 3 (Fig. 2) is very low

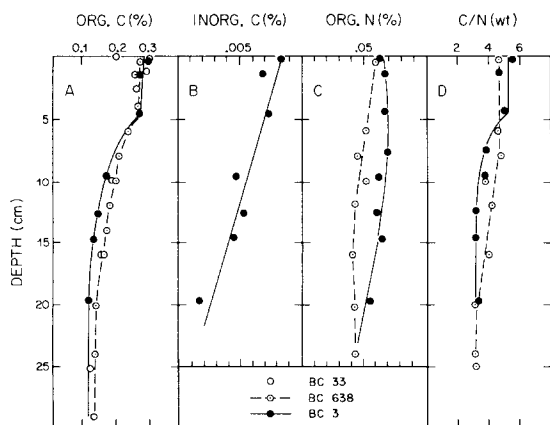


Fig. 2. Chemical data on sediment cores (all % dry weight in grams): (A) % organic carbon; (B) % inorganic carbon; (C) % organic nitrogen, and (D) organic C/organic N ratios (by weight).

and decreases from 0.0085 at the top to 0.002 at 20 cm. C/N ratios in cores 3 and 638 are especially low (4–5) and decrease with depth (Fig. 2). Muller [10] has attributed these low ratios to both the unusually high percentage of ammonium nitrogen (70%) and to organic N compounds sorbed within the clay minerals.

The radiocarbon data are presented in Fig. 3 and are listed in Table 2. The error bars represent one sigma (1σ) error from counting statistics. The upper 1 cm of sediment in cores 3 and 33 have $\Delta^{14}\text{C}$ values of -655‰ to -635‰ , reflecting an age of 7500–8500 years B.P. These ages are older than those found for inorganic carbon at other sediment locations in the world oceans [11,12] because these latter studies were performed in areas where the sedimentation rates were several times higher (and mixing rates were similar) than those in the North Pacific.

The ^{14}C activity in the surface slurry (0–0.2 cm) from core 33 was not significantly higher than the ^{14}C activity found at 0.2–0.4 cm, and just significantly greater than that in the 2.7–3.0 cm section (Table 2). This implies rapid mixing and/or rapid utilization in the upper 3 cm of POC reaching the seawater/sediment interface.

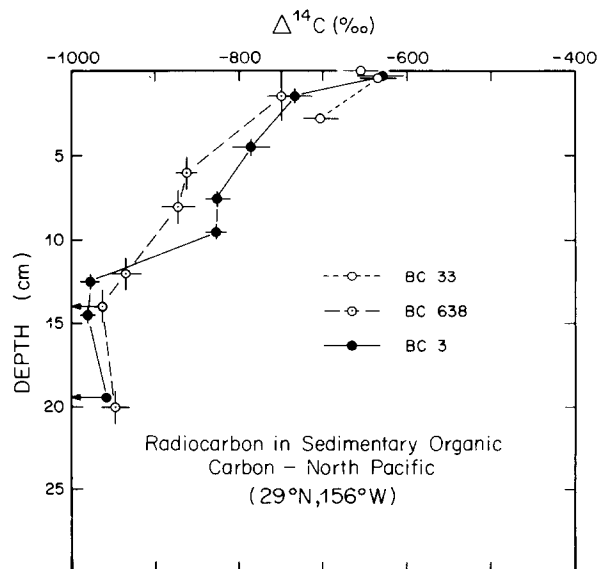


Fig. 3. $\Delta^{14}\text{C}$ measurements of organic carbon in sediment cores 3, 33 and 638.

TABLE 2

$\Delta^{14}\text{C}$ in permil, radiocarbon ages in years B.P. (Libby half-life 5568 years) and $\delta^{13}\text{C}$ of organic carbon in sediment samples. Radiocarbon results from core 638 have been corrected slightly ($\pm 1\sigma$) since they were first reported [14] due to refinements in backgrounds and standards

Core	Depth (cm)	Sample No.	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	^{14}C age (years B.P.)
33	surface slurry	^a	-19.7	-655 ± 22	8,500 ± 500
33	0.2-0.4	^a	-19.7	-635 ± 23	8,100 ± 500
33	2.7-3.0	^a	-18.7	-703 ± 22	9,700 ± 600
638	0-3	LJ-4223	-20.1	-750 ± 17	11,120 ± 550
638	5-7	LJ-4055	-18.3	-863 ± 12	15,960 ± 700
638	7-9	LJ-4221	-20.3	-872 ± 20	16,540 ± 1890
638	11-13	LJ-4222	-21.0	-936 ± 18	22,120 ± 2000
638	13-15	LJ-4301	-21.1	< -961	> 26,060
638	19-21	LJ-4054	-21.3	-948 ± 18	23,790 ± 2870
3	0-0.5	LJ-5067	-18.7	-630 ± 23	7,980 ± 500
3	1-2	LJ-4695	-19.2	-734 ± 18	10,650 ± 560
3	4-5	LJ-5068	-18.1	-786 ± 23	12,390 ± 900
3	7-8	LJ-5288	-17.5	-826 ± 13	14,050 ± 630
3	9-10	LJ-5069	-18.8	-829 ± 12	14,190 ± 550
3	12-13	LJ-5289	-19.3	-979 ± 10	31,060 ± 3800
3	14-15	LJ-5290	-19.0	-980 ± 9	31,350 ± 3660
3	19-20	LJ-4696	-21.3	< -958	> 25,520

^a reported by Williams et al. [14].

Radiocarbon is detected down to at least 20 cm depth in box core 638 and down to 15 cm in box core 3, implying an apparent enrichment of organic ^{14}C in these sediments with respect to the $^{230}\text{Th}/^{232}\text{Th}$ distribution. Given the maximum estimate for the sedimentation rate of $1\text{ mm}/10^3\text{ yr}$, the sediment below 10 cm depth is supposedly >100,000 years old, far beyond the detection limits of radiocarbon (35,000 years using small counter techniques). The $\Delta^{14}\text{C}$ values below 10 cm should be -1000‰ , if the mechanisms controlling the sedimentation and mixing of POC are the same as those for red clay. Instead the values range from about -900‰ to -980‰ . These data suggest that the flux of total organic carbon into the sediments is enhanced with respect to that for clay particles. There apparently is a mechanism responsible for the injection of significant quantities of recent organic matter into the sedimentary column to depths below 10 cm. Using a mass balance equation, only 4 or 5% recent carbon (with $\Delta^{14}\text{C}$ values of 150‰ (post-bomb) or -50‰ (pre-bomb) [13], respectively) would be required to raise the $\Delta^{14}\text{C}$ of SOC from -1000‰ to the ob-

served average value of -950‰ , present at depths between 10 and 20 cm in the sediment column (estimated from Fig. 3).

One mechanism responsible, at least in part, for the transport of recent organic carbon below 10 cm depth is the burrowing of organisms, where the numbers and lengths of their excursions, and hence the organic carbon flux, decreases with depth.

A second mechanism that could be responsible for the presence of measurable ^{14}C below the mixed layer is diffusion of bottom water DOC or of recently deposited POC that had been solubilized by bacterial decomposition and diffused down into the sediment column. If an estimate of the $\Delta^{14}\text{C}$ value for DOC in Pacific bottom waters is -400‰ (extrapolated from Williams et al. [14]), then only 8% by weight DOC would be required to raise the $\Delta^{14}\text{C}$ of SOC from -1000‰ to -950‰ .

Another important aspect of these radiocarbon data is the apparent variability among profiles (Fig. 3). Box cores 3 and 33 are 40-80% higher in $\Delta^{14}\text{C}$ than core 638 in the mixed layer and box core 3 is 60% lower than 638 below the mixed layer. These differences would be retained even if

1 cm of sediment had been lost from the top of core 638. Integration of the profiles reveals that there is 40% more ^{14}C in core 3 than in core 638 in the upper 10 cm, with no significant corresponding excess of total SOC in core 3. This may indicate that the $^{14}\text{C}/^{12}\text{C}$ ratio of at least a fraction of the organic matter in core 3 is higher than that in core 638. This could have been achieved had a significantly larger amount of post-bomb particulate organic carbon reached the core 3 location. This scenario is supported by the stable carbon isotope data (Table 2), which show less negative $\delta^{13}\text{C}$ values in core 3 than in core 638 in the upper 10 cm, indicating a more labile source of organic carbon in the mixed layer of core 3. However, higher $\delta^{13}\text{C}$ values are also found in core 3 below 11 cm, where the ^{14}C trend reverses to reveal lower $\Delta^{14}\text{C}$ values in core 3. This could be explained by higher levels of DOC in core 638 than in core 3 which would cause low $\delta^{13}\text{C}$ values (-22 to -20‰) and measurable quantities of ^{14}C below the mixed layer. In any case, the varying $\Delta^{14}\text{C}$ profiles indicate that there is spatial variability in red clay sediments caused by reworking (variable benthic or bottom current activity) and perhaps partially by variations of the rates of input of DO^{14}C to the sediments.

The $^{239,240}\text{Pu}$ and ^{137}Cs data tabulated in Table 3 are shown in Fig. 4. Both $^{239,240}\text{Pu}$ and ^{137}Cs were considerably more enriched in core 3 than in core 638. An inventory of those bomb-produced radioisotopes reveals that there is 6 times as much $^{239,240}\text{Pu}$ and 4 times as much ^{137}Cs in core 3 than in core 638, respectively. A similar trend is present in the radiocarbon data; core 3 was enriched by 1.4 times in ^{14}C compared to that in core 638 in the top 10 cm. This provides further evidence that these sediments are heterogeneous over a spatial scale of less than 2 km.

The apparently lower excess of ^{14}C in core 3 over core 638 (1.4 times) as compared to the Pu and Cs excesses (4–6 times), might be due to ambient levels of natural ^{14}C damping the post-bomb signal. If indeed there are 4–6 times more bomb ^{14}C in core 3 than in core 638, then about 80% of the ^{14}C present in core 638 is of pre-bomb origin. This scenario is consistent with the apparently deeper penetration of ^{14}C (19 cm) than

TABLE 3

 $^{239,240}\text{Pu}$ and ^{137}Cs activity in sediment cores ^a

Core No.	Depth (cm)	$^{239,240}\text{Pu}$ (dpm/kg dry wt.)	^{137}Cs (dpm/kg dry wt.)
33	0–3 ^a	1.7 ± 0.08	
638	0–3	1.2 ± 0.16	
638	0–1	2.1 ± 0.1	63 ± 7
638	1–2	0.8 ± 0.2	7 ± 4
638	2–3	1.3 ± 0.3	7 ± 4
638	3–4	1.0 ± 0.2	5 ± 3
638	4–5	0.1 ± 0.1	5 ± 3
638	5–6	0.3 ± 0.1	
638	6–7	0.8 ± 0.4	-3 ± 5
638	8–9	0.1 ± 0.1	3 ± 4
638	10–12		2 ± 2
3	0–1	19.5 ± 1.9	275 ± 9
3	1–2	10.8 ± 1.1	37 ± 6
3	2–3	7.3 ± 0.8	18 ± 4
3	4–5	1.3 ± 0.2	19 ± 11
3	6–7	0.7 ± 0.2	9 ± 4
3	10–12	0.3 ± 0.1	1 ± 3

^a All measurements were made at the Woods Hole Oceanographic Institution, except for those of core 33 which were made at the Scripps Institution of Oceanography.

for the other bomb nuclides (10–12 cm). The ^{14}C at levels below 10 cm may be natural or post-bomb DO^{14}C that diffused or natural PO^{14}C that was advected (or was solubilized by bacterial oxidation and then diffused) down through the sediment column. To estimate the possible diffusion of bomb-labelled DO^{14}C into the sediments we use

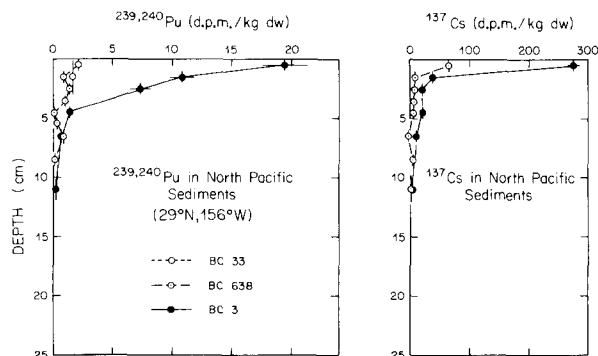


Fig. 4. $^{239,240}\text{Pu}$ and ^{137}Cs (disintegrations per minute/kg dry weight) measured in sediment from cores 33, 3 and 638. Unless otherwise noted, uncertainties are less than the size of the plotted symbols.

the Crank [15] estimation for the diffusion of a front, i.e., $X = 2\sqrt{DE}$, where X is the distance diffused in time t . If one assumes that bomb DO^{14}C is released at the sediment/water interface and diffuses with $D \approx 4 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ for ~ 10 years, the penetration would be about 20 cm or that observed for ^{14}C . The problem with the diffusion hypothesis is that the carbon content of DOC in the pore waters is much lower than that in the bulk sediment.

In addition to the above data (Fig. 4), Bowen et al. [9] published similar results from 17 other cores taken in the MPG-1 area during the time period 1974–1979. They showed that inventories of $^{239,240}\text{Pu}$ varied by a factor of 10 and that of ^{137}Cs by a factor of 7. Cores 3 and 638 were on the high and low end, respectively, of these trends. Likewise, the concentrations of $^{239,240}\text{Pu}$ and ^{137}Cs in the uppermost centimeter of these cores varied by as much as factors of 20 and 25, respectively. Bowen et al. [9] pointed out that there was neither a correlation of nuclide concentration with the year the core was collected, with the sampling device used, nor with the position of the sediment either on topographic highs or lows of the abyssal plain. They also revealed that the depth of bomb fallout nuclide penetration in these cores varied over a wide range (5–19 cm) for such a restricted and oligotrophic region, and that this penetration was not merely a function of the nuclide inventory. Thus, tracers that had been in the ocean for a period of < 20 years had penetrated down to 19 cm at some locations. Assuming the primary mixing mechanism for penetration of these tracers was bioturbation, then we must assume that longer term tracers, i.e., Th and ^{14}C , have also been mixed down to at least this depth. Thus, we can conclude that the mixing depth, at least on a long-term basis (> 100 years), is at least 19 cm in the sediment column in the North Central Pacific.

6. Comparison of various tracers

Profiles are presented for three different types of isotopic tracers in abyssal red clay sediments (Fig. 5). The first, represented by the thorium isotope ratios, is exclusively from natural sources

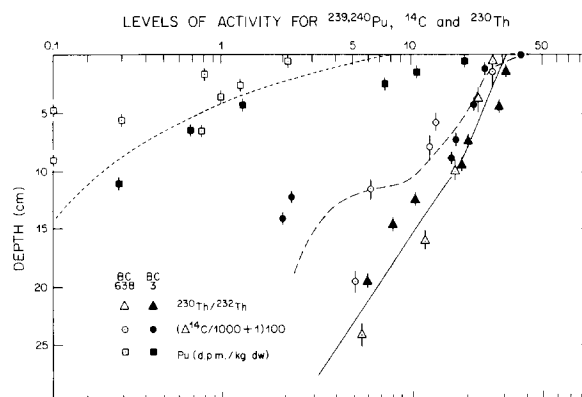


Fig. 5. Activities of three isotopes measured in cores 3 and 638: (1) $^{230}\text{Th}/^{232}\text{Th}$; (2) $(\Delta^{14}\text{C}/1000 + 1)100$; and (3) $^{239,240}\text{Pu}$ (dpm/kg dry wt.).

and its input is assumed to have remained constant during a period of several of its half-lives. Such radiotracers are a good measure of sedimentation rate if the appropriate half-lives are long enough for the tracer to remain detectable below the mixed layer. Shorter-lived species, such as ^{210}Pb are good indicators for mixing rate in the uppermost layers of the sediment.

The second type of tracer is purely of bomb origin. No natural source exists for isotopes such as $^{239+240}\text{Pu}$ or ^{137}Cs . Instead, thermonuclear bomb testing introduced these tracers to the stratosphere and then to the surface water during the course of a few years. These tracers were carried to the deep sea via particulate matter and were distributed into the sediment by particle mixing and, possibly, by mobilization into pore waters. Thus, sediment horizons containing Pu or Cs contain material that has been in the surface waters within the past 25 years. In low sedimentation areas, such as MPG-1, from purely mixing considerations one would not expect to find these tracers in measurable concentrations below horizons impacted by mixing processes active over time scales comparable to the period between their initial arrival at the sediment interface and sampling.

The third type of tracer measured in our cores has both natural and bomb origins. Radiocarbon in the SOC fraction of the red clay sediments originates from natural and post-bomb PO^{14}C car-

ried to the sediments via particulate matter. The half-life of ^{14}C is only 5730 years, short in comparison to the sedimentation rate ($< 1 \text{ mm}/10^3 \text{ yr}$). We have estimated that as much as 80% of the organic ^{14}C in our cores is from natural sources. Bomb ^{14}C is also present in these cores, and like Pu and ^{137}Cs , is probably virtually all in the upper 10 cm of the sediment column. Radiocarbon exhibits a steep gradient in the mixed layer, similar but not as great as that for Pu (Fig. 5). Had there been only natural ^{14}C present in the upper 10 cm, a lower gradient, such as that for Th, would have been expected. Thus, in several thousands of years, the activity gradients for ^{14}C and Pu in the upper 10–20 cm of these red clay sediments will become less than at present due mainly to bioturbation and possibly by remobilization in the dissolved form.

7. Mixing processes

Hessler and Jumars [4] presented a comprehensive description of the benthic communities in red clay sediments from the CLIMAX II location (MPG-1), where core 33 was collected. They found that the benthic community consisted of 55% polychaetes and the rest was made up of tanaids, bivalves, isopods and other deposit feeders. The typical individual was $< 0.5 \text{ cm}$ long and conducted an ambulatory mode of life. In the ten cores analyzed, no tube-dwellers were found, but investigations were not made for burrow-like structures.

The chemical and radioisotopic data presented here clearly show that sediment profiles display heterogeneity from location to location, even within a 2 km radius (as was the case with cores 3 and 638). Variability of ^{14}C , $^{239,240}\text{Pu}$, ^{137}Cs , ^{13}C and total organic carbon depth distributions within the sediments can be explained by three mechanisms. The first involves variation in the activity of benthic organisms. This requires that the organisms traverse down at least to the bottom of the 10–12 cm horizon in order to explain the presence of bomb-produced Pu and Cs down this far. The macrofaunal and meiofaunal benthic community, however, is concentrated in the upper 2 cm of the

sediment (R.R. Hessler, personal communication). This leaves the larger burrowing organisms as the probable culprits. Their burrow-like structures have been observed in red clay sediments to depths of 1.5 m in the South Pacific by Thomson and Wilson [16] and to 2.1 m in turbidite and red clay sediments in the northeast Atlantic [17]. The abundance of burrows at our study site is not likely to be as high as in areas where overlying waters are more productive, such as the eastern equatorial Pacific studied by Berger et al. [18], the Cascadia Plain Slope-Basin described by Carey [19] or the Walvis Ridge area studied by Thomson and Wilson [16]. Thomson and Wilson [16] and Weaver and Schultheiss [17] observed these structures by separating two halves of the core barrel or box core sediment on deck; fresh fracture surfaces were exposed at intervals by portions of sediment tearing away. The authors explain that these features would not have been observed using most conventional coring devices, including the USNEL box corer, unless the sediments were “fractured”. Recent habitation (within the past few hundred years) by burrowing organisms at or near our coring sites would provide the transport mechanism necessary to pump down organic- (and ^{14}C -) rich particles or seawater laden with DOC to well past 10 cm.

Smith and Baldwin [20] have shown that scavenging amphipods efficiently utilize large episodic falls of organic matter (i.e., fish) in the food-limited environment of the deep North Atlantic and western North Pacific Oceans. These falls constitute a second mechanism that can contribute to maintaining the heterogeneity of the sediments with respect to inventory and depth of bomb radionuclide distribution. Patchiness [21] or seasonal variability [22] of the primary productivity (and thus the particle flux) in the overlying waters can probably be ruled out as a cause of the variation in inventories of bomb-produced nuclides. As the time scale of most plankton blooms is of the order of a few weeks and that of seasonal variations is one year, one would expect patchiness in the sediments to have smoothed out over a 25–30 year period.

An additional mechanism that could be responsible for the observed heterogeneity in surficial

cial organic particulates involves sporadic local instances of high-energy bottom currents [9]. Currents measured 1.6 m above bottom in the location where box cores were collected averaged 2 cm s^{-1} ($< 0.5\text{--}5 \text{ cm s}^{-1}$ range) (C. Ingram, personal communication). Should faster currents occur very infrequently and at a period when the particle flux has an especially high concentration of bomb-produced radionuclides, this would be most effective in fixing a minimum inventory to a given location that had been swept by the current.

8. Conclusions

From the distributions of various chemical and radioisotopic parameters in red clay sediments from the central North Pacific, it appears that the major mixing mechanism is burrowing by large organisms (i.e. worms) to depths of at least 10–12 cm (≥ 19 cm on longer time scales). The presence of ^{14}C between 10 and 20 cm depth is most likely the result of pre-bomb PO^{14}C that has been mixed down into the sediment column by bioturbational processes. Spatial variation of the inventories and the depths of penetration of bomb products is a prominent feature in red clay sediments and may be due to intensification of worm burrowing activities in areas which have received enhanced recent episodic falls of food material or redistribution of incoming sedimentary material by high-energy bottom currents.

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