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^{210}Pb-Derived Bioturbation Rates in Sediments Around Seamounts in the Tropical Northwest Pacific

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To evaluate bioturbation coefficients (D_B) and mixing depths (L), ^{210}Pb and ^{226}Ra activity was measured in two sediments cores (from water depths of 5,398 m and 4,428 m), which were collected from seamount areas in the Northwest Pacific. Using a steady-state diffusion mode, we estimated D_B values of 16.8 and 24.1 cm^2/a, higher than those in abyssal sediments and those predicted by traditional empirical equations. Corresponding *L* values varied between 19.3 and 23.1 cm. These high values indicate that seamounts are the area of active bioturbation. A one-dimensional model for the transport of total organic carbon (TOC) from the surface layer of sediments to the deep layer was developed using the distribution pattern of the specific activity of excess ^{210}Pb ($^{210}Pb_{ex}$) and its relationship with TOC. The model showed that the TOC flux transmitted downward by bioturbation was 0.09 mmol/(cm^2·a) and 0.12 mmol/(cm^2·a).

Keywords: seamount, ^{210}Pb, ^{226}Ra, bioturbation, Northwest Pacific, TOC

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INTRODUCTION

Biological mixing of marine sediments (bioturbation) can substantially modify the physical, chemical, and biological properties of the sediment record (Trauth et al., 1997). These alterations are reflected in any high-resolution sedimentary record as an attenuation of the short-term variability and major phase shifts between various paleoclimatic tracers (Rodríguez-Tovar and Uchman, 2008). Bioturbation by benthic organisms can affect early diagenesis in surface sediments and the sedimentary record. For example, bioturbation can transport newly deposited material to deep sediment. Bioturbation can also affect the structure and evolution of seafloor communities (Aller, 1994). The importance of bioturbation in mediating biogeochemical processes in the upper centimeters of oceanic sediments provides a compelling reason for wanting to quantify *in situ* rates of bioturbation (Teal et al., 2008). The process of bioturbation, which involves both the dispersal of sediment particles (i.e., sediment reworking) and the transport of interstitial porewater (i.e., bioirrigation) by benthic organisms, occurs in the most oxic sediments and is therefore of global importance.

The bioturbation coefficient is one of the key parameters for the numerical simulation of sediment diagenesis. It is a measure of the transport of organic carbon into the sediment, which places constraints on the redox system of the sediment (Thiel and Tiefsee-Umweltschutz, 2001). Quantification of the bioturbation, therefore, is a prerequisite for the numerical modeling of geochemical processes induced by anthropogenic activities within deep-sea sediment (Suckow et al., 2001).

Seamounts are a unique ecosystem in oceanic environments and are hotspots for pelagic and benthic organisms (Yang et al., 2019). Limited by sampling conditions and other factors, bioturbation in marine sediments around seamounts has been rarely studied until now. Anthropogenic activities, such as the exploitation of polymetallic nodules, can disturb the deep-sea floor and have negative impacts on benthic ecology (Thiel and Tiefsee-Umweltschutz, 2001; Jones et al., 2017). For example, the biogeochemical environment of the seabed along and around seabed mining routes can be altered significantly due to the resuspension of sediments, the release of chemically active substances into the water column, and the subsequent resettlement of the aforementioned materials.

Radioactive disequilibria between radionuclides of the natural uranium and thorium series are used extensively to establish timescales of sedimentation and diagenetic processes within the sediment. ^{210}Pb is a natural radionuclide with a half-life of 22.3 years that has been used extensively to estimate sedimentation rates and biological mixing. ^{210}Pb, produced in the atmosphere and water column by the decay of ^{226}Ra and ^{222}Rn, is exported to the seabed by sinking particles. The ^{210}Pb incorporated into the sediment from this process is called "excess ^{210}Pb" ($^{210}Pb_{ex}$) in that it is of more than ^{210}Pb that is produced *in situ* from the decay of ^{226}Ra and ^{222}Rn within the sediment column (supported ^{210}Pb). The $^{210}Pb_{ex}$ signal decreases over time and approaches zero after about 100 years. If sediment accumulation alone controls the distribution of $^{210}Pb_{ex}$, then $^{210}Pb_{ex}$ activity should not be detectable in parts of the sediment column deposited 100 years ago. However, the $^{210}Pb_{ex}$ signal commonly extends downward, below the expected depth for zero activity in deep-sea sediments, owing to sediment mixing by bioturbation (Legeleux et al., 1994; Yang et al., 2019). In this study, we use ^{210}Pb and ^{226}Ra as radiotracers to quantify the bioturbation mixing depth and diffusion coefficient based on a steady-state diffusion model.

MATERIALS AND METHODS

Study Areas

A large area in the Western Pacific Basin is remarkable for its many large and small seamounts formed during the Cretaceous. Two sediment cores were collected from the MP4 seamount (McDonnell Guyot) of the Marcus-Wake Seamount Cluster in the subtropical Western Pacific Ocean (**Figure 1**). The heights of these seamounts range from 3,656 to 4,022 m, and the base depth is about 5,500 m.

Core MP4-S05-MC08 is from the seamount and MP4-S01-MC07 is from the foothill of mount MP4 in the Western Pacific Ocean. In the sea basin on the north and south sides of the MP4 seamount, the coverage of polymetallic nodules is more than 90%. The nodules on the north side are mainly medium sized, while those on the south side are mainly small (<3 cm).

Sampling

Two sediment cores were collected from the area around MP4 using multiple corers with an inner diameter of 9.5 cm during the R/V XIANGYANGHONG03 Monitoring and Protection of Ecology and Environment Cruise, which was at sea during July–August 2017 (**Table 1**). The multiple corers used in our sampling is able to collect sediments without disturbance. Once aboard the ship, multiple-core tubes were extruded and sectioned at 1 cm intervals for the upper 2-cm depth and then at 2-cm intervals to the end. Each subsample was sealed in a clean polyethylene bag and stored frozen at −18°C.

Assessment of Environmental Background Data

Before analysis, the sediment samples were freeze-dried and homogenized. Water content was determined gravimetrically during freeze-drying.

For the total organic carbon (TOC), 2-g samples were first acidified for 24 h with 4 mol/L HCl and rinsed at least three times with deionized water to remove carbonate carbon. The residues were dried at 50°C, ground, and homogenized. Carbon and nitrogen contents were determined using a Fisons CHN analyzer following the procedure described by Froelich (1980) and modified by Hedges and Stern (1984). Every sample was analyzed in duplicate and the results averaged.

Analysis of ^{210}Pb and ^{226}Ra

The radioactivity of ^{210}Pb was determined using a 46.5 keV gamma-ray with a branching ratio of 4.25% and high-purity germanium (HPGe) detectors (ORTEC 8030, AMETEK, Berwyn, PA, United States). The detection efficiency was calibrated using marine sediment reference standard IAEA-385 (International Atomic Energy Agency, Austria). The specific activity of ^{210}Pb was calculated by the following equation:

$$A = \sum_{i=1}^{n} \left(\frac{N_i}{t} - \frac{N_{bi}}{t_b} \right) \times \frac{1}{\varepsilon_i Y_i m},$$

where A is the specific activity of ^{210}Pb (Bq/kg), Ni and Nbi are peak areas at 46.5 keV of the sample and the blank respectively, t and tb are counting times for sample and blank respectively, ε_i is detection efficiency of ^{210}Pb, Y is branch ratio (4.25%), and m is the weight of the sample (kg).

All the values of excess ^{210}Pb were decay corrected (22.3-year half-life) to the date of the core collection. A correction for self-absorption of the low-energy ^{210}Pb gamma rays was made using the method of Cutshall et al. (1983).

The post-homogenized sediments were sealed in a polyethylene box for at least 20 days. The radioactivity of ^{226}Ra was determined by detection of its decay products ^{214}Pb and ^{214}Bi using gamma spectrometry with HPGe detector (ORTEC 8030). The energy transitions are 295.2 keV (18.4%) and 351.9 keV (35.6%) of ^{214}Pb, and 609.3 keV (45.495) and 1,120.3 keV (14.91%) of ^{214}Bi. Our results showed that the specific activities of ^{226}Ra calculated from peak areas under the 295.2 keV were consistent with those under 609.3 keV, but the activities *via* 351.9 and 1,120.3 keV were inconsistent. The specific activity of ^{226}Ra from 351.9 keV gamma ray was overestimated due to interference of ^{211}Bi, which emits a gamma

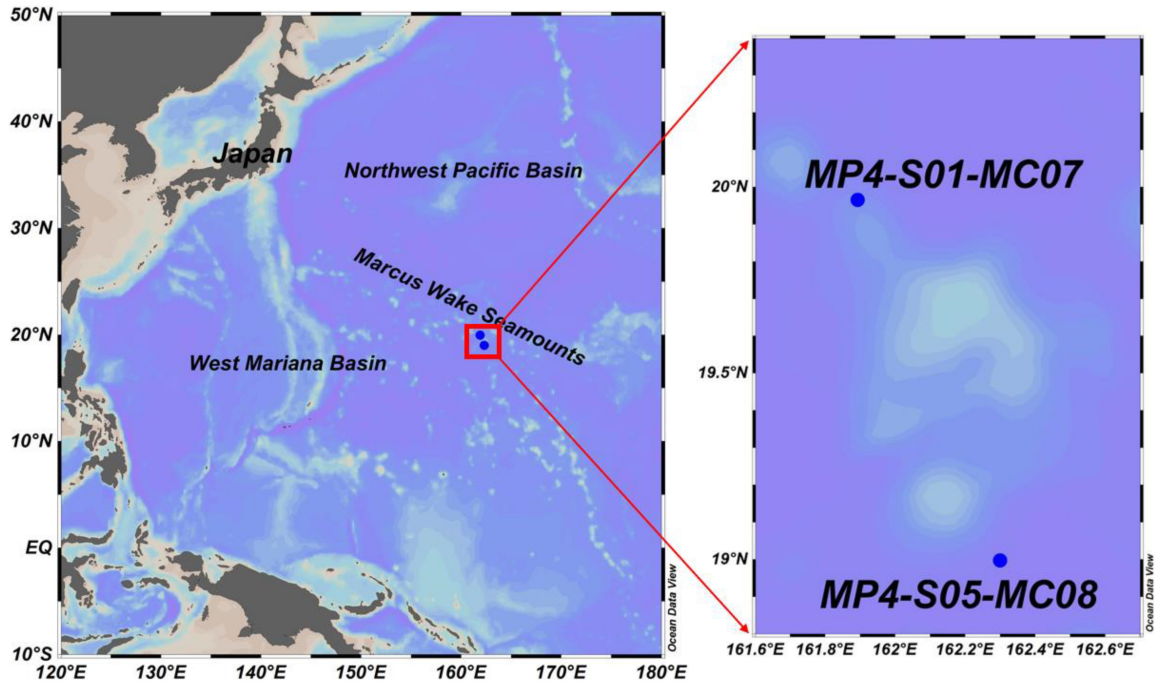

FIGURE 1 | Sampling locations.

TABLE 1 | Sampling locations, water depth, organic carbon content (C_{org}), bioturbation (D_B), and mixing depth (L).

Area	Station	Latitude (°N)	Longitude (°E)	Depth (m)	C_{org} (%)	D_B (cm^2/a)	L (cm)
Seamounts	MP04-S05-MC08	18.9975	162.2994	5398	0.28	16.8	19.3
	MP04-S01-MC07	19.9660	161.8922	4428	0.24	24.1	23.1

ray at 351.1 keV (12.91%). The specific activity of ^{226}Ra from the 1,120.3 keV gamma ray fluctuated substantially due to its low branch ratio (14.91%). Thus, only the peak areas under 295.2 and 609.3 keV were used to calculate the specific activity of ^{226}Ra in this study. The detection efficiency of ^{226}Ra was calibrated using marine sediment standard IAEA-385.

The excess ^{210}Pb ($^{210}Pb_{ex}$), i.e., the fraction exceeding parent-isotope activity, was determined by subtracting ^{226}Ra activity from the total ^{210}Pb activity.

RESULTS

Distribution of ^{210}Pb, ^{226}Ra, and $^{210}Pb_{ex}$ in the Sediment Cores

The ^{210}Pb, ^{226}Ra, and $^{210}Pb_{ex}$ profiles are shown in **Figure 2**. The ^{226}Ra values ranged from 42.75 to 298.87 Bq/kg, with an average of 138.14 ± 67.02 Bq/kg. In the two cores, the highest values were at the subsurface. All profiles show an approximately exponential decrease with depth.

The ^{210}Pb values ranged from 130.74 to 1659.62 Bq/kg, with an average of 487.73 ± 261.91 Bq/kg. The specific activity of ^{210}Pb in sediments increased with depth within a few centimeters of the surface layer and then decreased exponentially with the depth after reaching the maximum value. The specific activity of $^{210}Pb_{ex}$ decreases exponentially with depth and shows the same tread as ^{210}Pb.

Two stations are located near the Zhanlun seamounts. The highest value (848.02 Bq/kg) at station MP4-S05-MC08 appeared at 1–2 cm in the subsurface layer, while the highest value (759.51 Bq/kg) at station MP4-S01-MC07 appeared at 4–6 cm. These values are comparable to the ^{210}Pb values measured by Suckow et al. (2001) in abyssal sediments in the Peru Basin.

Back mixing, in which benthic animal activity such as feeding carries subsurface sediment to the surface, also occurs in many deep sediments. This activity makes the radionuclides at the surface decline rapidly with depth. However, in the subsurface "wide shoulder" (that is, the nuclide specific activity within a certain depth with the increase of the depth remains unchanged) or a great value.

Examples of this pattern include $^{210}Pb_{ex}$ and $^{234}Th_{ex}$ in abyssal sediments (140°W, 0°−5°N) in the equatorial Pacific (Smith et al., 1996) and $^{210}Pb_{ex}$ and ^{137}Cs in abyssal sediments from the northeastern tropical Atlantic (Pope et al., 1996). A three-dimensional distribution of ^{210}Pb of sediments from the continental slope of Newfoundland showed that the mixing of sediments is uneven and the inclined burrowing movement of benthic animals transports a large amount of surface sediments into the interior. As a result, the maximum value of ^{210}Pb

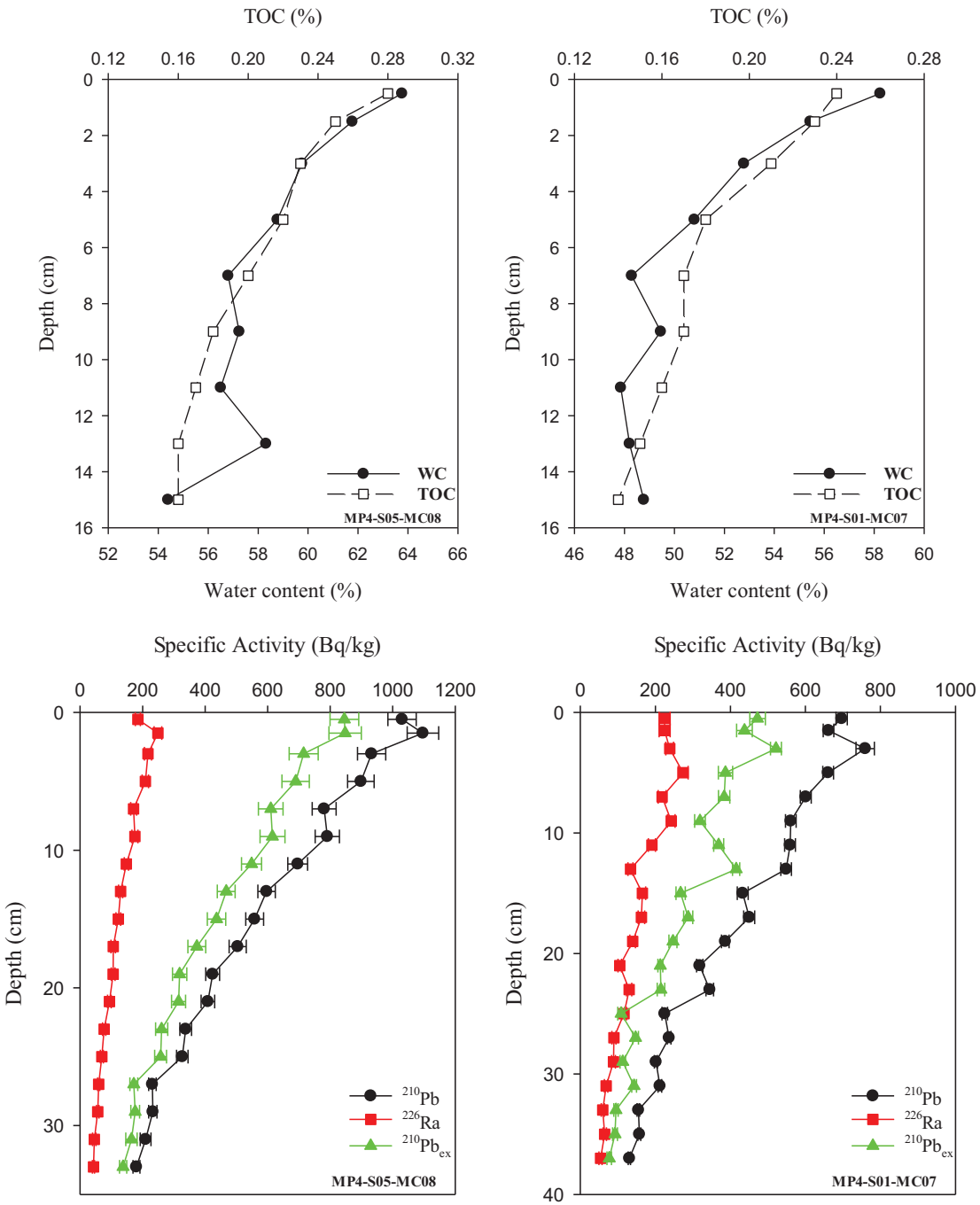

FIGURE 2 | Profiles of total organic carbon, water content, and activity of ^{210}Pb, ^{226}Ra, and ^{210}Pb$_{ex}$ in sediment cores.

is at a certain depth under the sediment–water interface (Smith and Schafer, 1984).

Distribution of Total Organic Carbon, Water Content, and Total Nitrogen

Total organic carbon varied between 0.14 and 0.28%, with an average of 0.19 ± 0.04%. The pattern shows an exponential decline with depth. The TOC in our study is lower than the central North Pacific (0.21–0.40%) (Müller and Suess, 1979) and the central equatorial Pacific (0.26–0.68%) (Smith et al., 1996).

Water content varied between 47 and 89%. The overall trend is a gradual decrease with depth, which is similar to the change in TOC.

Total nitrogen content at the sediment surface fluctuated between 0.06 and 0.07%, with values at the northern station

lower than the southern station. The surface C/N ratios were 4.9 at both stations.

Bioturbation (D_B and L)

The relevance of biological mixing in the inventory estimates was inferred from the bioturbation coefficient (D_B). D_B and bioturbation mixing depth (L) were estimated from the specific activity of the vertical distribution of $^{210}Pb_{ex}$ in the sediment.

Owing to the half-life of ^{210}Pb, the $^{210}Pb_{ex}$ signal is detectable for only about 100 years. Since sedimentation rates in the deep-sea area are less than 1 millimeter per thousand years (Nozaki et al., 1977; Yang et al., 2019), $^{210}Pb_{ex}$ should be detectable only within the top 1 mm of the sediment column. All the earlier studies have found ^{210}Pb in the deep-sea sediments down to a depth of several centimeters, which was interpreted to be a result of bioturbation (Nozaki et al., 1977; Smith and Schafer, 1984; Muñoz et al., 2007).

Goldberg and Koide (1962) and Guinasso and Schink (1975) described the process of bioturbation in a first approximation steady-state diffusion model that included radioactive decay.

This model was improved by Nozaki et al. (1977). When a biological diffusion model is applied, the biological mixing process of tracer material in sediments must meet two conditions: (1) the frequency of biological mixing must be much greater than the disappearance rate of the tracer and (2) the size of the particle exchange must be smaller than the size of the tracer profile and the thickness of the mixing layer.

$$\frac{\partial}{\partial t}(\rho A) = \frac{\partial}{\partial z}\left(\rho D_B \frac{\partial A}{\partial z}\right) - \frac{\partial}{\partial z}(\rho S A) - \lambda \rho A, \quad (1)$$

where z is the depth within the sediment column (cm), A is the tracer-specific activity of $^{210}Pb_{ex}$ (Bq/kg) in the depth of z, ρ is the bulk sediment density (g/cm^3), D_B is the bioturbation coefficient (cm^2/a), S is the sedimentation rate (cm/a), λ is the decay constant of ^{210}Pb (0.031 a^{-1}), and t is the time (a).

In this model, the bioturbation process is considered to be a vortices-like diffusion mixing process. It is assumed that in the mixing layer, the biological disturbance coefficient D_B, deposition rate S, and ρ of sediment density are in a constant state, such that $\frac{\partial}{\partial t}(\rho A) = 0$.

The solution with the boundary conditions, $A = A_0$ at $z = 0$ and $A \to 0$ at $z \to \infty$ (Equation 1) is given by:

$$A = A_0 exp\left[\frac{S - \sqrt{S^2 + 4\lambda D_B}}{2D_B} z\right]. \quad (2)$$

Since the deposition rate of oceanic sediments is generally in the order of mm/ka, and the timescale of the action of ^{210}Pb tracer bioturbation is only about 100 a, the deposition of sediments can be ignored within the timescale of the tracer, and the aforementioned equation is simplified to:

$$A = A_0 exp\left[-z\sqrt{\lambda / D_B}\right]. \quad (3)$$

An exponential fit to a measured depth profile of $^{210}Pb_{ex}$, therefore, gives a quantitative measure of the bioturbation. In this model, the mixing depth L is the depth in the sediment at which the fitted tracer concentration has decreased to 1/e and can be computed by:

$$L = \sqrt{D_B / \lambda}. \quad (4)$$

According to **Figure 3**, D_B and L in MP4-S01-MC07 are 24.1 cm^2/a and 23.1 cm, and are 16.8 cm^2/a and 19.3 cm in MP4-S05-MC08, respectively.

The average is 20.5 ± 5.2 cm^2/a, which is the same as the global average of 19.98 $\pm$ 42.64 cm^2/a (Teal et al., 2008) but higher than the bioturbation coefficients of the deep-sea sediments in the Western Pacific and high-productivity areas such as the Peru Basin (Suckow et al., 2001), Washington shelf edge (Yan and Zhou, 2004), Puget Bay (Carpenter et al., 1985), and the southwest polar shelf (Maire et al., 2008). Both stations were sampled in the summer, which, according to the statistics of Teal et al. (2008), is the time when the bioturbation rate is the highest. The aforementioned differences reveal the possible relationship between the intensity of the biological disturbance and sea productivity. Some studies also show that POC output flux in the water column regulates the depth of sediment mixing layer and the intensity of bioturbation (Smith et al., 1997; Boudreau, 1998).

DISCUSSION

There are many factors influencing the bioturbation of sediments, such as deposition rate, organic carbon deposition flux at the sediment–water interface, abundance of benthic organisms, community structure, living habits and disturbance mode, water depth, oxygen solubility in bottom water or penetration of dissolved oxygen in sediments, sediment type, and hydrodynamic conditions. These factors interact with each other to affect biological disturbance, but the relative importance of each factor varies in different marine environments. However, the intensity of biological disturbance in specific sea areas is usually regulated by major influencing factors.

Influence of Water Depth

It can be seen from **Table 1** that there is a higher bioturbation coefficient at the station with the shallower water depth. This is consistent with the law discovered by Middelburg et al. (1997) that global marine sediment bioturbation decreases with increasing water depth. An empirical is proposed to describe the relationship between D_B and water depth based on data from the Eastern Pacific and the North Atlantic ($D_B = 5.2 \times 10^{0.762 - 0.0004 \times Z}$). According to this equation, the values of D_B (0.51 and 0.21 cm^2/a) in our study are two orders of magnitude lower than those derived by $^{210}Pb_{ex}$.

Although statistics of Middelburg are based on the global sediment bioturbation data, there are only two deep water stations in this study. More data will be needed to confirm and support this theory in the future.

Relationship Between Bioturbation and Organic Carbon and Nitrogen Contents in Sediments

Animals that forage for sediments in the deep ocean far outnumber those that feed on the suspended matter. Because the

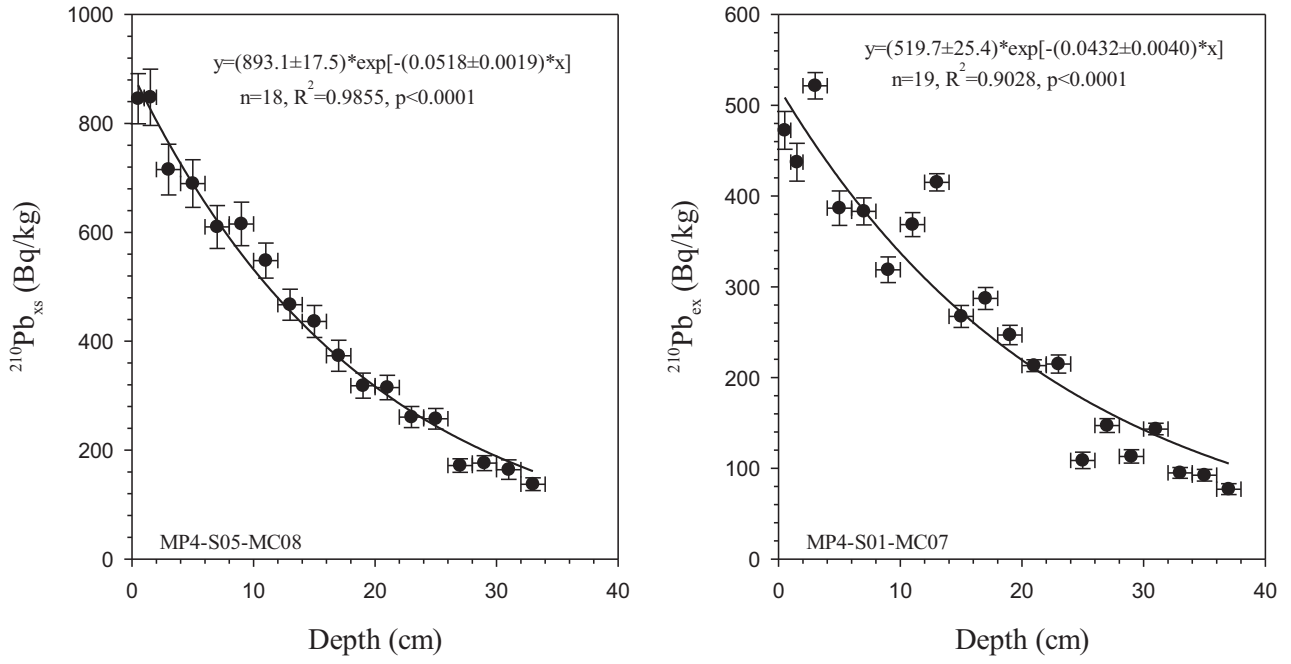

FIGURE 3 | The relationship between specific activity of $^{210}Pb_{ex}$ and depth in sediment cores. The fitting curve and equation are shown in each panel.

amount of nutrients in the form of bacteria and other particles is so small, sediment-eating animals have to eat large amounts of sediment to get enough organic carbon to survive. It is estimated that 100 g of sediment may pass through the digestive tract of sea cucumbers every day (Gage and Tyler, 1991). Therefore, the content of organic matter in sediments directly affects the ability of animals to process sediment particles. Boudreau (1998) believed that biological mixing strength increased with the increase of food quantity. They defined the biological diffusion coefficient as a function of the unstable concentration of active organic matter. That is, unstable organic matter degrades as it is mixed downward, and all available unstable organic matter degrades to a certain depth, so the biological diffusion coefficient as a function of organic matter disappears.

Bioturbation in this study area may be controlled by TOC content in sediments. It can be seen from **Figure 4**. In both cores, there is a good positive correlation between the specific activity of $^{210}Pb_{ex}$ and the content of TOC. This result is consistent with the positive correlation between food sources and bioturbation intensity observed in the northeast Atlantic (Legeleux et al., 1994) and the central equatorial Pacific (Pope et al., 1996; Smith et al., 2000).

Studies have shown that the POC output flux in the water column of the tropical Pacific controls the rate of benthic biological and chemical processes (Pope et al., 1996; Alperin et al., 2002). The research results in the polymetallic nodule area of the Eastern Pacific Ocean also show that the higher the organic carbon content, the stronger the biological disturbance effect (Yan and Zhou, 2004). Unfortunately, in this study, we did not estimate the accumulation flux of organic carbon in the surface sediments.

Transport of Total Organic Carbon by Bioturbation

In bioturbation mixed sediments, organic matter is transported to deep sediments to provide organic carbon for deep organisms. Using the distribution pattern of specific activity of $^{210}Pb_{ex}$ in **Figure 4** and the relationship between $^{210}Pb_{ex}$ and TOC, one-dimensional model for the transport of TOC from the surface layer of sediments to the deep layer can be established:

$$F_b = -D_b \frac{dC_{TOC}}{dz}, \tag{5}$$

where F_b represents the flux of TOC [mmol/(cm^2*a)], dC_{TOC}/dz represents the vertical density gradient of C_{TOC}, and the negative sign indicates the downward direction of the flux. The distribution of TOC content in the sediments of MP4-S05-MC08 and MP4-S01-MC07 stations was fitted, and the following equation was obtained:

$$C_{TOC} = 0.263 - 0.008z \left(R^2 = 0.93,\ P < 0.001\right), \tag{6}$$

$$C_{TOC} = 0.231 - 0.007z \left(R^2 = 0.91,\ P < 0.001\right). \tag{7}$$

It can be seen from the equations aforementioned that there is a good linear correlation in the two stations and the depth, which conforms to the following equation:

$$C_{TOC} = b + a \times z. \tag{8}$$

Differential of C_{TOC} with respect to depth z, we can get:

$$\frac{dC_{TOC}}{dz} = a. \tag{9}$$

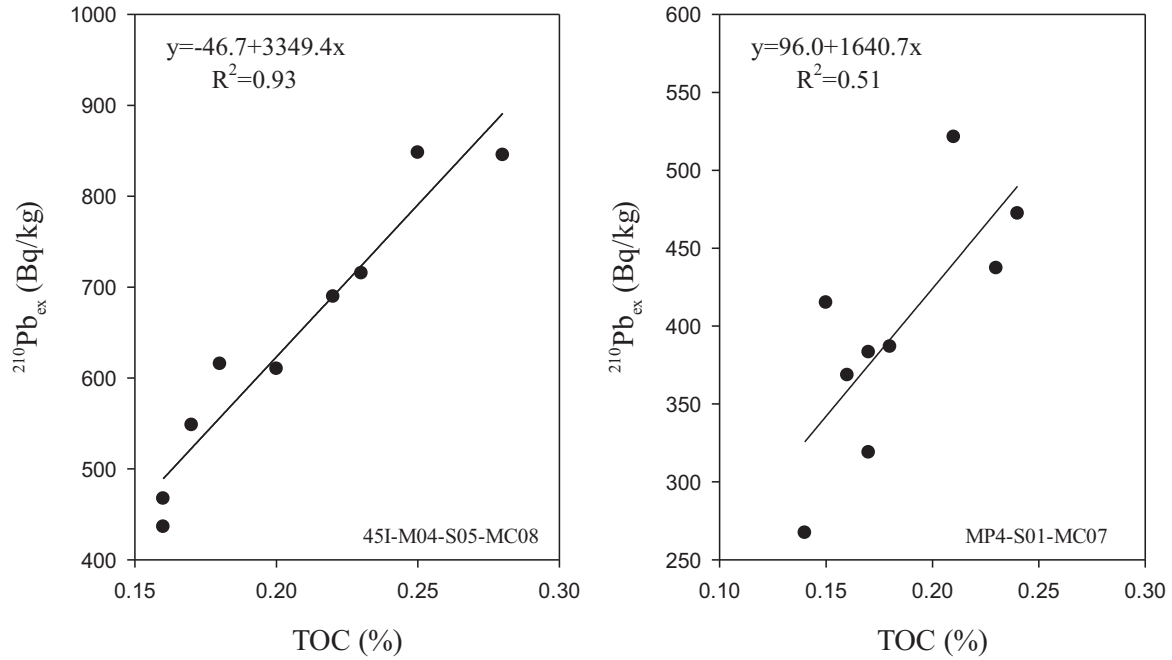

FIGURE 4 | The relationship between $^{210}Pb_{ex}$ and TOC.

The fitted a and the obtained bioturbation coefficient D_B were substituted, and the TOC flux transmitted downward by bioturbation at stations MP4-S05-MC08 and MP4-S01-MC07 were calculated to be 0.09 and 0.12 mmol/(cm^2·a), respectively.

It should be noted that this model is based mainly on the biological disturbance caused by deep $^{210}Pb_{ex}$ and TOC concentration in sediments and the direct relationship between the disturbance process of TOC to calculate the transmission, while getting the coefficient of the D_B has been considered in biological disturbance model ^{210}Pb downward mixing in the process of decay. However, this model does not take into account the degradation of downward transmission in the process of TOC; therefore, the results obtained with the model represent the upper limit of the TOC conveying.

CONCLUSION

Based on the distribution of $^{210}Pb_{ex}$ in sediment cores and one-dimensional steady-state vortex diffusion model, the bioturbation coefficient of marine sediments was found to range from 16.8 to 24.1 cm^2/a with an average of 20.5 ± 5.2 cm^2/a. The bioturbation mixing depth ranged between 19.3 and 23.1 cm with an average of 21.2 ± 2.7 cm, which is above the global average. This indicates that the region is experiencing a strong bioturbation effect. Bioturbation is influenced mainly by the TOC content in sediments, the composition of controlled biological communities, and water depth. The relationship between $^{210}Pb_{ex}$ and TOC was used to quantify the organic carbon transported from surface sediments to deep layers by core biological activity. We estimated the TOC flux transmitted downward by bioturbation was 0.09 and 0.12 mmol/(cm^2·a).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

FL, CL, and HL contributed to conception and design of the study. LL organized the database. XS performed the statistical analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

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