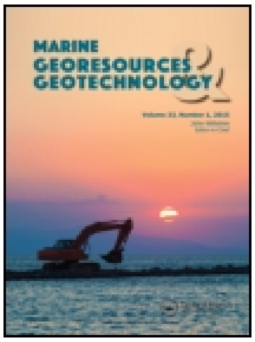

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Evaluation of Resuspended Sediments to Sinking Particles by Benthic Disturbance in the Clarion-Clipperton Nodule Fields

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The geochemical properties of sinking particles and sediments in the Clarion-Clipperton Zone were examined to develop a quantitative indicator with which to evaluate the contribution of sediment resuspended by nodule mining activity to sinking particles. The ratio of lithogenic material to organic carbon varies from ~3 in sinking particles to ~211 in sediments. This ratio is easily measured and is not easily affected by degradation and/or dissolution in the water column. A mixing model indicates that the ratio may be used as a potential proxy for estimating the contribution of resuspended sediment derived from mining operations to sinking particles.

Keywords: Abyssal manganese nodule mining, Clarion-Clipperton Zone, lithogenic/organic carbon ratio, particle fluxes, radiocarbon

Introduction

The abyssal sediments of the Pacific contain mineral resources of potential commercial and strategic interest; of particular interest are the polymetallic nodules commonly known as manganese nodules (Mero 1965; Glasby 1977). Manganese nodules are potato-sized concretions of manganese, iron, cobalt, copper, and nickel which occur over wide areas of the Pacific seafloor at water depths below 4000 m. The region of maximum commercial interest for manganese nodule mining lies in international waters at 118–157°W, 9–16°N, an area of 3×10^6 km^2 (Figure 1). At present, contractors are licensed by the International Seabed Authority (ISA) to explore manganese nodule resources and test mining techniques in seven claim areas in the Clarion-Clipperton Zone (CCZ) of the northeastern equatorial Pacific (http://www.isa.org.jm).

Mining operations discharge resuspended sediment into the water column that inevitably disturbs the marine environment (Khripounoff et al. 2006; Nath et al. 2012). The impact on the marine ecosystem is thought to depend mainly on the scale of disturbance and the amount of resuspended sediment (Hyun et al. 1998; Sharma et al. 2001). The ISA environmental guidelines compel contractors to obtain particle flux data at for least two years prior to deep-sea mining to determine the natural state of particle flux in the relevant contract areas. For instance, the National Institute of Oceanography of India conducted a benthic impact experiment (BIE) in the central Indian Ocean basin using time-series sediment traps as part of the Indian Deep-sea Environmental Experiment (INDEX) program (Parthiban 2000; Sharma et al. 2001), and reported that particle fluxes were two to five times higher during the disturbance period (ca. 8.5 days, August 1997) than during the predisturbance period (ca. 40 days, June–July 1997) (Parthiban 2000). However, as noted by Parthiban (2000), the difference in particle flux alone between the two periods was insufficient to differentiate between the primary flux from the overlying water column and the resuspended particle flux. In the CCZ of the northeastern equatorial Pacific, particle flux shows large natural variability due to the seasonal migration of the intertropical convergence zone (ITCZ) and differing ENSO (El Niño-Southern Oscillation) conditions (Kim et al. 2010, 2011, 2012). Therefore, it will be necessary to decouple the impact of mining from the natural variability in particle flux to quantitatively determine the contribution of resuspended particles derived from mining operations. However, mining-induced particle resuspension processes in the manganese nodule fields are poorly understood.

The aim of the present study is to develop a quantitative proxy to facilitate evaluation of the contribution of sediment resuspended by mining activities to the sinking particles, using a mixing model based on particle flux data from the CCZ covering a period of eight years.

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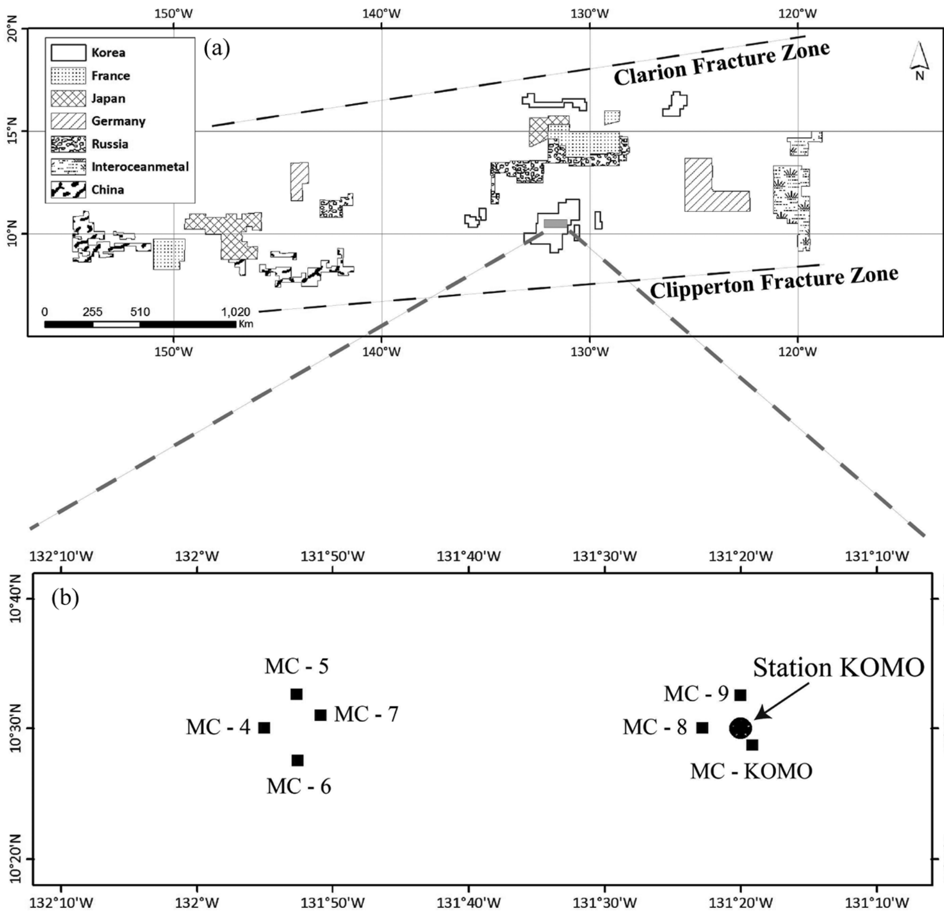

Fig. 1. (a) Manganese nodule exploration areas in the Clarion-Clipperton Zone of the northeastern equatorial Pacific Ocean under contract with the International Seabed Authority. (b) Locations of the sediment trap (Station KOMO) and sediment sample (black squares).

Study Area and Data

Study Area

Korea Institute of Ocean Science & Technology (KIOST, formerly known as KORDI) has completed a number of studies in the manganese nodule fields of the CCZ since 1997, including examination of the abundance of manganese nodules, deep-sea environmental properties, and particle fluxes (Figure 1) (Jeong et al. 1996; Jung et al. 2001; Hyun and Yang 2005; Kim et al. 2010, 2011, 2012). In general, meteorological and hydrographic conditions at Station KOMO (Korea Ocean Research & Development Institute Long-term Monitoring Station: 10°30′N, 131°20′W; ca. 5005 m water depth), such as wind speed, sea surface temperature (SST), sea surface salinity (SSS), and mixed layer depth are largely influenced by the meridional fluctuation of the ITCZ between 4°N during the winter–spring period (December–May), and 11°N through the summer–fall period (June–November) (Donguy and Meyers 1996; Amador et al. 2006; Kim et al. 2010, 2011). Being located in the equatorial Pacific, the interannual variation of environmental properties is also directly influenced by the ENSO cycle (Dymond and Collier 1988; Honjo et al. 1995; Kim et al. 2011).

Sinking Particle Flux at Station KOMO

A time-series sediment trap (PARFLUX Mark 78G-21, McLane) was deployed at a depth of 4950 m for eight years (July 1997 to May 1998, and July 2003 to June 2010) at Station KOMO (Figure 1) (Kim et al. 2011, 2012), and particle flux data from this site have been published previously (Kim et al. 2011, 2012). Briefly, the total mass flux varied between 3.5 and 130 $mg\,m^{-2}\,day^{-1}$, with an average of $28 \pm 23\,mg\,m^{-2}\,day^{-1}$ ($n = 86$) over the sampling period (Figure 2a). In general, high total mass fluxes (38 $mg\,m^{-2}\,day^{-1}$ on average, $n = 45$) were observed between December and May, whereas low values (16 $mg\,m^{-2}\,day^{-1}$ on average, $n = 41$) were observed between June and November (Figure 2a). This seasonal variability correlates with the migration of the ITCZ (Kim et al. 2010, 2011). Interannual variability in total mass flux in the CCZ was closely related to the ENSO cycle (Dymond and Collier 1988; Honjo et al. 1995; Kim et al. 2011, 2012). The average contribution of each component decreased in the following order: $CaCO_3$, lithogenic material, biogenic silica, and organic carbon, with values of 39.8%, 25.1%, 18.7%, and 8.4%, respectively.

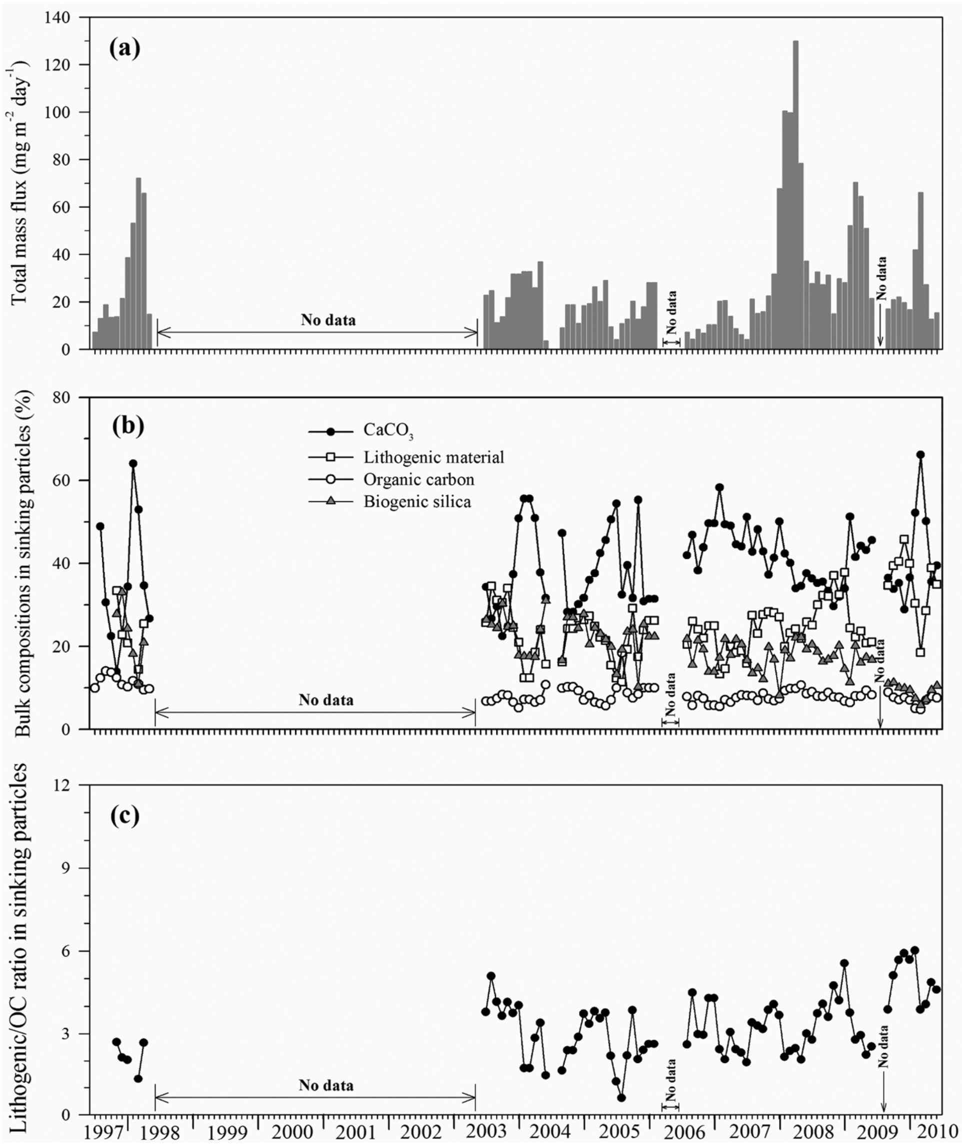

Fig. 2. Temporal variations of (a) total mass flux, (b) bulk composition of sinking particles, and (c) lithogenic/OC ratio in sinking particles at Station KOMO. (a) and (b) are redrawn from Kim et al. (2011, 2012).

Geochemical Properties of Sediment near Station KOMO

Sediment samples were collected from the seafloor using a multiple corer (9.5 cm in diameter and 60 cm in length) aboard the R/V *Onnuri* at and near Station KOMO between July and August 2010 (Figure 1, Table 1). Upon recovery of the corer, the supernatant water in the barrel was siphoned off, and the core was subdivided into slices 1 cm thick, which were then stored in polypropylene bottles and refrigerated waiting subsequent geochemical analysis in the laboratory. The freeze-dried sediment samples were analyzed for $CaCO_3$ (using a UIC CO_2 coulometric carbon analyzer), organic carbon (using a Carlo-Erba 1110 CNS elemental analyzer), and biogenic silica (using a time-series sequential dissolution method) (DeMaster 1981; Kim et al. 2011, 2012). The proportion of lithogenic material in each sample was estimated from the difference between the total mass and the sum of the other components, that is, organic matter (twice the weight of organic carbon), $CaCO_3$, and biogenic silica (Fischer and Wefer 1996; Palanques et al. 2005; Kim et al. 2011).

The bulk composition of the near-surface sediments obtained from depths of 0–1, 5–6, and 10–11 cm is shown in Figure 3. The organic carbon content of the sediments ranged between 0.10% and 0.75%, with an average of 0.45% ± 0.22% (n = 21) (Figure 3a), and decreased with increasing depth, from 0.56% to 0.75% at the top of the core, to 0.10% to 0.46% at a depth of 10 cm. Similarly, $CaCO_3$ content ranged between 0.07% and 0.19% (0.11% ± 0.03% on average, n = 21), and decreased gradually downcore (Figure 3b). Biogenic silica content ranged from 4.5% to 10.6%, with an average of 8.0% ± 1.8% (n = 21), and was the major component of the biogenic material. The proportion of all biogenic components decreased with depth; consequently, lithogenic material was the major component

Table 1. Sediment sampling locations and water depth at, and near, Station KOMO in the Clarion-Clipperton Zone. The proportion of each component is the average of the values at core depths of 0–1, 5–6, and 10–11 cm

	Sampling location		Water	Average content in sediment			
Core no.	Latitude (N)	Longitude (W)	depth (m)	Organic carbon	$CaCO_3$	Biogenic silica	Lithogenic material*
MC-KOMO	10°28.76′	131°19.22′	5004	0.50	0.09	7.6	92
MC-4	10°30.07′	131°55.10′	5077	0.50	0.09	10.2	89
MC-5	10°32.64′	131°52.70′	4956	0.47	0.14	6.3	93
MC-6	10°27.56′	131°52.65′	5028	0.31	0.09	6.7	93
MC-7	10°31.04′	131°50.94′	4973	0.33	0.16	7.6	92
MC-8	10°30.07′	131°22.83′	4861	0.53	0.12	7.8	91
MC-9	10°32.59′	131°20.04′	5016	0.50	0.08	9.7	89

*Lithogenic material was estimated as the difference between the total (100%) and the sum of the percentage contribution from the other components (organic matter, $CaCO_3$, and biogenic silica).

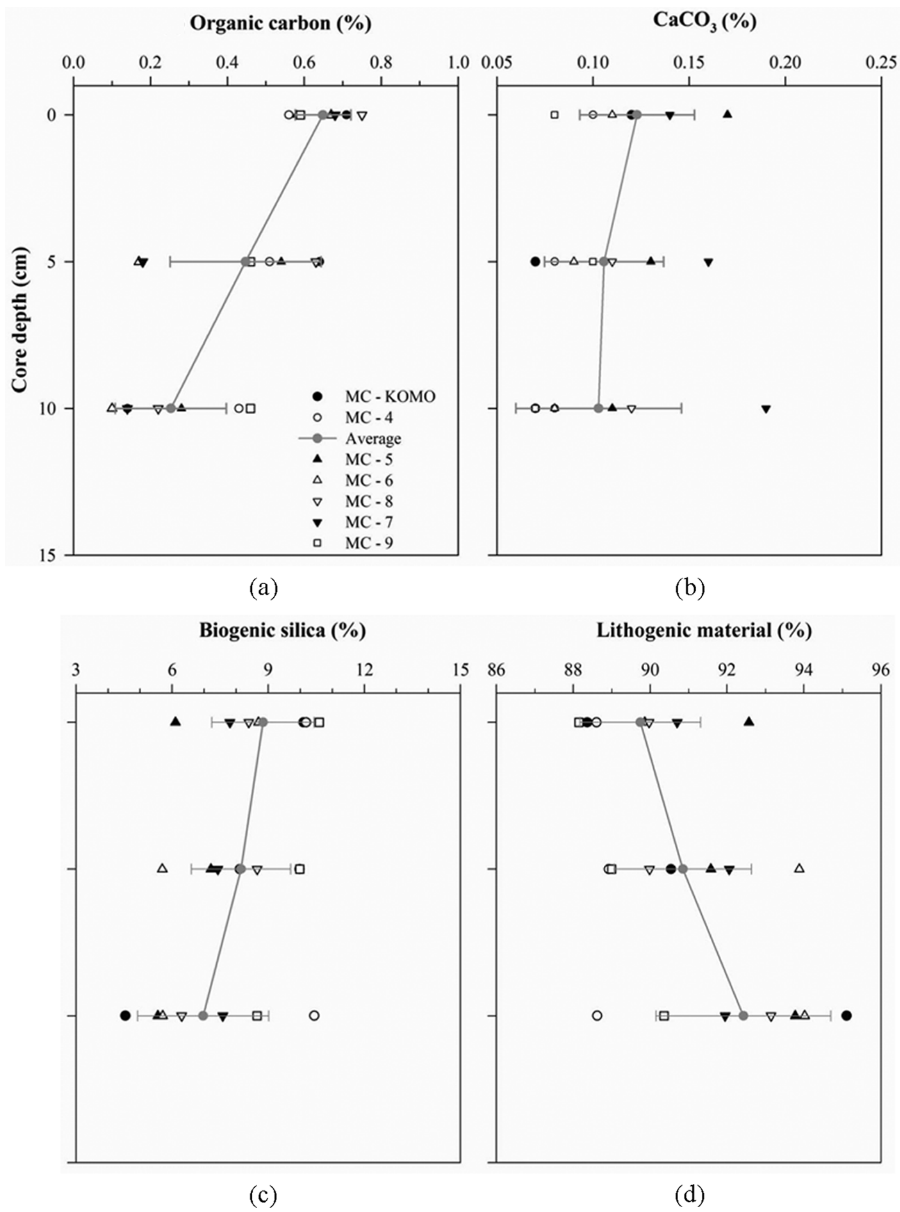

Fig. 3. Profiles of the contents of (a) organic carbon, (b) $CaCO_3$, (c) biogenic silica, and (d) lithogenic material in sediments from the Clarion-Clipperton Zone. Gray solid circles and bars denote the average and standard deviations, respectively.

of the sediments, and increased with depth from 88% at the top of the core, to >95% at a depth of 10 cm (Figure 3d). Overall, the amount of organic carbon and $CaCO_3$ in the sediments was considerably lower than that measured in particles settling through the water column, while the proportion of lithogenic material in the sediment was considerably higher than that in the sinking particles.

Development of Indicator for Sediment Resuspension

The mining of manganese nodules on the seafloor produces sediment plumes and disperses resuspended sediment particles into the water column, resulting in a number of potential impacts on the marine environment and ecosystem (e.g., Jumars 1981; Sharma et al. 2001; Khripounoff et al. 2006; Nath et al. 2012). One of the direct effects is an increased contribution to the sinking particle flux from resuspended sediment during the disturbance period. In the CCZ, the impact of resuspended sediment from abyssal mining activity has yet to be investigated. However, due to the large natural variations in particle flux in the CCZ, it would be difficult to determine the contribution of resuspended sediment from mining activity by a simple comparison of the total mass flux during normal and disturbed periods. Therefore, we must develop a quantitative indicator if we are to be able to evaluate the resuspended particle flux.

A useful quantitative indicator for resuspended sediment must satisfy several criteria:

- Signals from sediments should be significantly larger than those from natural sinking particles.
- The property of interest should not be altered in the water column by degradation and/or dissolution.
- The property should preferably be easy to measure.

Neither $CaCO_3$ nor biogenic silica can satisfy the above criteria because of their low concentration in sediments and the potential for dissolution when exposed to corrosive seawater. The low organic carbon content (0.45%) of the sediments would reduce its potential for use as a proxy for sediment resuspension. However, the radiocarbon signature of organic carbon in the sediments is considerably lower than that in the sinking particles, offsetting the problem of the low organic carbon content. For example, the radiocarbon content, expressed as the $\Delta^{14}C$ value, is +90‰ for freshly produced sinking particles (Broecker and Olson 1959) but is considerably lower in sediments (ca. −400‰) due to the slow mass accumulation rate and mixing with deeper, older sediment (Wang et al. 1998). Due to the difference in $\Delta^{14}C$ between the two organic carbon reservoirs, inclusion of resuspended sedimentary organic matter in sinking particles will significantly lower the $\Delta^{14}C$ value of sinking particulate organic carbon (POC). Relevantly, radiocarbon has been used to estimate the contribution of resuspended sediment to particulate organic carbon in the water column (e.g., Hwang et al. 2010). Figure 4 shows how the $\Delta^{14}C$ value evolves as the concentration of resuspended sedimentary material increases in the sinking particles. As the uncertainty associated with $\Delta^{14}C$ values is less than 10‰, the inclusion of resuspended sedimentary material with values greater than 30% can be detected by monitoring of $\Delta^{14}C$ values of sinking POC. It should be remembered that organic matter accounts for only a small fraction of the sediments of interest here (0.45% in the core-top sediments from our study site); consequently, any alteration of organic matter by decomposition would result in an error in estimation of the actual contribution of resuspended sediment. However, because sedimentary organic matter is generally refractory, and hence more stable, and is tightly associated with clay minerals, it is likely that the content in resuspended sediment can be estimated from the $\Delta^{14}C$ values of sinking POC. Another drawback of radiocarbon as an indicator for sediment resuspension is the cost of $\Delta^{14}C$ measurement by AMS (accelerator mass spectrometry).

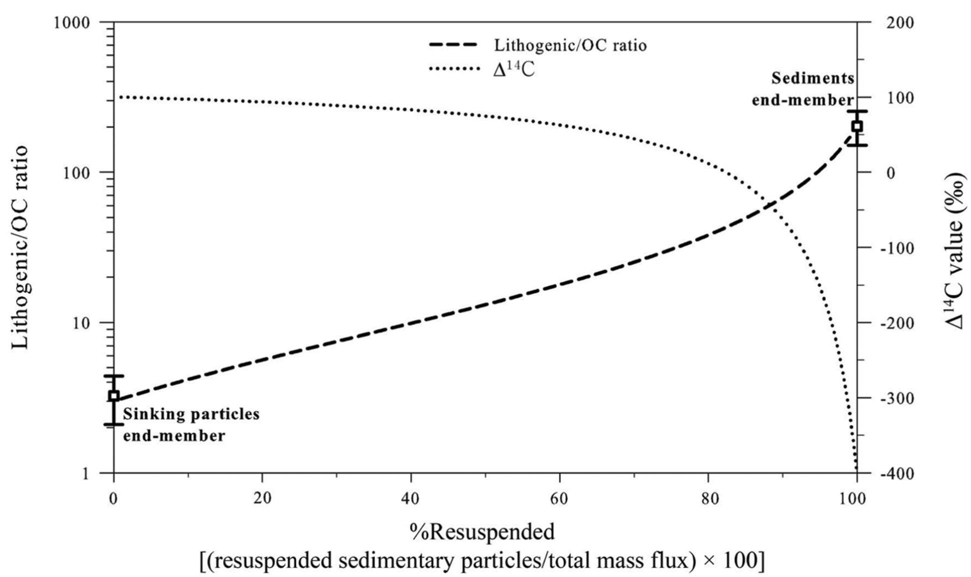

Fig. 4. Lithogenic/OC ratio and $\Delta^{14}C$ value (‰) with respect to the content of resuspended sediment in sinking particles. See Table 2 for the end-member properties used in the mixing model.

Lithogenic material may be a more suitable indicator because it accounts for a greater proportion of the sediments than of the sinking particles. However, the lithogenic content of sinking particles has a rather large natural variability in the CCZ and ranged from 11% to 46% over the eight-year study period (Figure 2b), which limits its usefulness as a direct indicator of resuspended sediment. We found that normalization of the lithogenic content by the organic carbon content amplified the signal, and also helped to differentiate the naturally varying signal from the disturbance signal. The mean ratio of lithogenic material (%) to organic carbon (%) (hereafter referred to as the lithogenic/OC ratio) was 211 ± 52 in the sediments, and 3 ± 1 in the sinking particles (Figure 2c), that is, two orders of magnitude difference. We constructed a simple mixing model to demonstrate the usefulness of this proxy. Table 2 shows the properties of the two end members used for this exercise. Figure 4 shows the evolution of the lithogenic/OC ratio as the contribution of resuspended sediment increases from 0% to 100%. A lithogenic/OC ratio for sinking particles greater than six (the upper limit of the natural variability) would indicate the input of resuspended sediment from mining activity. Consequently, having defined the two end-members for a given site, the lithogenic/OC ratio in sinking particles collected during a disturbance period can be used to estimate the contribution of resuspended sediment derived from benthic disturbance.

Although manganese nodules occur generally on the deep seafloor over broad areas of the Pacific and Indian oceans (Cronan 1980; Sharma et al. 2001), the regions of commercial interest and pioneer investigations for manganese nodule mining are mostly located in the CCZ. In general, the lithogenic/OC ratios of sinking particles and sediments at other locations in the CCZ appear to be similar to those in the present study (Honjo et al. 1982, 1995; Kim et al. 2008, 2011). For example, the lithogenic/OC ratios in the near-surface sediment (0–10 cm of core depth) on the floor of the northeastern equatorial Pacific region ranged from 153 to 207 (Honjo et al. 1982; Kim et al. 2011). Thus, the lithogenic/OC ratio suggested in this study may be used as an indicator of resuspended sediment more widely across the CCZ. However, this indicator will need to be examined further, and should be validated against real data from perturbation experiments in the future.

Table 2. Properties of the two end-members used in the mixing model. The geochemical properties are the average values for the sinking particles and sediments. Radiocarbon content of the sediment is the average observed at Station M in the northeastern Pacific (Wang et al. 1998)

	Sinking particles	Sediments
$CaCO_3$ (%)	39.8	0.1
Biogenic silica (%)	18.7	8.0
Organic carbon (%)	8.4	0.45
Lithogenic material (%)	25.1	91.0
Lithogenic/OC	3 ± 1	211 ± 52
$\Delta^{14}C$ (‰)	+100	−400

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