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Implications of excess ^{210}Pb and ^{137}Cs in sediment cores from Mikawa Bay, Japan

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Abstract

Four sediment cores were collected from Mikawa Bay, Japan, and excess ^{210}Pb and ^{137}Cs were measured by gamma spectrometry. Sedimentation rates for the four cores were determined by ^{210}Pb method. The sedimentation rate range is 0.10–0.70 g/(cm^2·year). The bio-mixing depth for each core is less than 7.0 cm, and was determined by the excess ^{210}Pb profiles as well. Therefore, the bioturbation is slight. The ^{210}Pb-derived dates coincided with the results from ^{137}Cs geochronology. Acceleration in sedimentation rate due to environmental alteration has been found in cores A2.5 and 05AS8, representing two depocenters due to their topography. Evidence of the Tokai Flood in 2000 was found in core 05AS8 according to the profiles of both radioisotopes and trace metals.

Key words: ^{210}Pb; ^{137}Cs; sedimentation rate; Mikawa Bay

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Introduction

The ^{210}Pb with a half-life of 22.3 years, as a member of the naturally occurring ^{238}U decay series, is one of the most widely-used radioisotopes to determine the sedimentation rates in coastal seas on a timescale of around 100 years (Koide *et al*., 1972; Robbins *et al*., 2000; Lu and Matsumoto, 2005c). Meanwhile, ^{137}Cs, an artificial radioisotope, has often been used as a tracer to provide supplementary information on sedimentation rates to compare with the result derived from ^{210}Pb method (Ritchie and McHenry, 1990; Smith, 2001; Lu, 2004; Lu and Matsumoto, 2005c; Palinkas and Nittrouer, 2007).

Mikawa Bay facing a highly urbanized and industrialized region is one of the largest semi-enclosed seas in Japan. Due to the coastal urbanization and industrialization, sedimentation rates in the coastal seas have been significantly affected by changes in river sediment discharge (Owen and Lee, 2004; Siakeu *et al*., 2004). The understanding of sedimentation in coastal seas is of great importance to coastal zone management, for example, pollution, harbor maintenance, fisheries, coast protection, conservation or recreational activities (Coltorti, 1997; Hansom, 2001). Therefore, this study focused on the determination of sedimentation rates in Mikawa Bay over the last century using the ^{210}Pb method and insights into its implications.

Change in natural system (e.g., climate change) can also cause change in sedimenation rate. Environmental change events are often recorded in sediment cores. There was a heavy rain in the Mikawa Bay area and the adjacent Ise Bay area (Ushiyama and Takara, 2002). A flood caused by the heavy rain has been called the Tokai Flood. It was expected to find sedimentation evidence in the Ise Bay or Mikawa Bay sediments. However, the Tokai layer could not be observed in Ise Bay (Lu and Matsumoto, 2005c). Therefore, another aim of this study was to check if there was a record of the Tokai Flood in Mikawa Bay.

1 Sampling and methods

1.1 Study area

Mikawa Bay, located on the Pacific side of Honshu Island, Japan, is a semi-enclosed embayment separated from Ise Bay by the Chita Peninsula (Fig. 1). It has a surface area of 602 km^2 and a volume of about 5.5 km^3. The catchment area of Mikawa Bay is 3752 km^2, with a population of about 2.4 million. The annual discharges of the Yahagi River and the Toyo River are 50 and 32 m^3/s, respectively. Tidal currents through the Moroyoki and Nakayama channels bring oceanic water into the bay; once inside, the currents branch to North and East (Saijo and Unoki, 1977; Bodergat *et al*., 1997). Due to the relatively low river discharge and the semi-enclosed nature of the Mikawa Bay, bay water exchange is slow (Saijo, 2002).

The bay is close to the Chubu industrial district of Japan (Nagoya, Toyota, Toyohashi etc.). Due to an increasing load of nutrients from rapid industrial development since

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the mid-1950s, as well as from livestock farms and municipalities, the bays have become highly eutrophicated and hence have induced intense red tides almost every year during summer (Bodergat *et al*., 1997). To satisfy the intensified need of land to develop industries after World War II, reclamation works in coastal seas of Japan increased significantly after 1945, particularly during the 1960s–1980s (Wakabayashi, 2000). The reclamation in Mikawa Bay, with an area of more than 30 km^2 up to 1996, was carried out in Mikawa Harbor (near Toyohashi) and Kinuura Harbor (north to the Yahagi River estuary) (Saijo, 2002).

Sediments in Mikawa Bay are predominantly silt- and clay-sized mud. Coarse-grained sediments, for example sand- and gravel-grained sediments, are deposited near the bay mouth.

1.2 Sampling

Using a modified gravity corer consisting of an acrylic pipe with a 5.5-cm inner diameter, four sediment cores were collected onboard the T/S Seisui-maru, Mie University during two cruises in July 2003 and September 2005. The sampling sites are shown in Fig. 1 and Table 1. Lowering the corer as slowly as possible, sediment cores with undisturbed sedimentary strata were obtained. Immediately after collection, the sediment cores were sectioned at 2–5 cm intervals and then sealed in plastic containers (Lu and Matsumoto, 2005a, 2005b). The sediments were later homogenized and dried for radionuclide analyses including ^{210}Pb, ^{214}Pb, and ^{137}Cs.

1.3 Analytical methods

The analytical details have been described in Lu and Matsumoto (2005c). The homogenized sediment samples were dried at 110°C and ground to fine powder in a quartz mortar. An EG&G ORTEC model GWL-120230 (USA) well-shaped germanium detector equipped with a SEIKO EG&G model 7800 MCA (Japan) was used for the low-energy gamma-ray spectrum analyses. The dried and homogenized samples weighing 2.5 g each in calibrated geometries were counted for 48 to 72 h. Uranium-Thorium ore DL-1a from the Canadian Center for Mineral and Energy Technology was used as a reference standard. The activities of ^{210}Pb, ^{214}Pb, and ^{214}Bi were measured based on their various characteristic gamma peaks (46.5 keV for ^{210}Pb, 295.2 keV and 351.9 keV for ^{214}Pb, 609.3 keV for ^{214}Bi). The radioactivity of ^{226}Ra (supported ^{210}Pb) and its error are calculated using a weighted average of activities of ^{214}Pb and ^{214}Bi. Excess ^{210}Pb profiles were analyzed using a program named LEADAT (Lu and Matsumoto, 2006). In addition, the activities of ^{137}Cs were measured by counting its 661.63 keV gamma radiation.

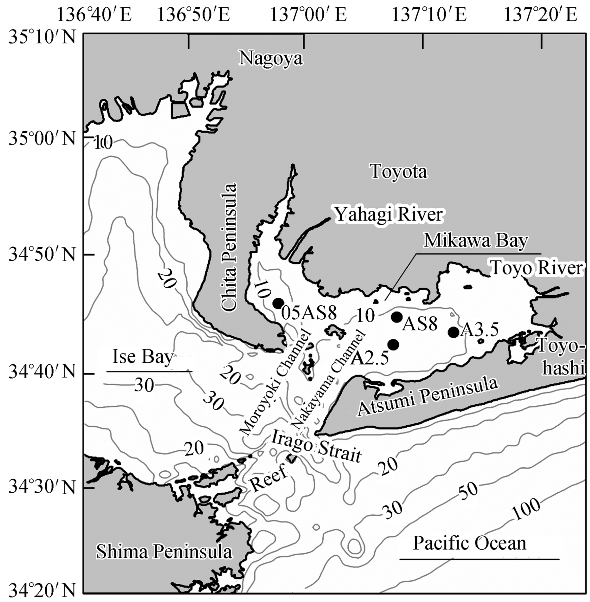

Fig. 1 Sampling sites (solid circle) in Mikawa Bay, Japan.

2 Results

The collected sediments are generally grayish homogeneous clay or silty clay. However, sediments for core 05AS8 are characterized as greenish gray homogenous silt with fine sand. Fine sedimentary structures such as lamina were not found in any cores.

To remove the compaction effect, mass depth (g/cm^2) instead of depth (cm) has been used (Lu and Matsumoto, 2005a, 2005c; Lu, 2007). Mass depth was calculated using the data of water content and porosity shown in Fig. 2. Density of solid phase in sediment is assumed to be 2.55 g/cm^3 (Robbins, 1978). Sedimentation rates were determined by the slope of excess ^{210}Pb profiles using least squares regression (i.e., the CIC model, Appleby and Oldfield, 1992). Mixed layers were determined by the flatten activities of excess ^{210}Pb in upper parts of the cores (Fig. 3). The mass depth vs. date curves derived from the excess ^{210}Pb profiles have been given in Fig. 4 to compare with the ^{137}Cs penetration mass depth.

Table 1 Locations, water depth, and the chararastics of ^{210}Pb and ^{137}Cs

Core	Latitude (N)	Longitude (E)	Water depth (m)	Sampling date	Supported ^{210}Pb	Excess ^{210}Pb		^{137}Cs
						Inventory (dpm/cm^2)	Flux (dpm/(cm^2·year)	Inventory (dpm/cm^2)
A2.5	34°42.58′	137°07.49′	17	July 17, 2003	1.15 ± 0.17	111.58 ± 3.13	3.47 ± 0.10	7.61 ± 0.39
A3.5	34°43.71′	137°12.45′	12	July 17, 2003	1.04 ± 0.17	35.25 ± 1.74	1.10 ± 0.05	2.89 ± 0.20
AS8	34°45.05′	137°07.59′	12	July 17, 2003	0.98 ± 0.07	35.55 ± 1.86	1.11 ± 0.06	1.79 ± 0.35
05AS8	34°46.19′	136°57.91′	15	Sep 17, 2005	0.94 ± 0.14	276.66 ± 4.59 (70.94 ± 4.87*)	8.62 ± 0.14 (2.21 ± 0.15*)	11.57 ± 0.76 (2.94 ± 0.80*)

* Values denotes that the contribution from the Tokai Flood in 2000 has been removed. dpm: decay per minute.

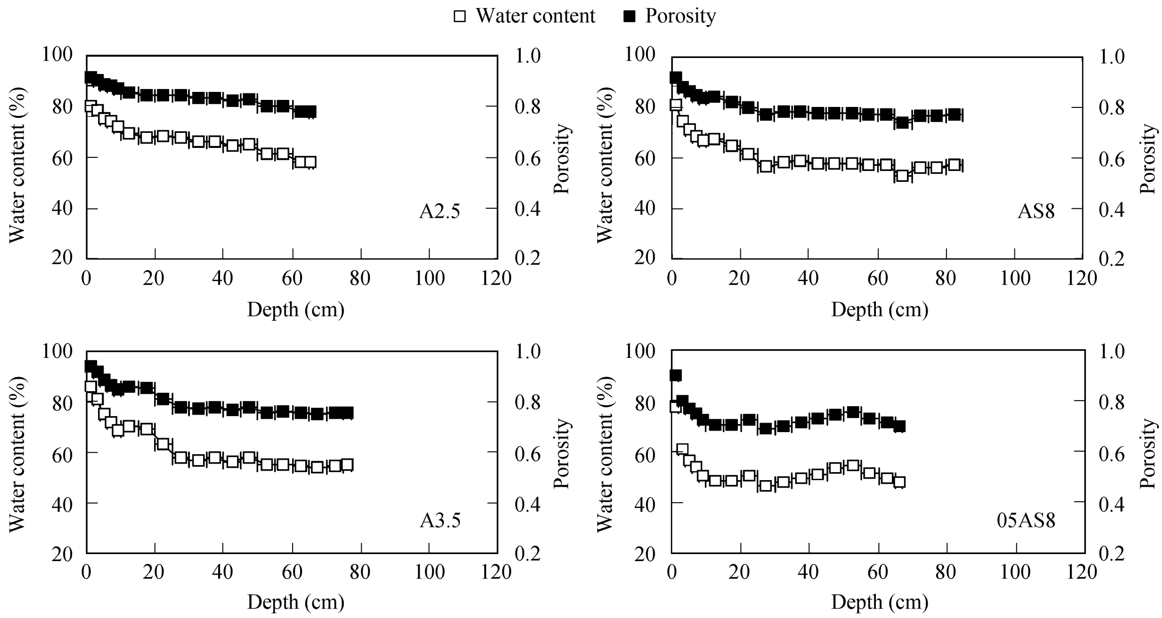

Fig. 2 Water content and porosity in sediment cors collected from Mikawa Bay.

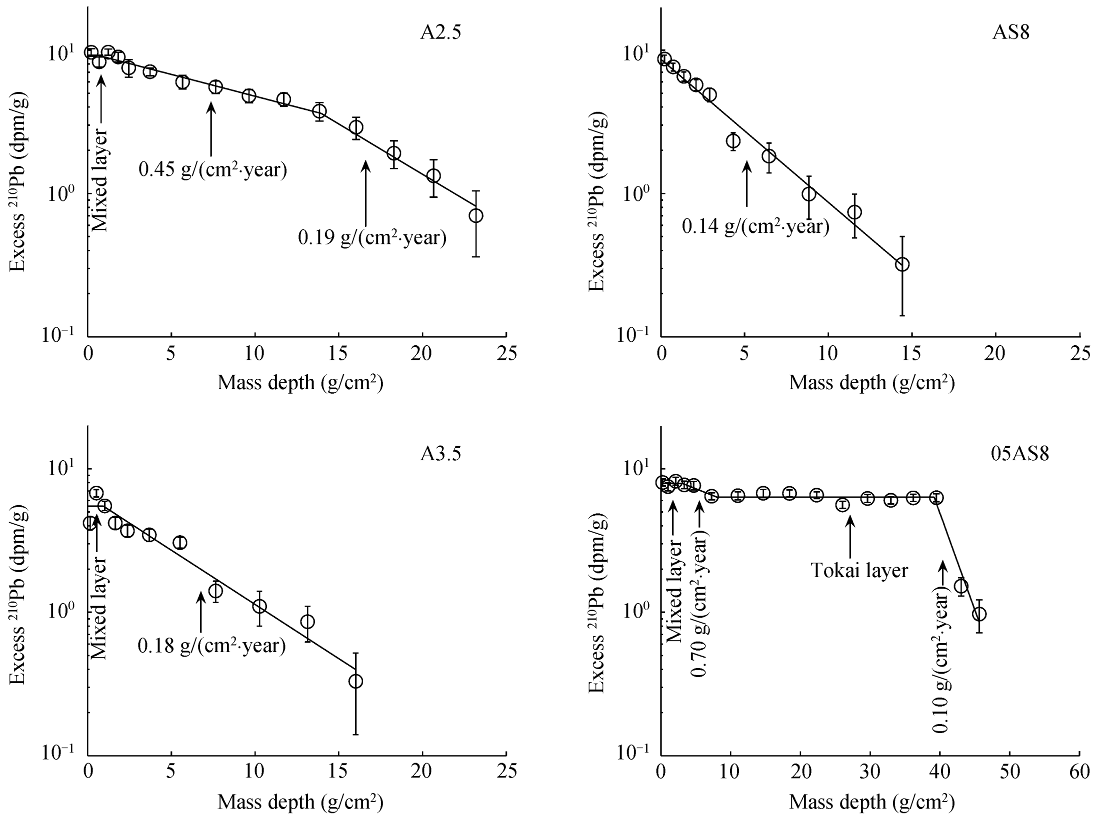

Fig. 3 Profiles of excess ^{210}Pb (1 dpm/g = 60 Bq/g). Sedimentation rates have been calculated from the least squares lines.

2.1 Mixing mass depth and sedimentation rates derived from ^{210}Pb profiles

As shown in Fig. 3, for core A2.5, the mass depth for its mixed layer is 0.60 g/cm^2 (2.61 cm). Sedimentation rates for sections in 0.60–13.95 g/cm^2 and below 13.95 g/cm^2 are 0.45 and 0.19 g/(cm^2·year), respectively. The shift in sedimentation rate occurred in ca. 1970 (A.D.).

For core A3.5, the mixed layer is down to the mass depth, 0.92 g/cm^2 (4.41 cm). Sedimentation rate below the mixed layer is 0.18 g/(cm^2·year). For core AS8, sedimentation rate is 0.14 g/(cm^2·year), and there is no clear mixed layer.

The excess ^{210}Pb profile for core 05AS8 is complex. The mixed layer is down to 3.11 g/ cm^2 (6.63 cm). Sedimentation rate for section 3.11–8.05 g/cm^2 is 0.70 g/(cm^2·year); excess ^{210}Pb at mass depth from 8.05 to 39.17 g/cm^2 (ca. 10–55 cm) shows almost no change; sedimentation rate below 39.17 g/cm^2 is 0.10 g/(cm^2·year).

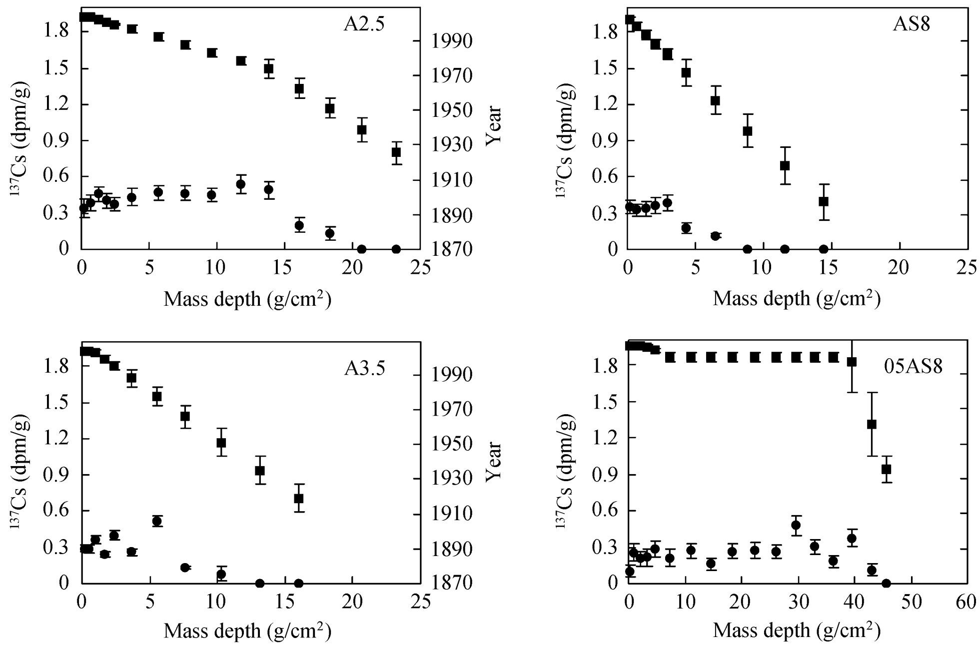

Fig. 4 Mass depth vs. ^{210}Pb-derived dates (solid squares) and ^{137}Cs profiles (solid circles).

2.2 ^{137}Cs profiles

In Japan, ^{137}Cs was first introduced into the environment in the early 1950s and showed a fallout peak in 1963 (e.g., Matsumoto, 1987). In sedimentary environments, the 1963 peak is often flattened or absent due to one or more factors, such as the mixing effect, the additional catchment-derived input, averaging effects within residence time (system time averaging) and sectioning thickness (Kim *et al*., 1997; Robbins *et al*., 2000; San Miguel *et al*., 2004; Lu and Matsumoto, 2005a). As shown in Fig. 4, the 1963 peak is not obvious for the profiles of ^{137}Cs for the four cores in Mikawa Bay. Therefore, the maximum penetration mass depth of ^{137}Cs, represented as the early 1950s, was used to compare with the ^{210}Pb-derived date vs. mass depth curve. The maximum penetration mass depths of ^{137}Cs are 18.29 ±1.11, 10.27 ± 1.42, 6.46 ± 1.12, and 43.05 ± 1.83 g/cm^2 for cores A2.5, A3.5, AS8 and 05AS8, respectively. The corresponding ^{210}Pb-derived dates at the above maximum mass depths are 1951 ± 6, 1951 ± 8, 1956 ± 8, and 1961 ± 18 (A.D.), showing in good consistency with ^{137}Cs dating within dating errors.

2.3 Inventories and fluxes for excess ^{210}Pb and ^{137}Cs

Excess ^{210}Pb and ^{137}Cs inventories were calculated as the sum of excess ^{210}Pb and ^{137}Cs through a sediment core, respectively. The mean input flux of excess ^{210}Pb was estimated using that inventory times the decay constant of ^{210}Pb. The results are listed in Table 1.

3 Discussion

3.1 Implications of the excess ^{210}Pb profiles

Due to urbanization and industrialization in the coastal areas, it is well known that metal concentrations in coastal marine sediments generally show an increasing trend from the bottom to the surface (e.g., Matsumoto 1988; Dai *et al*., 2007). Owen and Lee (2004) also recognized an increasing trend in sedimentation due to coastal reclamation and dredging. Indeed, a generally increasing trend in sedimentation rates was previously found in Ise Bay due to environmental alteration of coast and hinterland over the last century (Lu and Matsumoto, 2005c). This might be used to explain the sedimentation rate change in ca. 1970 for core A2.5, which might be a local depocenter in the eastern part of Mikawa Bay according to its topography. There are, however, no obvious changes in sedimentation rate for cores A3.5 and AS8. Similarly, according to the bathymetric topography (Fig. 1), core 05AS8, where water depth is deep, might be the other depocenter in the western part of Mikawa Bay. The abrupt shift in sedimentation rate indicates that the local sedimentary environment has changed greatly.

For core 05AS8, the uniform excess ^{210}Pb for section 8.05–39.17 g/cm^2 (ca. 10–55 cm) might be related to the Tokai Flood in the Yahagi River catchment in September 2000 (Ushiyama and Takara, 2002). This estimation is supported by the dating results shown in Fig. 4. The Tokai layer was dated as 2000 ± 3 (A.D.) by ^{210}Pb geochronology. As reported by Ohno (2007), the concentrations of Cr, Co, and Zn in a duplicate core of core 05AS8 also appeared to have no significant change in section 3.11–8.05 g/cm^2 (10–55 cm), which is similar to excess ^{210}Pb profile. The profiles of metals reflect that the section 10–55 cm might be deposited during one sedimentation event, i.e., the Tokai Flood.

The lack of the Tokai layer in the adjacent Ise Bay may be attributed to the much weaker circulation and slower water exchange in Mikawa Bay than those in Ise Bay (Saijo, 2002). Namely, the flood discharge in Ise Bay might disperse more broadly than that in Mikawa Bay. Moreover, the maximum rainfall was observed in the upstream of the Yahagi River during the Tokai flood (Ushiyama and Takara, 2002).

In addition, core 05AS8 has a mixing depth of 0–6.63 cm and shows evidence that eutrophication and weak exchange of bay water caused oxygen depletion in the deep layer (Saijo, 2002). Likely, bioturbation would therefore be limited due to the oxygen depletion.

3.2 Inventories and fluxes for excess ^{210}Pb and ^{137}Cs

The ^{210}Pb flux from atmosphere to land has been reported 1.5–2.8 dpm/(cm^2·year) at Hakodate (Fukuda and Tsunogai, 1975) and 0.8–1.2 dpm/(cm^2·year) in Osaka and Tokyo (Yamamoto *et al*., 2006). The higher fluxes for cores A2.5 and 05AS8 indicate a supplementary riverine input of excess ^{210}Pb. In particular, the Tokai Flood in 2000 has a significant contribution for core 05AS8. If subtracting the excess ^{210}Pb within the Tokai layer, the excess ^{210}Pb inventory and flux for core 05AS8 is 70.94 dpm/cm^2 and 2.21 dpm/(cm^2·year), respectively, which can be interpreted by the direct atmospheric flux. Furthermore, the range of the excess ^{210}Pb fluxes (1.10–2.21 dpm/(cm^2·year)) for the four cores in Mikawa Bay coincides the range in the nearby Ise Bay (0.51–4.31 dpm/(cm^2·year)) as reported by Lu and Matsumoto (2005c). In addition, the lower excess ^{210}Pb fluxes for cores A3.5 and AS8 might be related to the relatively low scavenging efficiency of excess ^{210}Pb from the water column due to the low sedimentation rates.

The observed values of ^{137}Cs inventory range from 1.79 to 11.57 dpm/cm^2, which coincide with 1.14–34.92 dpm/cm^2 at Lake Nakaumi (Kanai *et al*., 2002) and 2.54–29.50 dpm/cm^2 at Ise Bay (Lu and Matsumoto, 2005c). Taking radioactive decay into account, the total fallout of ^{137}Cs in Tokyo until 2003 is 17.99 dpm/cm^2 (Matsumoto, 1987; Lu, 2004; Meteorological Research Institute of Japan, 2005). The ^{137}Cs inventories for all cores are lower than this. This may be caused by the inefficient scavenging and the mobility of ^{137}Cs (e.g., Simpson *et al*., 1976; Sholkovitz and Mann, 1984; Cooper *et al*., 1995; San Miguel *et al*., 2004).

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