INFLUENCE OF DAM RESERVOIR ON DEEP MARINE SEDIMENTOLOGICAL ENVIRONMENT: AN EXAMPLE OF THE KUMANO TROUGH, CENTRAL JAPAN

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Abstract Sedimentation rate (mass accumulation rate; MAR) of surface hemipelagic sediments in the Kumano Trough, a forearc basin approximately 2000 m deep off the eastern Kii Peninsula, central Japan, was estimated from excess Pb-210 radioactivity profile and dry bulk density of the core sample. The estimated excess Pb-210 radioactivity profile was subdivided into three segments. The top segment was inferred to be affected by biological mixing in the surface mixing layer (SML). In contrast, a difference between segment-2 and segment-3 would reflect decease in MAR. With a simple model, the influence of the biological mixing and boundary age between segment-2 and segment-3 were estimated. The relationship between decreasing age of hemipelagic sediment MAR in the Kumano Trough (1950s) and dam construction age (1950s–1960s) was reasonable. Additionally, the relationship was supported by similarity in sediment grain size of dam reservoir and hemipelagic environment. Consequently, the construction of dams probably influences the deep marine hemipelagic environment of the forearc basin 2000 m below sea level.

Key words: Pb-210, mass accumulation rate, hemipelagic deep marine, dam reservoir, Kumano Trough

1. Introduction

It is well known that dams construction on rivers causes a decrease in sediment supply and serious coastal erosion (e.g. Stanley and Warne 1998). Along the Japanese islands, coastal erosion has been reported by Koike (1996) and others; in particular, Tanaka *et al.* (1993) calculated an average erosion rate of 1.6 $km^2 y^{-1}$ for the coastal area around the Japanese islands. Considering that dam reservoir deposits consist mainly of silt–clay sized grains (e.g. Okano *et al.* 2005; Hakoishi 2008), it is necessary to investigate whether interruption of sediment transport by dam reservoirs influences deposition in the deep marine hemipelagic environment.

The Kumano Trough is a forearc basin located off the southeast coast the Kii Peninsula, central Japan (Fig. 1a). Although the Kumano River has large sediment loads due to the heaviest precipitation among the Japanese islands, decreases in the sedimentation rate (mass accumulation rate; MAR) of surface sediments in the Kumano Trough during the mid-20th century were detected using excess lead-210 (Pb-210) radioactivity. The method for estimating changes in

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MAR and inferred reason for decreases of MAR in the deep marine hemipelagic environment are introduced in this paper.

2. Samples

Geological and geographical settings

The Kumano Trough is a forearc basin approximately 2000 m deep between the eastern side of the Kii Peninsula and the Nankai Trough (Fig. 1b). The Kumano River has the largest discharge and sediment load on the eastern Kii Peninsula. It incises a narrow valley by penetrating the Kii Range. During the rainy season, its maximum discharge (ca. 8000 m^3 sec^{-1}) is approximately 50 times its average discharge, which was ca. 160 m^3 sec^{-1} from 1968 to 2003 (Infrastructure Development Institute, Japan 2005). The sediment volume drained from the river mouth is estimated to be 26 × 10^4 m^3 y^{-1}. In the watershed of the Kumano River, huge dams constructed during the 1960s caused deposition in dam reservoirs, the total volume of which was estimated to be 3.8 × 10^7 m^3. Particularly, the Kazaya and Futatsuno dams, completed in 1960 and 1962, respectively, occupy 68% of the dam reservoir sediments. Dam reservoir deposition and sand mining, which removed riverbed sands at a rate of 2 × 10^5 m^3 y^{-1} during the mid-20th century, caused coastal erosion since the 1970s (Research Committee on the Kumano River Bed 2005).

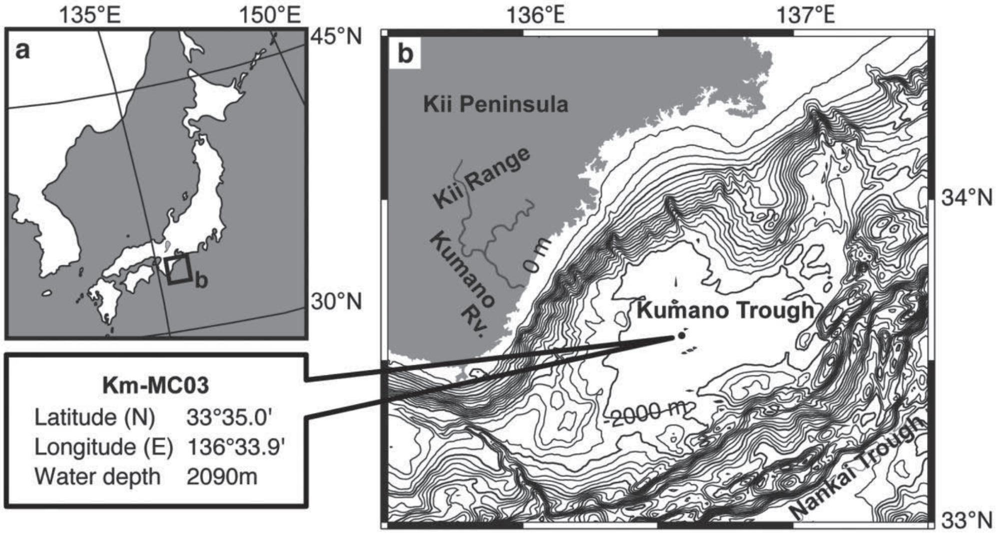

Fig. 1 Location of the core sample.

Sediment core

Surface sediment samples from the Kumano Trough were obtained on the R/V Tansei-maru, KT-08-30 cruise, autumn 2008 using a multiple corer without serious disturbance. Most of core samples intercalating sand layers, which implies disturbance of depositional environment with erosion and rapid deposition due to sandy turbidity current, were excluded for the study. The rest of the 35 cm long muddy Km-MC03 core sample was used. Coring sites were ca. 60 km from the Kumano river mouth (Fig. 1b). Core sediments consisted mainly of hemipelagic olive black

(7.5Y3/2) clayey silt. Shells of foraminifers and mottles of burrows were dispersed in the hemipelagic silt, indicating that the sediment was bioturbated moderately to intensely. The top of the core, brown-black (5YR2/2) soupy fine silt, was rich in organic particles. Soupy sediments become consolidated around 2.5 cmbsf (cm below seafloor; Shirai *et al.* 2010).

3. Methods

Pb-210 method

One of the most popular methods for estimating sedimentation rate during the last ca. 100 years is by means of Pb-210, a naturally occurring radionuclide with a half-life of 22.3 yrs (e.g. Oldfield and Appleby 1984). The Pb-210 method has been applied into surface marine sediment dating (e.g. Koide *et al.* 1972; Lu and Matsumoto 2005). Pb-210 is a part of radioactive decay chain derived from U-238. As part of the decay chain, radioactive inert gas Rn-222 (half-life of 3.8 days) is produced and escapes from the air-soil interface to the atmosphere before it decays into Po-218 (half-life of 3.1 minutes). Po-218 and subsequent radionuclides of the decay chain, which almost all eventually exist as Pb-210 because of its extremely long half-life compared to subsequent radionuclides (Table 1), fall to the earth's surface accompanied by aerosol. The supply of airfall Pb-210, defined as "excess Pb-210" or "unsupported Pb-210", was estimated to be constant on an annual scale (Sheets and Lawrence 1999). Hence, sedimentation rate was estimated based on the attenuation rate of excess Pb-210 activity in the downcore direction. Pb-210 in sediments consists not only of excess Pb-210 but also of supported Pb-210, which is derived from U-238 decay chain radionuclides that remained in the sediment and did not escape to the atmosphere as Rn-222. Therefore, excess Pb-210 activity is calculated by subtracting Pb-214 (half-life of 26.8 minutes) activity from "total" Pb-210 activity assuming radioactive equilibrium (e.g. Lu and Matsumoto 2005).

Table 1 Half-lives of radionuclides in U-238 decay chain

Radionuclides	Half-life	Radionuclides	Half-life	Radionuclides	Half-life
U-238	4.5×10^9 years	Ra-226	1.6×10^3 years	Po-214	164 seconds
Th-234	24.1 days	Rn-222	3.8 days	Pb-210	22.3 years
Pa-234	1.2 minutes	Po-218	3.1minutes	Bi-210	5.0 days
U-234	2.5×10^5 years	Pb-214	26.8 minutes	Po-210	138.4 days
Th-230	7.5×10^4 years	Bi-214	19.7 minutes	Pb-206	(stable)

The upper part of the core (0–11 cmbsf) was horizontally sliced into samples with 1 or 2 cm thick. Then, after drying at 110°C for more than 12 hours, sliced samples were crushed. Radioactivity of the prepared samples was measured using the ORTEC High Purity Ge gamma spectrometer housed at the Department of Geography, Tokyo Metropolitan University with a 48 hour counting. In addition to recording the activity of Pb-210 and Pb-214 for excess Pb-210 calculation, the activity of Cs-137 (half-life of 30.1 years) was estimated in order to verify our estimation of depositional age based on the Pb-210 method; Cs-137 is an artificial radionuclide derived from atmospheric nuclear tests, and its detection indicates a depositional age younger than 1954 (e.g. Peirson 1971; Nakajima and Kanai 2000).

Estimation of mass accumulation rate (MAR)

Sedimentation of surface layer in deep marine environment is generally evaluated as MAR (g cm^{-2} y^{-1}) instead of sedimentation rate (cm y^{-1}) because the thickness of muddy sediment decreases in the downcore direction due to compaction. To convert depth (cm) of sediment to mass depth (cumulative weight/weight depth; g cm^{-2}), dry bulk density of cubic samples with 7 cm^3 volume obtained from the Km-MC03 core was calculated from wet/dry weight and dry grain volume measured by the AccuPyc 1330 gas pycnometer (Micromeritics Instrument Co.) housed at the Atmosphere and Ocean Research Institute, the University of Tokyo.

4. Results and Discussion

Inventory and flux of excess Pb-210

Excess Pb-210 activity per the unit weight tended to decrease in the downcore direction (Fig. 2a). To evaluate MAR, the CRS/CF (constant rate of supply/constant flux) model, which assumes constant flux of Pb-210 and does not guarantee constant excess Pb-210 activity at the surface layer of deposit, or the CIC/CA (constant initial concentration/constant activity) model, which assumes constant sediment supply and constant excess Pb-210 activity at the surface layer of deposit, is utilized (e.g. Appleby and Oldfield 1978; Turner and Delorme 1996). The former is used when excess Pb-210 is primarily supplied by airfall, whereas the latter is used when Pb-210 is primarily supplied via sediment particle transport from land (e.g. Kanai 2000). Inventory, which implies depth-integrated radionuclide activity through the sediment column, was calculated as 261 dpm (decay per minute) cm^{-2}. Then, by multiplying the decay constant of Pb-210 (0.031) by inventory, flux of excess Pb-210 was calculated as 8.1 dpm cm^{-2}, which is much higher than the Pb-210 fallout from atmosphere (1.5–2.8 dpm cm^{-2}) measured at Hokkaido, northern Japan (Fukuda and Tsunogai 1975). This implies that excess Pb-210 was transported primarily from land (e.g. Kanai 2000), probably from the drainage basin of the Kumano River, and that the CIC model should be used for MAR evaluation of the Km-MC03 core sample.

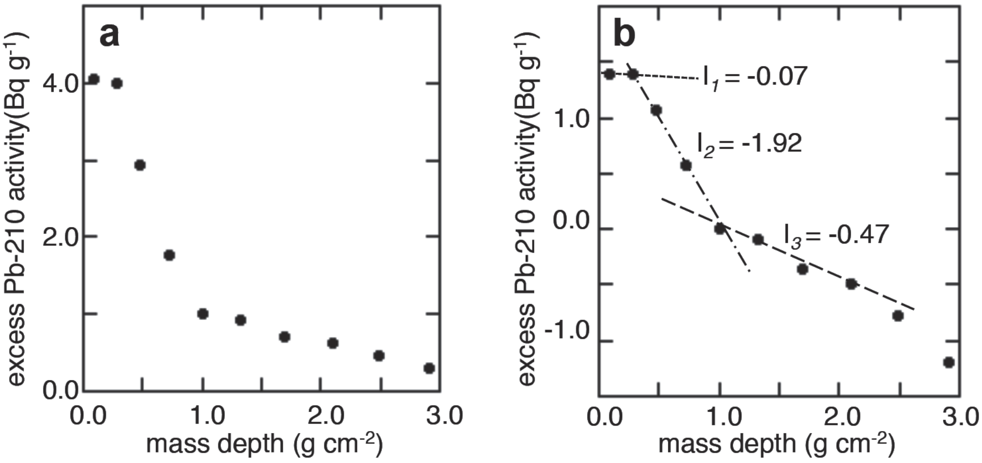

Fig. 2 Profile of excess Pb-210 on a (a) linear and (b) logarithmic scale.

Estimation of MAR and dating of the core

In Fig. 2b, excess Pb-210 is plotted on a logarithmic scale. If MAR is constant, excess Pb-210 on a logarithmic scale is expressed as a straight line, and MAR is estimated by dividing the decay constant of Pb-210 by the depth increment of excess Pb-210 in the sediment column (e.g. Kanai 2000). Although Fig. 2b shows that excess Pb-210 is not plotted in a straight line, it can be expressed as the succession of three straight segments. The top segment (segment-1: 0–0.29 g cm^{-2}), with a depth increment of -0.07 is correlated with 0.0–2.6 cmbsf, which is almost coincident with the surface brown-black soupy layer (0–2.5 cm) and inferred to be the surface mixing layer (SML) formed by biological mixing (bioturbation; e.g. Carpenter *et al*. 1982; Trauth *et al.* 1997). Segment-2 (0.29–1.01 g cm^{-2}, 2.6–5.5 cmbsf), with a depth increment of -1.92, does not show remarkable lithologic differences compared to segment-3 (below 1.01 g cm^{-2}), with a depth increment of -0.47.

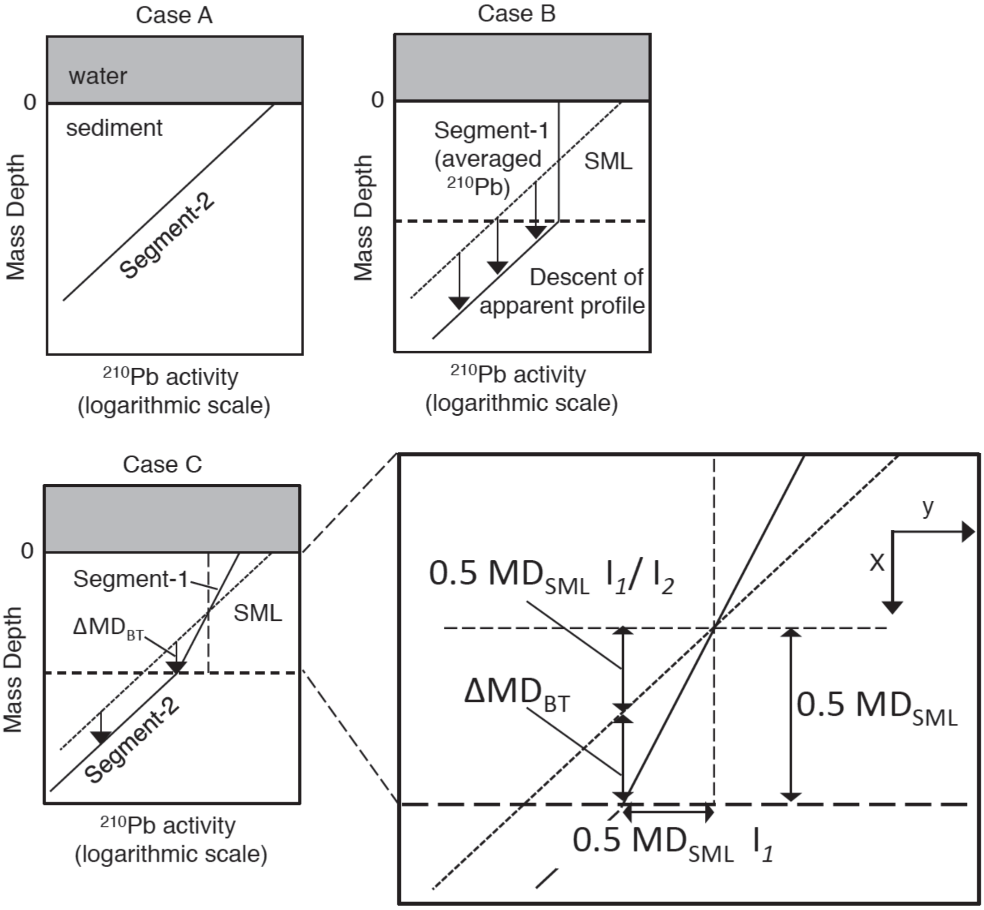

Fig. 3 Evaluation of the effect of biological mixing.

Although MARs of segment-1, segment-2 and segment-3 are calculated as 0.48, 0.02 and 0.07 g cm^{-2} y^{-1}, respectively, MAR of segment-1 was affected by biological mixing. On the assumption that the biological mixing effect has been constant, the influence of biological mixing was estimated using the simple model described below. If biological mixing was completely inactive, MAR of the surface layer would have been equivalent to MAR of segment-2 (case A in Fig. 3). Alternatively, if the effect of biological mixing was active enough relative to the sedimentation effect, excess Pb-210 activity concentration would have averaged within the SML and MAR would have been calculated as infinite (case B in Fig. 3). As a result of mixing, the activity of excess Pb-210 has been equivalent to the midpoint of the SML, which is recorded in the sediment immediately below the SML. Therefore, in the case B, the apparent depositional age estimated from MAR of segment-2 is older than the true depositional age and its displacement is obtained by dividing MAR into the mass depth of one half of the SML (e.g. Kanai 2000). Segment-1 of the excess Pb-210 profile in Fig. 2b shows an intermediate version of cases A and B and is inferred to be a result of the effect of bioturbation on successive sedimentation with respect to MAR of segment-2. For evaluating displacement of apparent and true ages, displacement of the apparent excess Pb-210 profile from the original profile with mass depth was estimated. Displacement of apparent and original profiles ($\Delta \mathrm{MD_{BT}}$) is expressed as follows:

$$\Delta \mathrm{MD_{BT}} = 0.5\ \mathrm{MD_{SML}}\ [1 - \mathrm{I}_1/\mathrm{I}_2] \tag{1}$$

where $\mathrm{MD_{SML}}$ is the mass depth of SML and I_1 and I_2 are the depth increments of excess Pb-210 of segment-1 and segment-2, respectively (case C in Fig. 3). Therefore, by dividing the MAR of segment-2 (0.02 g $\mathrm{cm^{-2}\ y^{-1}}$) into $\Delta \mathrm{MD_{BT}}$ (0.14 g $\mathrm{cm^{-2}}$), displacement of age estimation by biological mixing is obtained. Consequently, the true age of the boundary between segment-2 and segment-3 is estimated to be around 1955. The estimated age of the Cs-137 appearance zone (5–6 cmbsf; 1963–1952) based on the model corresponds with the beginning age of Cs-137 detection (1954; Peirson 1971), and demonstrates the validity of the model.

Inferred reason for a decrease in MAR during the 1950s

It is possible to infer that a remarkable change in the depth increment from segment-3 to segment-2 in the excess Pb-210 profile was caused by an abrupt decrease in MAR around 1955. Because a high flux of excess Pb-210 implies transportation of excess Pb-210 from land, the supply of terrigeneous muddy grains via the Kumano River was investigated. In the watershed of the Kumano River, huge dam reservoirs constructed during the 1960s and sand mining in the lower reaches that peaked in the early 1970s have caused riverbed and coastal erosion since the 1970s (Research Committee on the Kumano River Bed 2005). Sand mining does not influence the hemipelagic environment because of a difference in the types of sediment grains between the riverbed of the Kumano River (gravel to sand) and hemipelagic deep marine environment (silt to clay). In contrast, deposition in dam reservoirs may influence the hemipelagic environments because silt to clay sized grains generally occupy more than half of dam reservoir deposits (e.g. Okano *et al.* 2005; Hakoishi 2008). The Kazaya and Futatsuno dams, which are major reservoirs of sediments in the Kumano watershed, were built from 1954 to 1960 and from 1959 to 1962, respectively (The Japan Dam Foundation 2012). Therefore, it is reasonable to assume that construction of the Kazaya and Futatsuno dams caused a decrease in the MAR of hemipelagic sediments in the Kumano Trough since around 1955. This means that the influence of the construction of dams possibly reaches the central part of the forearc basin.

5. Conclusion

Using an excess Pb-210 activity profile and a simple biological mixing model, a decrease in MAR of the central part of Kumano Trough during the mid-20th century was recognized. MAR decreased from 0.07 to 0.02 g cm^{-2} y^{-1} around 1955 during construction of major dams. This result implies that human activity (dams construction) influences the hemipelagic deep marine environment. Although it is well known that dams construction influences coastal erosion, its impact on the deep marine has not been recognized because the deep sea floor hides below the vast sea water. It is necessary to be aware of the effect of human activity on the unseen environment. To pursue the influence of dam construction on the deep marine environment, it is necessary to investigate changes in MAR with high resolution using deep marine cores high sedimentation rates.

Acknowledgements

This paper is dedicated to Professor Haruo Yamazaki on his retirement from Tokyo Metropolitan University. The authors would like to thank the officers and crew of the R/V Tansei-maru during the KT-08-30 cruise. Thanks are also due to the members of the Scientific Party of the KT-08-30 cruise for their help with core sampling: Dr. M. Oishi, Dr. T. Wakabayashi, Dr. Y. Niwa, Dr. T. Ito, Mr. K. Kameo and others. The authors are grateful to Mr. R. Hayashizaki, Ms. T. Utsugawa, Ms. M. Watanabe and other members of the Laboratory of Geomorphology and Quaternary Geology, Tokyo Metropolitan University for their assistance with sample measurement. This study was supported by JSPS KAKENHI Grant Number 24650603.

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(*: in Japanese, **: in Japanese with English abstract)