

【Original Paper】

Influence of benthic biomagnification process on the total mercury content of fish and mega-benthos in an enclosed bay

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Abstract

The contents of heavy metals and non-biodegradable chemicals of the body tissues tend to increase in the organisms of higher trophic levels of the biological community. However, we were not able to recognize any significant relationship between the trophic positions (TP) and total mercury (THg) contents of the body tissues among 24 species of fishes and mega-benthos collected in the inner part of Isahaya Bay, Kyushu, western Japan. The two species of the tertiary consumers of fish, *Lateolabrax japonicus* (Japanese seabass) and *Paralichthys olivaceus* (bastard halibut), contained 266 ± 99 ng/g d.w. (mean \pm S.D., $n = 5$) and 249 ng/g d.w. ($n = 1$) of THg, while the contents of the six species of fishes of the secondary consumers, or the intermediate consumers between the secondary and tertiary ones, exceeded those of the tertiary consumers of fish. In particular, extremely high contents of THg were detected from *Hemirygion akajei* (red stingray) ($3,700$ ng/g d.w., extra-large size class (72.0 cm, 5,150 g); 671 ± 340 ng/g d.w., large size class (63.3 ± 4.9 cm, $1,847 \pm 145$ g, $n = 4$)), and *Acanthopagrus schlegelii* (blackhead seabream) (942 ng/g d.w.). They have common feeding habits that favor macro-benthic animals for diets, including bivalves, polychaetes, crabs, shrimps, etc., and are referred to as “benthopelagic species”. In the study area, the mercury discharged by volcanic activities was accumulated in the sediment, and the THg was concentrated on some macro-benthic animals through the biomagnification process in the detritus food chain in the benthic system. The high THg contents found in the benthopelagic fishes seem to be transferred from the preferential predation of the macro-benthic animals with high levels of THg contents.

Keywords: benthopelagic, biomagnification, fish, food chain, Isahaya Bay, mercury, total mercury content

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I INTRODUCTION

When mercury has been discharged from the surrounding lands to the coastal shallow waters, it is absorbed by primary producers such as phytoplankton, algae, and sea grass, and accumulates in their body tissues, which is referred to as “bioconcentration”. In the pelagic system, the phytoplankton is preyed on by various organisms linked with a food chain, including zooplankton, fishes, marine mammals, birds, etc., increasing markedly the mercury contents of the bodies at higher trophic levels¹⁻⁴⁾. In parallel with the biomagnification process in the pelagic system, the mercury contents of the animals tend to increase along the detritus food chain in the benthic system. The primary producers that absorbed mercury in the water become directly or indirectly particulates of organic matter (POM), tend to sink down toward the sea floor, and deposit as detritus on the sediment. Benthic animals feed on the sediment with detritus, and/or filter POM suspended or re-suspended in the overlying water on the sediment, and this starts another biomagnification process in the benthic system^{5,6)}.

Our studies have focused on the biomagnification process of total mercury (THg) that proceeds in the benthic system in the coastal shallow waters. In the latest results of our studies in the benthic system in the inner part of Isahaya Bay⁷⁾, 27.2 ± 9.7 ng/g d.w. (mean \pm S.D.) of THg was detected from POM suspended in the bottom water, while about 4.9 times higher THg content, 133 ± 23 ng/g d.w., was noted in the surface layer of the sediment. There, abundant various macro-benthic animals including bivalves, polychaetes, amphipods, etc. occur, and work as primary consumers, exploiting the detritus deposited

on the sediment and POM in the overlying water on the sediment. Among these animals, we found a high THg content group with 101 ± 23 ng/g d.w. of THg contents, which consisted of deposit-feeding polychaetes and bivalves and suspension-feeding bivalves burrowing in the sediment. The secondary consumers such as carnivorous crabs and starfish that favored the bivalves for diets had further about 2.1 times higher THg contents, 215 ± 47 ng/g d.w. than those of the primary consumers. The provisional regulation value of THg for fish and shellfish for foods is set 400 ng/g w.w.⁸⁾ in Japan, which is equivalent to about 2,000 ng/g d.w. If some fishes and mega-benthos prey on these macro-benthic animals with high THg contents preferentially, it is likely that their THg contents exceed the provisional regulation value due to the effects of biomagnification.

In this study, we conducted sampling of fishes and mega-benthos with a gill net, fixed net, and cast net in the inner part of Isahaya Bay, which is an enclosed bay located in the western side of the inner part of Ariake Bay, Kyushu, western Japan. The purposes of this study were to determine the stable isotope ratios of carbon and the nitrogen and THg contents of the body tissues of fishes and mega-benthos, to clarify the relationship between their trophic positions in the community of aquatic animals and THg contents, and to discuss the influence of biomagnification of THg among the micro-benthic animals on the THg content of fishes and mega-benthos occurring in the bay.

II MATERIALS AND METHODS

Study area

Isahaya Bay is an enclosed bay located in the western

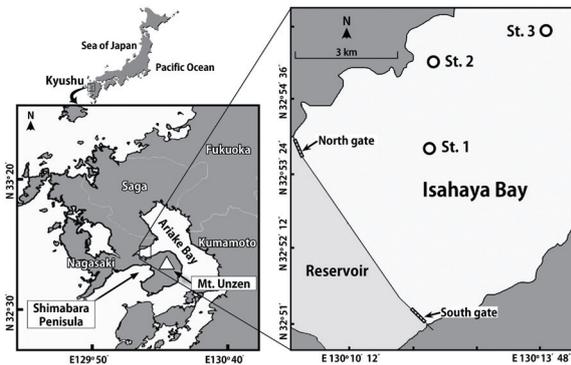


Fig. 1 Study area of this study, Inner part of Isahaya Bay, Kyushu, western Japan.

side of the inner part of Ariake Bay, Kyushu, Japan (Fig. 1). The total area of the bay is about 65 km², and its average depth is 10 m. Shimabara Peninsula with an active volcano, Mt. Unzen, located on the southern side of the bay. In general, these volcanic eruptions were some of the principal natural sources of mercury in the atmosphere⁹⁾. It has erupted at least three times (1663, 1792, 1990 to 1995) since the dawn of human history in Kyushu¹⁰⁾. At the last eruption of Mt. Unzen, about 2.95 tons of mercury were emitted to the atmosphere over 1,928 days¹¹⁾. Furthermore, there are many hot springs and fumaroles around the volcano, from where hot water and gases containing mercury are being continuously emitted¹²⁻¹⁴⁾. They also seem to work as sources of discharging mercury to the bay. Here, we set three sampling stations in the inner part of the bay to collect fishes and mega-benthos with a gill net at St. 1, a fixed net at St. 2, and a cast net at St. 3.

Sampling

On 17 October 2015, January 27, May 24, and August 3 in 2016, we collected fishes and mega-benthos, leaving a gill net in the water from a fishing boat for approximately 30 minutes, at St. 1, and with a fixed net

which was permanently set at St. 2. At St. 3, we conducted samplings of a school of fish with a cast net from the fishing boat, searching for it with an echo sounder, on 27 November 2017. All of the collected specimens of the fishes and mega-benthos were kept in cooler boxes until they were brought back to the laboratory.

Treatment of the samples

At the laboratory, the specimens of the fishes and mega-benthos were identified, measured, weighed, and dissected with clean instruments to take the dorsal muscles without skin and bones of fishes and muscle of mega-benthos. About 6 g in wet weight of the muscles of each specimen was collected to use for the chemical analyses. These samples were washed with distilled water, put in 5 ml of plastic vials, and kept in a freezer at -20 °C. The frozen samples were freeze-dried for 48 hours with a freeze dryer, powdered with Agate mortar, and kept in the plastic vials.

Prior to determination of stable isotope ratios of carbon and nitrogen of the samples, about 10 mg d.w. of each sample was placed in the microtubes 1.5 mL, treated with 2N HCl to remove CaCO₃, vacuum-dried for 48 hours, delipidated with chloroform-methanol mixture solutions (2:1, v/v), and centrifuged at 10,000 rpm for five minutes at 4 °C twice. They were treated with 100 % methanol, centrifuged at 10,000 rpm for five minutes at 4 °C again, and vacuum-dried for 48 hours. Finally, they were ground to powder with pellet pestle. The remaining samples were used for determination of THg contents.

Chemical analyses

The stable isotope ratios of carbon and nitrogen of the samples were determined using an elemental

analyzer (Flash Elemental Analyzer 1112 Series, Thermo Electron) and continuous flow isotope ratio mass spectrometer (Delta Plus, Thermo Electron). All isotopic data were reported in conventional delta notation (in ‰) as follows:

$$\delta^{13}\text{C} = \left[\frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}}}{(^{13}\text{C}/^{12}\text{C})_{\text{standard}}} - 1 \right] \times 1000 \text{ (‰)}$$
$$\delta^{15}\text{N} = \left[\frac{(^{15}\text{N}/^{14}\text{N})_{\text{sample}}}{(^{15}\text{N}/^{14}\text{N})_{\text{standard}}} - 1 \right] \times 1000 \text{ (‰)}$$

Pee Dee Belemnite (PDB) and atmospheric nitrogen were used as references for ^{13}C and ^{15}N , respectively. Glycine was used as a working standard in this study. The overall analytical error was within ± 0.2 ‰.

The THg contents of the samples were determined with an MA-3000 mercury analyzer (Thermal vaporization atomic absorption, Nippon Instruments). The NIMJ CRM 7402-a (cod fish tissue) was used to test the accuracy of the method as a standard reference for the determination of THg content of the specimens of the fishes and mega-benthos.

Analyses of trophic relationship and biomagnification of mercury

The trophic position of each species of the fishes and mega-benthos collected in this study was determined with its $\delta^{15}\text{N}$ value of the body tissues. The $\delta^{15}\text{N}$ value of the secondary consumers, 13.4 ± 0.7 ‰ (mean \pm S.D.), was obtained with the data of the seven species of the secondary consumers of the macro-benthic animals collected in the study area⁷⁾. We assumed the isotopic shift of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values between the prey and predator as $+1$ ‰ and $+3.4$ ‰, respectively¹⁵⁾. Being based on these assumptions, the trophic position value of each species (TP_i) in the community of the aquatic animals was determined by

the following equation.

$$\text{TP}_i = 3 + (\delta^{15}\text{N}_i - \delta^{15}\text{N}_{\text{s.c.}}) / 3.4 \text{ (‰)}$$

TP_i : trophic position of species i , $\delta^{15}\text{N}_i$: $\delta^{15}\text{N}$ value of species i , $\delta^{15}\text{N}_{\text{s.c.}}$: the mean of $\delta^{15}\text{N}$ values of seven species of the secondary consumers (S.C.) of the macro-benthic animals occurring in the study area = 13.4 (‰)⁷⁾, 3.4 (‰): isotopic shift of $\delta^{15}\text{N}$ value between prey and predator¹⁵⁾.

In this study, the animal which has a TP value between 2.8 and 3.2 or one between 3.8 and 4.2 is regarded as a secondary consumer or a tertiary one, respectively, considering the range of the standard deviation of the $\delta^{15}\text{N}$ values (± 0.7 ‰) of the seven species of the secondary consumers of the macro-benthic animals collected in the study area⁷⁾. The difference of 0.7 ‰ in $\delta^{15}\text{N}$ value is equivalent to that of 0.2 in TP value. The animal with a TP value between 3.3 and 3.7 is treated as “the intermediate consumer” between the secondary consumer and tertiary one, which is referred to “the intermediate consumer” in this paper.

III RESULTS

Isotopic signatures of the body tissues of fishes and mega-benthos

Fig. 2 indicates the relationship between $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the body tissues of 24 species of animals collected by the samplings in the inner part of Isahaya Bay in this study, which were made up of 21 species of fishes, two species of cephalopoda, and one species of malacostraca, and their trophic positions in the food chain of the aquatic animal community in the bay. (The

data on the stable isotope ratios of carbon and nitrogen of these species are noted in Table 1). The mean values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of these animals ranged between -18.0 ‰ and -14.5 ‰, and 12.8 ‰ and 17.3 ‰, respectively. According to the general trend of isotopic shift between prey and predator¹⁵⁾, the range of the $\delta^{13}\text{C}$ values, 3.5 ‰, indicates that they exploited the organic matters derived from multiple sources of the primarily producing organisms, and that of the $\delta^{15}\text{N}$ values, 4.5 ‰, which exceeded the general isotopic shift of $\delta^{15}\text{N}$ value between the predator and prey, 3.4 ‰, indicates that they preyed on the animals of different trophic positions.

The fishes and mega-benthos collected in this study possess large mobility, and seem to feed on various diets in both of the food chains of the pelagic and benthic ecosystems. It is, therefore, hard to define their trophic

positions in the aquatic animal community simply from the observations of their feeding habits. However, judging from the TP values calculated with their $\delta^{15}\text{N}$ values (Table 1), two species of fishes, *Lateolabrax japonicus* (Japanese seabass, TP = 4.1) and *Paralichthys olivaceus* (bastard halibut, TP = 3.9), were regarded as tertiary consumers in the community of the aquatic animals in the bay. Six species of fishes, *Hemirygion akajei* (large size (63.6 ± 4.9 cm, $1,847 \pm 145$ g, mean \pm S.D., $n = 4$) of red stingray), *Callionymus beniteguri* (whitespotted dragonet), *Takifugu rubripes* (Japanese pufferfish), *Pseudopleuronectes herzensteini* (yellow striped flounder), *Cynoglossus abbreviatus* (three-lined tongue sole) and *Mugil cephalus* (flathead grey mullet), and one species of cephalopoda, *Octopus* sp. (octopus) had TP values between 2.8 and 3.2, and were treated as secondary consumers.

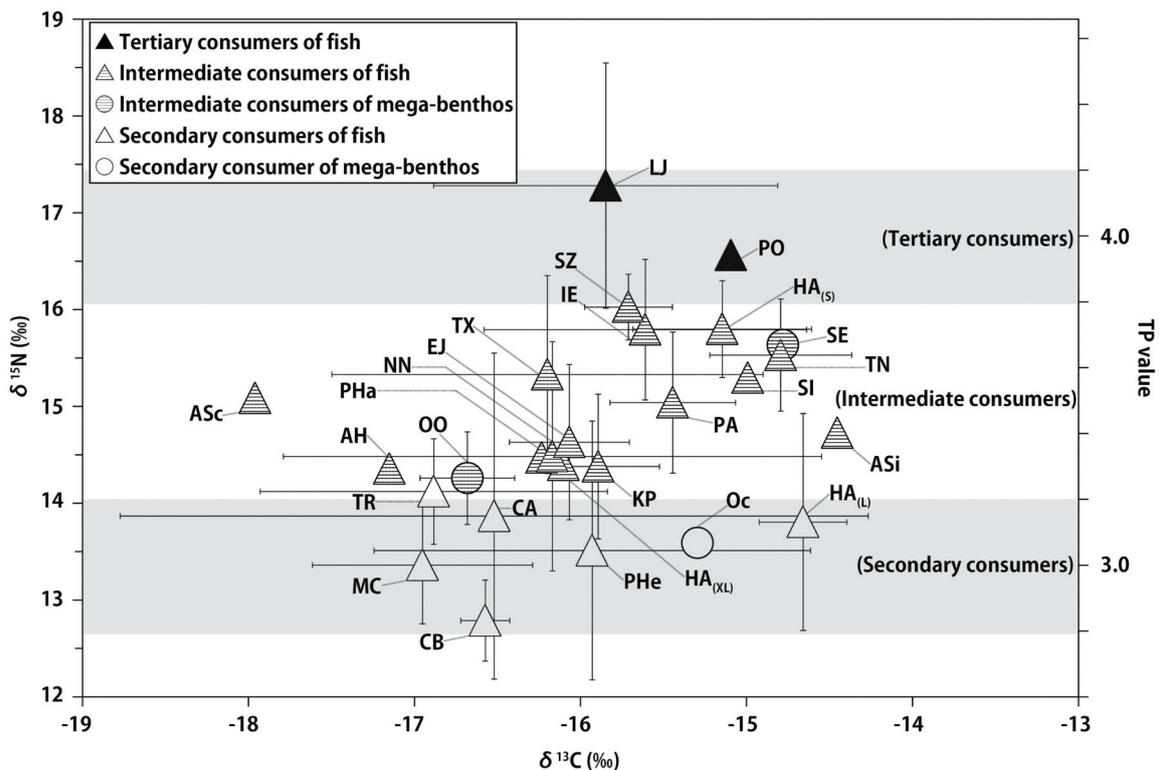


Fig. 2 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures of 24 species of the fishes and mega-benthos collected from the inner part of Isahaya Bay. The data of the plots are noted in Table 1. Error bars represent standard deviation of the data.

Table 1 A species list of 24 species of the fishes and mega-benthos collected in the inner part of Isahaya Bay and the information on their body sizes, stable isotope ratios of carbon and nitrogen, THg contents, and trophic position.

Species name	Common name	Code	Body length (cm) mean ± S.D.	Body weight (g) mean ± S.D.	$\delta^{13}\text{C}$ (‰) mean ± S.D.	$\delta^{15}\text{N}$ (‰) mean ± S.D.	THg Content(ng/g d.w.) mean ± S.D.	TP	No. of data
F: <i>Hemirygion akajei</i> (Extra Large)	Red stingray	HA _(XL)	72.0	5,150	-16.1	14.4	3,700	3.3 I.C.	1
F: <i>Hemirygion akajei</i> (Large)	Red stingray	HA _(L)	63.6 ± 4.9	1,847 ± 145	-14.7 ± 0.3	13.8 ± 1.1	671 ± 340	3.1 S.C.	4
F: <i>Hemirygion akajei</i> (Small)	Red stingray	HA _(S)	30.6 ± 2.4	98.2 ± 29.1	-15.1 ± 0.5	15.8 ± 0.5	142 ± 76	3.7 I.C.	6
F: <i>Lateolabrax japonicus</i>	Japanese seabass	LJ	30.1 ± 7.6	285 ± 201	-15.8 ± 1.0	17.3 ± 1.3	266 ± 99	4.1 T.C.	5
F: <i>Paralichthys olivaceus</i>	Bastard halibut	PO	45.0	1,000	-15.1	16.6	249	3.9 T.C.	1
F: <i>Sardinella zunasi</i>	Japanese sardinella	SZ	9.5 ± 0.4	7.4 ± 1.0	-15.7 ± 0.3	16.0 ± 0.3	232 ± 31.7	3.7 I.C.	4
F: <i>Ilisha elongata</i>	Elongate ilisha	IE	25.0 ± 4.4	112 ± 51	-15.6 ± 1.0	15.8 ± 0.7	175 ± 54	3.7 I.C.	5
F: <i>Takifugu niphobles</i>	Grass puffer	TN	11.2 ± 2.1	30.7 ± 15.2	-14.8 ± 0.4	15.5 ± 0.6	558 ± 226	3.6 I.C.	4
F: <i>Sebastes inermis</i>	Dark-banded rockfish	SI	15.5	73.3	-15.0	15.3	157	3.6 I.C.	1
F: <i>Takifugu xanthopterus</i>	Yellowfin pufferfish	TX	17.7 ± 3.9	128 ± 85	-16.2 ± 1.3	15.3 ± 1.0	186 ± 74	3.6 I.C.	8
F: <i>Acanthopagrus schlegelii</i>	Blackhead seabream	ASc	42.0	2,000	-18.0	15.1	942	3.5 I.C.	1
F: <i>Pennahia argentata</i>	Silver croaker	PA	17.5 ± 3.5	65.2 ± 32.5	-15.4 ± 0.4	15.0 ± 0.7	225 ± 122	3.5 I.C.	5
F: <i>Acanthopagrus sivicolus</i>	Okinawa seabream	ASi	19.5	142	-14.5	14.7	219	3.4 I.C.	1
F: <i>Engraulis japonicus</i>	Japanese anchovy	EJ	9.0 ± 0.6	4.5 ± 0.8	-16.1 ± 0.4	14.6 ± 0.8	70.9 ± 18.6	3.4 I.C.	12
F: <i>Planiliza haematocheila</i>	So-iyu mullet	PHa	62.5	2,225	-16.2	14.5	328	3.3 I.C.	2
F: <i>Nuchequula nuchalis</i>	Spomape ponyfish	NN	10.1 ± 0.6	14.7 ± 2.5	-16.2 ± 1.6	14.5 ± 1.2	418 ± 68	3.3 I.C.	4
F: <i>Konosirus punctatus</i>	Dotted gizzard shad	KP	15.3 ± 0.4	31.2 ± 3.3	-15.9 ± 0.4	14.4 ± 0.7	109 ± 22	3.3 I.C.	9
F: <i>Amblychaeturichthys hexanema</i>	Pinkgray goby	AH	12.0	9.7	-17.2	14.4	41.1	3.3 I.C.	2
F: <i>Takifugu rubripes</i>	Japanese pufferfish	TR	21.1 ± 3.1	191 ± 55	-16.9 ± 1.0	14.1 ± 0.5	340 ± 208	3.2 S.C.	4
F: <i>Cynoglossus abbreviatus</i>	Three-lined tongue sole	CA	31.5 ± 3.5	187 ± 52	-16.5 ± 2.3	13.9 ± 1.7	191 ± 50	3.1 S.C.	3
F: <i>Pseudopleuronectes herzensteini</i>	Yellow striped flounder	PHe	18.7 ± 7.0	103 ± 18	-15.9 ± 1.3	13.5 ± 1.3	134 ± 126	3.0 S.C.	5
F: <i>Mugil cephalus</i>	Flathead grey mullet	MC	53.7 ± 2.9	1,367 ± 388	-17.0 ± 0.7	13.4 ± 0.6	23.3 ± 14.1	3.0 S.C.	3
F: <i>Callionymus beniteguri</i>	Whitespotted dragonet	CB	10.8 ± 2.0	8.0 ± 3.1	-16.6 ± 0.1	12.8 ± 0.4	71.2 ± 29.5	2.8 S.C.	3
C: <i>Sepia esculenta</i>	Cuttlefish	SE	11.5	123	-14.8	15.6	168	3.6 I.C.	1
C: <i>Octopus</i> sp.	Octopus	Oc	19.0	22	-15.3	13.6	167	3.1 S.C.	1
M: <i>Oratosquilla oratoria</i>	Mantis shrimp	OO	9.6 ± 0.2	12.2 ± 0.8	-16.7 ± 0.3	14.3 ± 0.5	93.9 ± 10.6	3.3 I.C.	3

F: fish, C: cephalopoda, M: malacostraca, THg: total mercury, TP: trophic position, Secondary consumers (S.C.): TP = 2.8 to 3.2, Intermediate consumers (I.C.): TP = 3.3 to 3.7, Tertiary consumers (T.C.): TP = 3.8 to 4.2

The remaining 15 species of the aquatic animals were made up of 13 species of fishes, *Ilisha elongate* (elongate ilisha), *Pennahia argentata* (silver croaker), *Konosirus punctatus* (dotted gizzard shad), *Sebastes inermis* (dark-banded rockfish), *Takifugu niphobles* (grass puffer), *Takifugu xanthopterus* (yellowfin pufferfish), *Planiliza haematocheila* (so-iuy mullet), *Acanthopagrus schlegelii* (blackhead seabream), *Acanthopagrus sivicolus* (Okinawa seabream), *Nuchequula nuchalis* (spotnape ponyfish), *Amblychaeturichthys hexanema* (pinkgray goby), *Engraulis japonicas* (Japanese anchovy), and *Sardinella zunasi* (Japanese sardinella), two different

size classes of red stingray (*H. akajei*, extral-large size; 72.0 cm, 5,150 g, (n = 1), small size; 30.6 ± 2.4 cm, 98.2 ± 29.1 g, (n = 4)), one species of cephalopoda, *Sepia esculenta* (cuttlefish), and one species of malacostraca, *Oratosquilla oratoria* (mantis shrimp), had TP values between 3.3 and 3.7. They were considered to be “intermediate consumers”, which fed on mixtures of the primary and the secondary consumers for diets.

THg contents of the body tissues of fishes and mega-benthos

Figure 3 shows the relationship between the

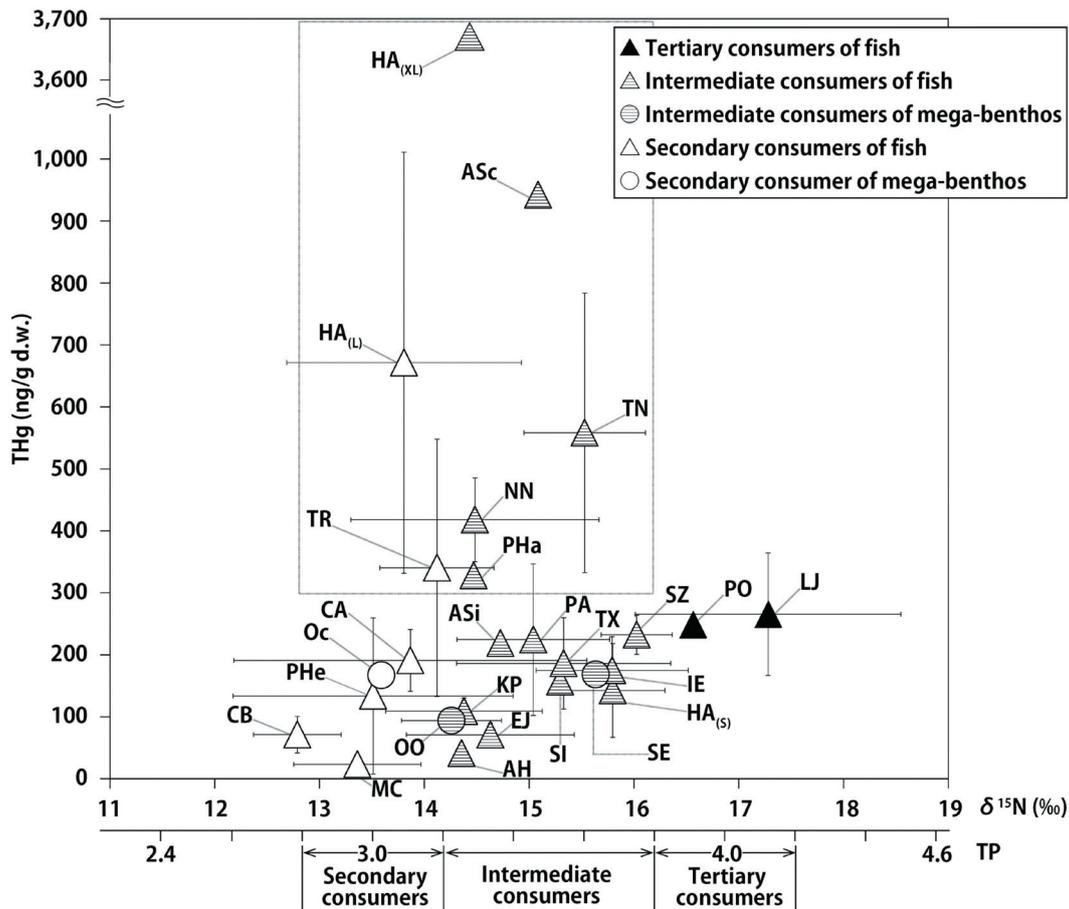


Fig. 3 The relationship between the $\delta^{15}\text{N}$ values and THg contents of the body tissues of the fishes and mega-benthos collected in the inner part of Isahaya Bay. Error bars represent standard deviation of the mean values. The data of the plots are noted in Table 1.

$\delta^{15}\text{N}$ values and THg contents of the body tissues of 24 species of fishes and mega-benthos collected in the inner part of Isahaya Bay. A general trend of biomagnification of THg content in the food chain of the animal community was not found in the THg contents of the fishes and mega-benthos collected in the study area. The values of two species of the tertiary consumers, *L. japonicas* and *P. olivaceus*, were 266 ± 99 ng/g d.w. (mean \pm S.D., $n = 5$) and 249 ng/g d.w. ($n = 1$), respectively, while five species of the intermediate consumers of fish, extra-large size class of *H. akajei* (TP = 3.3), *T. niphobles* (TP = 3.6), *A. schlegelii* (TP = 3.5), *P. haematocheila* (TP = 3.3) and *N. nuchalis* (TP = 3.3), and two species of the secondary consumers of fish, *T. rubripes* (TP = 3.2) and large size class of *H. akajei* (TP = 3.1), contained THg between 328 and 3,700 ng/g d.w. Although they were located at the lower trophic positions to the two species of the tertiary consumers in the community of aquatic animals, their THg contents exceeded those of the tertiary consumers.

IV DISCUSSION

According to the descriptions on the feeding habits of the two species of fishes as the tertiary consumers, *Lateolabrax japonicas*¹⁶⁾ and *Paralichthys olivaceus*¹⁷⁾, they prefer juveniles of fish and/or small species of fishes for main food items. The latter one is a demersal fish, but it swims up in the water to catch the pelagic animals such as Japanese anchovy, *Engraulis japonicas* during nighttime¹⁸⁾. The small fishes as ones of their main food items seem to grow feeding on zooplankton in the water, which increase preying on phytoplankton. Therefore, their relatively low THg contents as the tertiary consumers (*L. japonicas*: $266 \pm$

99 ng/g d.w. (mean \pm S.D.), *P. olivaceus*: 249 ng/g d.w.) seem to be responsible for their feeding activities in the pelagic system.

Among the six species that exceeded the THg contents of the tertiary consumers, *Hemitrygon akajei* (red stingray) with extra-large body size (72.0 cm, 5,150 g, $n = 1$) as the intermediate consumer (TP = 3.3) and large ones (63.3 ± 4.9 cm, $1,847 \pm 145$ g, $n = 4$) as the secondary consumer (TP = 3.1) had conspicuously high THg contents, 3,700 ng/g d.w. and 671 ± 240 ng/g d.w., respectively, while the THg content of the small ones (30.6 ± 2.4 cm, 98.2 ± 29.1 g, $n = 6$) was 142 ± 76 ng/g d.w., and had a much higher TP value (3.7) than those of the extra-large and large individuals. These facts indicate that the trophic position of *H. akajei* went down significantly as it grew up to adults, increasing the THg contents markedly.

In the study on the feeding habits of *H. akajei* collected in the inner part of Ariake Bay, which is located outside Isahaya Bay, the majority of the stomach contents were occupied by crustaceans including crabs and mysids and fishes, and the bivalves were not found at all in them¹⁹⁾. These results are, however, not contradictory to those of this study, since most of the specimens of red stingray were less than 50 cm¹⁹⁾, which are classified to small individuals that hardly prey on the bivalves in this study.

In the study area, the inner part of Isahaya Bay, the macro-benthic animals were divided into two groups in THg content, “High THg content group” and “Low THg content group” in both members of the primary and secondary consumers⁷⁾. The “High THg content group” of the primary consumers consisted of deposit feeding bivalves and polychaetes and bivalves burrowing in the sediment, which included a venerid

bivalve, *Ruditapes philippinarum*, with the THg content of 80.8 ng/g d.w., and that of the secondary consumers was made up of the predators of the primary consumers of “High THg content group” such as crabs and starfish⁷⁾. It is, therefore, very likely that *H. akajei* depended on *R. philippinarum* for diets more preferentially as it grew up, and the preferential predation resulted in the accelerated accumulation of THg in its body although its trophic position went down.

Acanthopagrus schlegelii had the second highest THg content (942 ng/g d.w., n = 1), and was one of the intermediate consumers (TP = 3.5). It is a demersal fish with a restricted migration habit²⁰⁾, and feeds predominantly on mollusks, crustaceans, and polychaetes^{21, 22)}. In particular, it prefers oysters (*Crassostrea gigas*) for diets exclusively²⁰⁾, which was also a member of “High THg content group” of the primary consumers (94.1 ± 22.3 ng/g d.w., n = 8) of the macro-benthic communities in the study area⁷⁾.

The remaining four species with high THg contents between 328 and 558 ng/g d.w. were two species of carnivorous pufferfish (*Takifugu niphobles* and *Takifugu rubripes*), *Planiliza haematocheila*, and *Nuchequula nuchalis*. The pufferfishes favor macro-benthic animals such as bivalves and crabs for diets^{17, 22-24)}, which were included in the members of “High THg content groups” of the primary and secondary consumers of the macro-benthic communities in the study area, respectively⁷⁾. *Planiliza haematocheila* belongs to Mugilidae. In general, the fish of this family feeds on the sediment with detritus, microphytobenthos and small benthic invertebrates²⁵⁾. *Nuchequula nuchalis* has a mouth with a downward opening to suck up the food items from the bottom, and favors macro-benthic animals including bivalves, polychaetes, crustaceans, etc., and small fish for diets²⁶⁾.

Thus, the six species of the fishes of the secondary and intermediate consumers of which the THg contents exceeded those of the pelagic fishes of the tertiary consumers prefer commonly macro-benthic animals for diets. Therefore, they are referred to as benthopelagic fishes⁹⁾, and their preys include the members of “High THg content groups” of the primary and secondary consumers⁷⁾. On the sea floor in the present study area, the sediment contained 133 ± 23 ng/g d.w. of THg due to deposition of POM with 27.2 ± 9.7 ng/g d.w. of THg contents⁷⁾. Therefore, the results of this study emphasize the strong influence of the THg accumulation process on the sediment of the sea floor and its biomagnification by the macro-benthic animals to the THg contents of the benthopelagic fishes in the coastal shallow water.

As we predicted from the results of the study on the bioaccumulation of THg in the macro-benthic animals occurring in the bay⁷⁾, one species of the benthopelagic fish, *H. akajei* (extra-large size), which favors macro-benthic animals of “High THg content groups” for diets (in particular, venerid bivalve, *R. philippinarum*), had a THg content, 3,700 ng/g d.w., which exceeded the Japanese provisional standard value of THg for fish and shellfish for foods, 400 ng/g w.w. (about 2,200 ng/g d.w.)⁸⁾. The extremely high THg content was almost equivalent to those of the marine mammals and sharks occurring in unpolluted areas by the anthropogenic factors and far from the active volcanos^{3, 5, 27, 28)}. Therefore, the results of this study indicate that the mercury discharge by the volcanic activities of Mt. Unzen and its bioconcentration by the phytoplankton and accumulation on the sediment of the sea floor in the bay and biomagnification in the benthic system have a great potential for pushing up the THg contents of some

benthopelagic fishes to the levels equivalent to those of the animals located at the top of the food web system of the animals in the pelagic system.

V CONCLUSIONS

We collected 24 species of aquatic animals with nets from a fishing boat in the inner part of Isahaya Bay between 17 October 2015 and 27 November 2017. They were made up of 21 species of fishes, two species of cephalopoda, and one species of malacostraca, and determined their trophic positions in the food chain of the aquatic animal community using the results of stable isotope ratios of carbon and nitrogen. They included two species of the tertiary consumers of fish, seven species of the secondary consumers including six species of fishes and one species of cephalopoda (octopus), and 16 species of the intermediate consumers between the secondary and tertiary ones including 14 species of fishes, one species of cephalopoda (cuttlefish), and one species of malacostraca (mantis shrimp).

The results of the analysis of THg content of these animals revealed that a general trend of biomagnification of mercury in the food chain of the animal community was not found in the fishes and mega-benthos collected in the study area. The two species of the tertiary consumers, *Lateolabrax japonicus* (Japanese seabass) and *Paralichthys olivaceus* (bastard halibut) contained 266 ± 99 ng/g d.w. (mean \pm S.D., $n = 5$) and 249 ng/g d.w. ($n = 1$) of THg, respectively, while five species of the intermediate consumers of fish, an extra-large size class of *Hemirhamphus akajei*, *Takifugu niphobles*, *Planiliza haematocheila*, *Acanthopagrus schlegelii*,

and *Nuchequula nuchalis*, and two species of the secondary consumers of fish, *Takifugu rubripes* and a large size class of *H. akajei*, contained 328 to 3,700 ng/g d.w. of THg. The secondary and intermediate consumers of the fishes, of which the THg contents exceeded those of the tertiary consumers, have common features in feeding habits in that they preferentially prey on macro-benthic animals including bivalves, polychaetes, crabs, and shrimps as main diets. They are referred to as “benthopelagic species”. Some of the diet species of the macro-benthic animals contain high levels of THg through the deposition of THg discharged by the volcanic activities on the sediment of the sea floor and biomagnification process in the detritus food chain in the macro-benthic communities. Thus, the high contents of THg detected from the benthopelagic fishes seemed to be transferred from the mercury deposited on the sediment via biomagnification process in the detritus food chain of the macro-benthic communities and their preferential predation on the macro-benthic animals.

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【和訳】 この文献を引用する場合は、英文の文献を引用のこと。翻訳：堤 裕昭

閉鎖性内湾に生息する魚類およびメガベントスへの海底における総水銀の生物濃縮過程の影響

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要 旨

重金属や難分解性化学物質の体組織の含量は、生物群集においてより高い栄養段階の生物ほど高くなるという傾向がある。しかしながら、西日本の九州に位置する諫早湾の湾奥部で採集した24種の魚類およびメガベントスでは、栄養段階と体組織の総水銀含量の間に、有意な関係をまったく見出すことができなかった。第三次消費者である2種の魚類 (*Lateolabrax japonicus* (スズキ) と *Paralichthys olivaceus* (ヒラメ)) は、それぞれ体組織に 266 ± 99 ng/g 乾重 (平均値 \pm 標準偏差, $n = 5$) および 249 ng/g 乾重 ($n = 1$) の総水銀を含んでいた。一方、第二次消費者または第二次消費者と第三次消費者の中間的な栄養段階に位置する6種の魚類の総水銀含量は、前述の第三次消費者の値を上回っていた。特に、アカエイ (*Hemitrygon akajei*) で特大サイズの個体 (72.0 cm, 5,150 g) ならびに大サイズの個体 (63.3 ± 4.9 cm, $1,847 \pm 145$ g, $n = 4$) の体組織からは、それぞれ $3,700$ ng/g 乾重および 671 ± 340 ng/g 乾重、クロダイ (*Acanthopagrus schlegelii*) からも 942 ng/g 乾重の高い総水銀含量が検出された。これらの6種の魚類は食性に1つの共通点が見られ、いずれも二枚貝類、多毛類、カニ類、エビ類を含む底生生物を餌として好んで摂食し、"benthopelagic 種" と呼ばれている。本研究の調査域では、火山活動によって放出された総水銀が堆積物中に蓄積し、その水銀が海底の腐食食物連鎖における生物濃縮過程を通して、特定の底生生物に高濃度の水銀が蓄積していた。このような "benthopelagic 種" に見られる高濃度の総水銀含量は、これらの魚類が水銀含量の高い底生生物を選択的に捕食することを通してもたらされたと考えられる。

キーワード：benthopelagic, 生物濃縮, 魚類, 諫早湾, 食物連鎖, 水銀, 総水銀含量

I はじめに

沿岸浅海域では、もっとも有害な重金属類の1つである水銀が陸上の周辺域から流入すると、植物プランクトン、海藻、海草のような一次生産

者に吸収され、それらの組織の中で濃度が濃縮される。水中では、植物プランクトンが動物プランクトンに捕食され、魚類、海生ほ乳類、鳥類など、食物連鎖で繋がった様々な生物によって捕食されて、栄養段階の高い生物になると、体組織の

水銀含量が著しく増加する¹⁻⁴⁾。この水中の生態系における生物濃縮過程と並行して、海底においても腐食食物連鎖に沿って動物の水銀含量が増加する傾向が見られる⁵⁻⁶⁾。水中で水銀を吸収した第一次生産者の多くは、直接的または間接的に(動物プランクトンによる捕食を通して)水中に懸濁する粒状有機物(POM)となり、海底に向けて沈降し、デトリタスとして海底に堆積する⁷⁾。大型底生生物の第一次消費者は、その水銀を含む堆積物や、水中に懸濁したり海底直上に再懸濁した粒状有機物を摂食し、海底におけるもう1つの生物濃縮過程が始まる^{5, 6)}。

本研究では沿岸浅海域の海底で進行する水銀の生物濃縮過程に焦点を当てる。著者らの近年の諫早湾における研究では⁷⁾、水中から水銀がほとんど検出されない条件でも、水中に懸濁する粒状有機物からは 27.3 ± 9.7 ng/g 乾重(平均値 ± 標準偏差)の総水銀が検出され、海底堆積物表層にはその約4.9倍の 133 ± 23 ng/g 乾重の総水銀が含まれていた。その海底には二枚貝類、多毛類、ヨコエビ類などの様々な大型底生生物が棲息し、堆積物に含まれる有機物や海底直上水に懸濁するPOMを主な餌にして、第一次消費者としての働きを果たしている。これらの生物群には、 101 ± 23 ng/g 乾重の高い総水銀含量のグループが見出され、主に堆積物中に生息する堆積物食の多毛類や懸濁物食の二枚貝類で構成されていた。また、この二枚貝類を主要な餌とする肉食性の第二次消費者(カニ類やヒトデ類)からは、さらに約2.3倍高い 215 ± 47 ng/g 乾重の総水銀含量が検出された。日本では食用魚介類の総水銀量の暫定基準値を400 ng/g 湿重と定めている(標本の乾燥重量に換算すると、約2,000 ng/g 乾重に相当する)⁸⁾。これらの高総水銀含量の大型底生生物を選択的に捕食する魚類やメガベントスが

存在すれば、それらの生物の中で、総水銀含量が生物濃縮の効果によって、この暫定基準値を超える種が生じる可能性も考えられる。

本研究では、西日本の九州、有明海奥部西側に位置する閉鎖性の内湾である諫早湾の奥部で、刺し網、定置網、投げ網を用いて魚類やメガベントスを採集した。本研究の目的は、諫早湾奥部に生息する魚類およびメガベントスの体組織の炭素および窒素の安定同位体比と総水銀含量を測定し、水生生物群集における栄養段階と総水銀含量の関係を明らかにし、大型底生生物間で生じる総水銀の生物濃縮過程が魚類およびメガベントスの総水銀含量にどのような影響を及ぼすのかについて考察する。

II 材料と方法

調査地

諫早湾は、九州の有明海奥部西側に位置する閉鎖性内湾である(図1)。総面積は65 km²で、平均水深は10 mである。活火山の雲仙普賢岳を擁する島原半島が湾の南側に隣接している。一般に、火山噴火は大気中への自然現象による水銀の主要な放出源の1つとなっている⁹⁾。雲仙は九州の有史以来少なくとも3回(1663年、1792年、1990~1995年)の噴火を繰り返してきた¹⁰⁾。

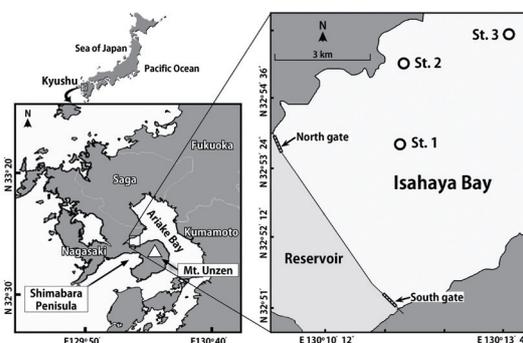


図1 調査地(諫早湾奥部)と調査地点

1990年代の噴火では、1,928日間に約2.95トンの水銀が大気中に放出された¹¹⁾。また、この火山の周辺では水銀を含む熱水が湧出したり、噴気の上がる場所が至るところにあり¹²⁻¹⁴⁾、それらも諫早湾への水銀の負荷源となりうる。この湾奥部に3調査地点を設置し、St. 1では刺し網、St. 2では定置網、St. 3では投網を用いて魚類およびメガベントスを採集した。

生物標本の採集

St. 1では、2015年10月17日、2016年1月27日、3月24日、8月3日に、漁船から刺し網を約30分流して、St. 2では年間を通して設置された定置網を用いて、魚類およびメガベントスを採集した。St. 3では、2017年11月27日に、漁船の魚群探知機で魚を探し、投網で魚類およびメガベントスを採集した。採集したすべての標本はクーラーボックスに入れて、研究室に持ち帰った。

サンプルの処理

研究室で魚類およびメガベントスの標本は種を同定し、サイズと重量を計測し、皮と骨のない背側の筋肉組織を採取した。各標本の背側の筋肉を湿重量で約6gを採取して、ポリプロピレン製の容器(5ml)に蒸留水を用いて流し込み、-20℃の冷凍庫に保管した。その後、凍結乾燥器を用いて48時間処理して乾燥し、粉状のサンプルにしてプラスチック容器に保管した。

炭素と窒素の安定同位体比の分析には、上述のサンプルから約1gを取り出して1.5mlのマイクロチューブに入れ、2N塩酸を加えて炭酸カルシウムを除去し、48時間真空乾燥した。このサンプルにクロロホルムとメタノールの混合液(体積比2:1)を加えて脱脂し、4℃で毎分1万回転で遠心分離する処理を2回繰り返して、メタノー

ル(100%)を加えて毎分1万回転で遠心分離を5分間行い、真空乾燥を48時間行った。最後に、ペレットベッセルを用いて粉状にした。残りのサンプルは総水銀量の測定に使用した。

化学分析

サンプルの炭素および窒素安定同位体比は元素分析計(Flash Elemental Analyzer 1112 Series, Thermo Electron)と同位体質量分析計(Delta Plus, Thermo Electron)を用いて測定した。すべての同位体データは、次の式を用いて示す。

$$\delta^{13}\text{C}=[(^{13}\text{C}/^{12}\text{C}_{\text{sample}})/(^{13}\text{C}/^{12}\text{C}_{\text{standard}})-1]\times 1000(\text{‰})$$

$$\delta^{15}\text{N}=[(^{15}\text{N}/^{14}\text{N}_{\text{sample}})/(^{15}\text{N}/^{14}\text{N}_{\text{standard}})-1]\times 1000(\text{‰})$$

この研究では、グリシンを作業用標準物質として使用した。分析誤差は±0.2‰である。

サンプルの総水銀含量(THg)は、MA-3000水銀分析計(Thermal vaporization atomic absorption, Nippon Instruments)を用いて測定した。NIMJ CRM 7402-a(タラの組織)を用いて、魚類およびメガベントスの標本の総水銀含量を測定するための標準物質として使用し、測定誤差を測定した。

栄養段階と水銀の生物濃縮の分析

本研究で採集した魚類およびメガベントス各種の栄養段階を、体組織の $\delta^{15}\text{N}$ の値を用いて決定した。第二次消費者の $\delta^{15}\text{N}$ の値は、諫早湾湾奥部で採集した大型底生生物8種の値を用いて、 $13.4 \pm 0.7 \text{‰}$ (平均値±標準偏差)とした⁷⁾。また、餌生物と捕食者の間では、 $\delta^{13}\text{C}$ と $\delta^{15}\text{N}$ の値がそれぞれ1‰と3.4‰増加すると仮定した¹⁵⁾。これらの仮定をもとにして、水生生物群集における各生物の栄養段階値(TP値)を次の式で求めた。

て、「第二次と第三次の中間消費者」と呼ぶ。

III 結果

$$TP_i = 3 + (\delta^{15}N_i - \delta^{15}N_{\text{第二次消費者}}) / 3.4 (\text{‰})$$

TP: 種 i の生物群集における栄養段階, $\delta^{15}N_i$: 種 i の $\delta^{15}N$ 値, $\delta^{15}N_{\text{第二次消費者}}$: 第二次消費者の $\delta^{15}N$ 値の平均値 = 13.4 (‰)⁷⁾, 3.4 (‰): 餌生物および捕食者の間における $\delta^{15}N$ 値の変化¹⁵⁾

本研究の調査地の諫早湾奥部で採集した大型底生生物の7種の二次消費者は、その体組織の $\delta^{15}N$ 値の標準偏差値が ± 0.7 ‰を示した⁷⁾。この値は、TPでは ± 0.2 に相当する。そこで、本研究では、2.8 ~ 3.2 のTP値を有する生物を第二次消費者、3.8 ~ 4.2 の生物を第三次消費者とする。TP値 3.3 ~ 3.7 の生物は、第二次消費者と第三次消費者の中間に位置すると生物とし

魚類とメガベントスの炭素・窒素安定同位体比

図2には諫早湾奥部で採集され24種の生物の体組織の $\delta^{13}C$ と $\delta^{15}N$ の値の関係を示す。これらの生物は、21種の魚類、2種の頭足類、1種の軟甲類から構成されていて、同湾の水生生物群集の食物連鎖における各種の位置を示している（これらの種の炭素・窒素安定同位体比のデータは表1に示す）。これらの生物の $\delta^{13}C$ および $\delta^{15}N$ の平均値はそれぞれ -18.0 ‰ ~ -14.5 ‰ および 12.8 ‰ ~ 17.3 ‰ の範囲にあった。餌生物とその捕食者間における安定同位体比の変化に関する一般的な傾向から判断して、 $\delta^{13}C$ の範囲が 3.5 ‰に

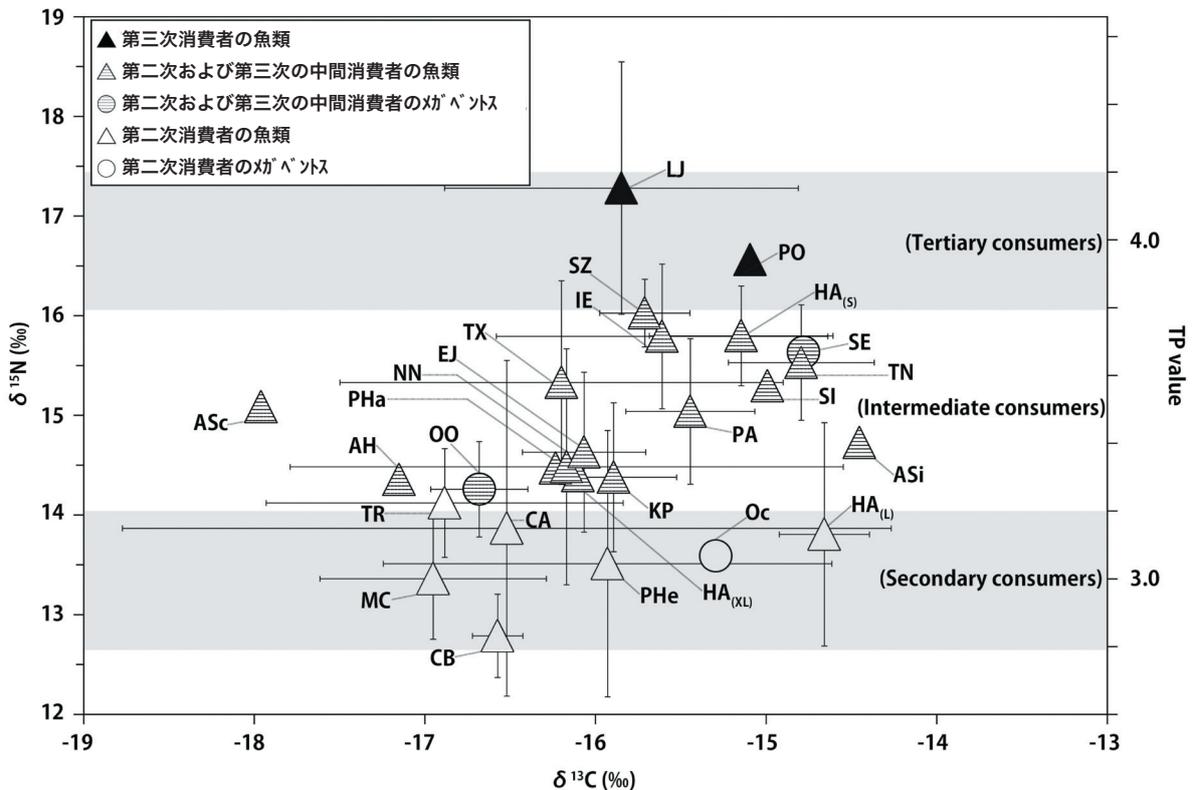


図2 諫早湾奥部で採集した24種の魚類とメガベントスの $\delta^{13}C$ と $\delta^{15}N$ の関係
エラーバーは値の標準偏差値を示す。

表1 諫早湾奥部で採集した魚類およびメガベントス24種のリスト, ならびにそれぞれの種の体サイズ, 炭素・窒素安定同位体比, 総水銀含量および栄養段階に関する情報

種名	和名	Code	体長 (cm) mean ± S.D.	体重 (g) mean ± S.D.	$\delta^{13}\text{C}$ (‰) mean ± S.D.	$\delta^{15}\text{N}$ (‰) mean ± S.D.	総水銀含量 (ng/g 乾重) mean ± S.D.	TP	No. of data
F: <i>Hemirygion akajei</i> (Extra Large)	アカエイ (超大型個体)	HA _(XL)	72.0	5,150	-16.1	14.4	3,700	3.3 I.C.	1
F: <i>Hemirygion akajei</i> (Large)	アカエイ (大型個体)	HA _(L)	63.6 ± 4.9	1,847 ± 145	-14.7 ± 0.3	13.8 ± 1.1	671 ± 340	3.1 S.C.	4
F: <i>Hemirygion akajei</i> (Small)	アカエイ (小型個体)	HA _(S)	30.6 ± 2.4	98.2 ± 29.1	-15.1 ± 0.5	15.8 ± 0.5	142 ± 76	3.7 I.C.	6
F: <i>Lateolabrax japonicus</i>	スズキ	LJ	30.1 ± 7.6	285 ± 201	-15.8 ± 1.0	17.3 ± 1.3	266 ± 99	4.1 T.C.	5
F: <i>Paralichthys olivaceus</i>	ヒラメ	PO	45.0	1,000	-15.1	16.6	249	3.9 T.C.	1
F: <i>Sardinella zunasi</i>	サッパ	SZ	9.5 ± 0.4	7.4 ± 1.0	-15.7 ± 0.3	16.0 ± 0.3	232 ± 31.7	3.7 I.C.	4
F: <i>Ilisha elongata</i>	ヒラ	IE	25.0 ± 4.4	112 ± 51	-15.6 ± 1.0	15.8 ± 0.7	175 ± 54	3.7 I.C.	5
F: <i>Takifugu niphobles</i>	クサフグ	TN	11.2 ± 2.1	30.7 ± 15.2	-14.8 ± 0.4	15.5 ± 0.6	558 ± 226	3.6 I.C.	4
F: <i>Sebastes inermis</i>	メハル	SI	15.5	73.3	-15.0	15.3	157	3.6 I.C.	1
F: <i>Takifugu xanopterus</i>	シマフグ	TX	17.7 ± 3.9	128 ± 85	-16.2 ± 1.3	15.3 ± 1.0	186 ± 74	3.6 I.C.	8
F: <i>Acanthopagrus schlegelii</i>	クロダイ	ASC	42.0	2,000	-18.0	15.1	942	3.5 I.C.	1
F: <i>Pemphidia argentata</i>	シログチ	PA	17.5 ± 3.5	65.2 ± 32.5	-15.4 ± 0.4	15.0 ± 0.7	225 ± 122	3.5 I.C.	5
F: <i>Acanthopagrus shirocolus</i>	ミナミクロダイ	ASI	19.5	142	-14.5	14.7	219	3.4 I.C.	1
F: <i>Engraulis japonicus</i>	カタクチイワシ	EJ	9.0 ± 0.6	4.5 ± 0.8	-16.1 ± 0.4	14.6 ± 0.8	70.9 ± 18.6	3.4 I.C.	12
F: <i>Planiliza haematocheila</i>	メナダ	PHa	62.5	2,225	-16.2	14.5	328	3.3 I.C.	2
F: <i>Nuchequula nuchalis</i>	ヒイラギ	NN	10.1 ± 0.6	14.7 ± 2.5	-16.2 ± 1.6	14.5 ± 1.2	418 ± 68	3.3 I.C.	4
F: <i>Konosirus punctatus</i>	コノシロ	KP	15.3 ± 0.4	31.2 ± 3.3	-15.9 ± 0.4	14.4 ± 0.7	109 ± 22	3.3 I.C.	9
F: <i>Amblychaeturichthys hexanema</i>	アカハゼ	AH	12.0	9.7	-17.2	14.4	41.1	3.3 I.C.	2
F: <i>Takifugu rubripes</i>	トラフグ	TR	21.1 ± 3.1	191 ± 55	-16.9 ± 1.0	14.1 ± 0.5	340 ± 208	3.2 S.C.	4
F: <i>Cynoglossus abbreviatus</i>	コウライアカシタヒラメ	CA	31.5 ± 3.5	187 ± 52	-16.5 ± 2.3	13.9 ± 1.7	191 ± 50	3.1 S.C.	3
F: <i>Pseudopleuronectes herzensteini</i>	マガレイ	PHe	18.7 ± 7.0	103 ± 18	-15.9 ± 1.3	13.5 ± 1.3	134 ± 126	3.0 S.C.	5
F: <i>Mugil cephalus</i>	ボラ	MC	53.7 ± 2.9	1,367 ± 388	-17.0 ± 0.7	13.4 ± 0.6	23.3 ± 14.1	3.0 S.C.	3
F: <i>Callionymus beniteguri</i>	ノビヌメリ	CB	10.8 ± 2.0	8.0 ± 3.1	-16.6 ± 0.1	12.8 ± 0.4	71.2 ± 29.5	2.8 S.C.	3
C: <i>Septia esculenta</i>	コウイカ	SE	11.5	123	-14.8	15.6	168	3.6 I.C.	1
C: <i>Octopus</i> sp.	タコの1種	Oc	19.0	22	-15.3	13.6	167	3.1 S.C.	1
M: <i>Oratosquilla oratoria</i>	シヤコ	OO	9.6 ± 0.2	12.2 ± 0.8	-16.7 ± 0.3	14.3 ± 0.5	93.9 ± 10.6	3.3 I.C.	3

F: 魚類, C: 頭足類, M: 軟甲類, THg: 総水銀含量, TP: 栄養段階値, S.C.: 第二次消費者 (TP = 2.8 ~ 3.2), I.C.: 第二次と第三次の中間消費者 (TP = 2.2 ~ 3.7), T.C.: 第三次消費者 (TP = 3.8 ~ 4.2)

およぶことは、これらの生物が複数の一次生産者由来の有機物を利用していただことを示している。また、 $\delta^{15}\text{N}$ の範囲が 4.5 ‰におよび、餌生物と捕食者間に見られる $\delta^{15}\text{N}$ 値の増加分の 3.4 ‰を上回っていて、このことは異なる栄養段階の生物を餌として利用していただことを示している。

本研究で採集した魚類およびメガベントスは高い移動能力を有し、水中および海底の生態系の両方の食物連鎖上で摂餌していると考えられる。そのため、これらの生物の水生生物群集における栄養段階を簡単には決められない。しかしながら、 $\delta^{15}\text{N}$ の値より算出した TP 値より (表 1), 2 種の魚類 *Lateolabrax japonicas* (スズキ, TP = 4.1) および *Paralichthys olivaceus* (ヒラメ, TP = 3.9) は、諫早湾の水生生物群集における第三次消費者と見なされた。6 種の魚類, *Hemistrygon akajei* (アカエイの大型個体 (63.6 ± 4.9 cm, 1,847 ± 145 g, 平均値 ± 標準偏差, n = 4), *Callionymus beniteguri* (ノビヌメリ), *Takifugu rubripes* (トラフグ), *Pseudopleuronectes herzensteini* (マガレイ), *Cynoglossus abbreviatus* (コウライアカシタビラメ), *Mugil cephalus* (ボラ), ならびに 1 種の頭足類, *Octopus* sp. (タコの 1 種) は, TP 値が 2.8 ~ 3.2 範囲にあり, 第二次消費者と見なされた。

残りの 15 種の水生生物には, 13 種の魚類, *Ilisha elongate* (ヒラ), *Pennahia argentata* (シログチ), *Konosirus punctatus* (コノシロ), *Sebastes inermis* (メバル), *Takifugu niphobles* (クサフグ), *Takifugu xanthopterus* (シマフグ), *Planiliza haematocheila* (メナダ), *Acanthopagrus schlegelii* (クロダイ), *Acanthopagrus sivicolus* (ミナミクロダイ), *Nuchequula nuchalis* (ヒイラギ), *Amblychaeturichthys hexanema* (アカハゼ), *Engraulis japonicas* (カタクチイワシ), *Sardinella zunasi* (サツパ) と, 2 つの体サイズの *H. akajei* (ア

カエイ) (超大型個体; 72.0 cm, 5,150 g, n = 1, 小型個体; 30.6 ± 2.4 cm, 98.2 ± 29.1 g, n = 4), 1 種の頭足類, *Sepia esculenta* (コウイカ), 1 種の軟甲類, *Oratosquilla oratoria* (シャコ) が含まれていて, TP 値は 3.3 ~ 3.7 の範囲にあった。これらの生物は, 第一次消費者と第二次消費者の両方を餌として利用しており, 以下, 「第二次と第三次の中間消費者」と呼ぶ。

魚類とメガベントスの体組織の総水銀 (THg) 含量

図 3 に諫早湾奥部で採集した 24 種の魚類およびメガベントスの体組織の $\delta^{15}\text{N}$ 値と総水銀 (THg) 含量の関係を示す。本研究地で採集した魚類およびメガベントスには, 動物群集の食物連鎖において広く見られるように水銀の生物濃縮傾向が見られなかった。第三次消費者である 2 種 (*L. japonicas*, *P. olivaceus*) の総水銀含量はそれぞれ 266 ± 99 ng/g 乾重 (平均値 ± 標準偏差, n = 5), 249 ng/g 乾重 (n = 1) を記録した。一方, 5 種の「第二次と第三次の中間消費者」の魚類 (*H. akajei* の超大型個体 (TP = 3.3), *T. niphobles* (TP = 3.6), *P. haematocheila* (TP = 3.3), *A. schlegelii* (TP = 3.5), *N. nuchalis* (TP = 3.3) と, 2 種の第二次消費者の魚類 (*T. rubripes* (TP = 3.2), *H. akajei* の大型個体 (TP = 3.1) は, 体組織に 328 ~ 3,700 ng/g 乾重の総水銀を含んでいた。これらの生物は, 魚の群集における前述の 2 種の第三次消費者より低い栄養段階に位置しているが, 総水銀含量では第三次消費者を上回っていた。

IV 考 察

第三次消費者である 2 種の魚類 (*Lateolabrax japonicas*, *Paralichthys olivaceus*) の摂餌習慣の記載によれば^{16, 17)}, これらの種は稚魚や小型魚

類を主要な餌としている。後者は底生魚であるが、夜間に水中を浮上し、遊泳しているカタクチイワシ (*Engraulis japonicas*) を摂食する¹⁸⁾。これらの種の餌となる小型魚類は、水中の動物プランクトンを摂食して成長し、それは植物プランクトンを餌としている。したがって、第三次消費者の2種の魚類の比較的に低い総水銀含量 (*L. japonicas*: 266 ± 99 ng/g 乾重 (平均値 ± 標準偏差), *P. olivaceus*: 249 ng/g 乾重) は、水中の食物連鎖上で生産される餌を主として利用する摂餌習慣に起因していると考えられる。

第三次消費者の総水銀含量を上回った6種の

中で、*Hemitygon akajei* (アカエイ) の超大型個体 (72.0 cm, 5,150 g, n = 1, 第二次消費者, TP = 3.3) および大型個体 (63.3 cm, 1,847 ± 145 g, n = 4, TP = 3.1) は、それぞれ際だって高い総水銀含量を有していた (3,700 ng/g 乾重, 671 ± 240 ng/g 乾重)。これに対して、同種の小型個体 (30.6 ± 2.4 cm, 98.2 ± 29.1 g, n = 6) の総水銀含量は 142 ± 76 ng/g 乾重と大幅に低く、TP 値は 3.7 と逆に大幅に高い値となった。これらの事実は、*H. akajei* は成体に成長するにつれて栄養段階が大きく低下し、総水銀含量は著しく増加していくことを示している。

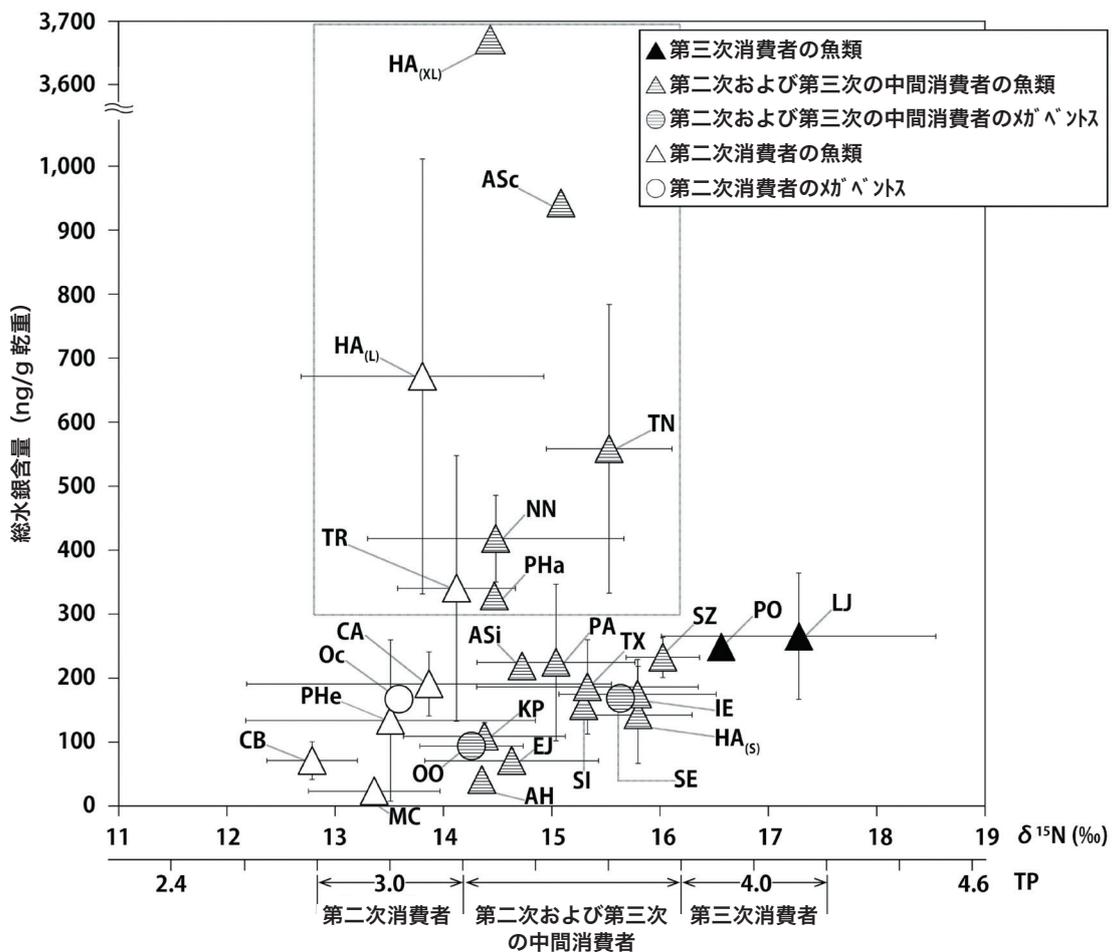


図3 諫早湾奥部で採集した魚類およびメガベントスの体組織の $\delta^{15}\text{N}$ 値と総水銀含量の関係。エラーバーは標準偏差を示す。各プロットのデータは表1に示す。

諫早湾の外側に位置する有明海奥部海域におけるアカエイの摂餌習慣に関する研究では、胃内食物の多くはカニ類やアミ類などの甲殻類や魚類によって占められ、二枚貝類はまったく見られなかった¹⁹⁾。しかしながら、この報告は本研究で得られた結果と矛盾するものではない。甲殻類や魚類を捕食していた個体のほとんどは体長 50 cm 未満で、本研究では二枚貝類をほとんど捕食していない小型個体に分類される。

本研究の調査地である諫早湾奥部では、大型底生生物が第一次消費者および第二次消費者の両方の生物群で、「高総水銀含量グループ」と「低総水銀含量グループ」に分けられる⁶⁾。第一次消費者の「高総水銀含量グループ」にはアサリ (*Ruditapes philippinarum*) が含まれ、80.8 ng/g 乾重の総水銀を含んでいた⁶⁾。したがって、*H. akajei* は成長に伴って餌を *R. philippinarum* に依存する割合が高くなり、その食性の変化が、栄養段階は低下しつつも、むしろそのことが体組織への水銀の蓄積を加速していることが考えられる。

Acanthopagrus schlegelii からは 2 番目に高い総水銀含量 (942 ng/g 乾重) が検出され、TP 値が 3.5 の「第二次と第三次の中間消費者」であった。この種は移動能力が限られた底生魚類であり²⁰⁾、貝類、甲殻類、多毛類を好んで摂食し^{21, 22)}、特に、マガキ (*Crassostrea gigas*) を好んでいるが²⁰⁾、この種も本調査域の大型底生生物群集の第一次消費者の「高総水銀含量のグループ」に入っている (94.1 ± 22.3 ng/g 乾重, n = 8)⁷⁾。

総水銀含量の高い残りの 4 種 (328 ~ 558 ng/g 乾重) は、肉食性の 2 種のフグ類 (*Takifugu niphobles*, *Takifugu rubripes*)、*Planiliza haematocheila*、および *Nuquequula nuqualis* が挙げられる。フグ類は二枚貝類やカニ類などの底生生物を餌として好み^{17, 22-24)}、本調査地の底生

生物群集では一次消費者および二次消費者の生物の高総水銀含量のグループの種が含まれていた⁷⁾。*Planiliza haematocheila* はボラ科に属している。一般にこの科の魚類はデトリタスを含む底質、底生微細藻類、小型の底生生物を摂食する²⁵⁾。*Nuquequula nuqualis* は海底に生息し、海底から餌を吸い込むための下向きに開口部のある口を有し、二枚貝類、多毛類、甲殻類などの底生生物や小型の魚類を餌としている²⁶⁾。

以上のように、水生生物群集の第三次消費者の魚類を上回る総水銀含量の「第二次消費者」および「第二次と第三次の中間消費者」の 6 種の魚類は、共通して餌として底生生物を摂食している。これらの種は "benthopelagic fish" と呼ばれる⁵⁾、その餌生物には第一次および第二次消費者の高総水銀含量グループの種が含まれている⁷⁾。本調査地の海底では、27.3 ± 9.7 ng/g 乾重を含む POM の堆積によって、堆積物には 133 ± 23 ng/g 乾重の総水銀が含まれている⁷⁾。したがって、本研究の結果は、沿岸浅海域においては、海底堆積物上での総水銀の蓄積過程および大型底生生物による生物濃縮過程が、benthopelagic 種の魚類への総水銀含量に大きな影響を及ぼしていることを示している。

諫早湾に生息する大型底生生物における総水銀の生物濃縮に関する研究の結果より予測されたように⁷⁾、餌として高総水銀含量の大型底生生物を好む benthopelagic 種の魚類 (*H. akajei* (超大型および大型個体)、は、餌として一次消費者の高総水銀含量グループの底生生物 (特にマルスダレガイ科のアサリ) を好んで摂食し、日本の食用魚介類の総水銀量に関する暫定基準値 400 ng/g 湿重 (約 2,200 ng/g 乾重に相当する。)⁸⁾ を超えていた。これらの種の超大型個体の総水銀含量 (3,700 ng/g 乾重) は、人為的な要因によって汚

染されておらず、活火山からも遠く離れた場所に生息する海棲ほ乳類や海鳥の値に匹敵するものである^{3, 5, 27, 28)}。したがって、本研究の結果は、雲仙の火山活動による水銀の放出、諫早湾内の水中における植物プランクトンによる水銀の生物濃縮および海底堆積物への蓄積、ならびに大型底生生物による生物濃縮が、"benthopelagic種"の魚類の総水銀含量を、その効果がもっとも大きい場合には、沿岸域に棲息する動物の食物網の頂点に位置する種と同等なレベルまで引き上げてしまうことを示している。

V まとめ

2015年10月17日～2017年11月27日に、諫早湾奥部において漁船から24種の水生生物を水生生物を採集した。それらは21種の魚類、2種の頭足類、1種の軟甲類からなり、炭素・窒素安定同位体比の分析より、水生動物群集の食物連鎖における栄養段階を決定した。これらの生物には2種の第三次消費者の魚類、第二次消費者の6種の魚類と1種の頭足類(タコ類)、15種の「第二次と第三次の中間的な消費者(13種の魚類、1種の頭足類(コウイカ)、1種の軟甲類(シャコ))」が含まれていた。

これらの動物の総水銀含量を測定した結果、本調査地で採集した魚類およびメガベントスには、動物群集の食物連鎖における生物濃縮に関する一般的な傾向が見られないことがわかった。2種の第三次消費者の魚類、*Lateolabrax japonicus* (スズキ) と *Paralichthys olivaceus* (ヒラメ) は、それぞれ体組織に 266 ± 99 ng/g 乾重 (平均値 \pm 標準偏差, $n = 5$) および 249 ng/g 乾重 ($n = 1$) の総水銀を含んでいた。一方、5種の第二次と第三次の中間消費者の魚類 (*Hemitrygon*

akajei の超大型個体, *Takifugu niphobles*, *Planiliza haematocheila*, *A. schlegeli*, *Nucchequula nuchalis*) および2種の第二次消費者の魚類 (*Takifugu rubripes*, *H. akajei* の大型個体) は、体組織に $328 \sim 3,700$ ng/g 乾重の総水銀を含んでいた。これらの第三次消費者の総水銀含量を上回った第二次消費者および第二次と第三次の中間消費者の魚類は、二枚貝類, 多毛類, カニ類, エビ類を含む底生生物を主要な餌としているという共通した摂餌習慣の特徴を有している。このような種は "benthopelagic種" と呼ばれている。これらの餌に利用される底生生物には、火山活動によって放出された水銀の海底堆積物への蓄積と底生生物群集の食物連鎖における生物濃縮過程を経て、高レベルの総水銀が体組織に蓄積している種が含まれている。このように、benthopelagic種の魚類から検出された高い総水銀含量は、海底堆積物に蓄積した水銀が、底生生物群集の腐食食物連鎖における生物濃縮過程と底生生物の選択的な捕食を通してもたらされたものである。

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