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Turbidity Distribution in the Surrounding Ocean Area of Miyake-shima Island after the Eruption of Mt. Oyama

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Abstract : The turbidity distribution around Miyake-shima was investigated by measuring beam attenuation, suspended solid (SS), suspended inorganic matter, and particle size distribution aboard the RT/V Umitaka-maru of Tokyo University of Fisheries. The investigation is a part of the project on "Influence of Miyake-shima Volcanic Activity on Fishing Environment" supported by Tokyo University of Fisheries. The observation was carried out on October 17–20, and November 17–19, 2000, three and four months after the eruption of Oyama. In the observations, high-turbidity waters with the beam attenuation coefficients 0.35–0.54 m^{-1} were observed in the pycnocline at the depth of 60–90 m on the east side of the island in October and on the northwest side of the island in November. The SS concentration of the high-turbidity water displayed extremely high values, 0.82 mg/l in October and 0.71 mg/l in November. The relationship between the turbidity (Y) and the SS concentration (X) was $Y=0.32X+0.14$, ($r^2=0.42$). The concentration of the suspended inorganic matter in the high-turbidity water also displayed extremely high values, 0.52 mg/l in October and 0.41 mg/l in November; these values correspond to 63.4% and 57.7%, respectively, expressed as the weight percent of inorganic matter in the total suspended solids. For the particles of the size of 8–14 μm, the particle volume concentration of the high-turbidity water (November, Stn. 3, depth of 75 m) was higher than that of the surface water at the same location. That is, the high-turbidity water layer is formed in the vicinity of the pycnocline and mainly contains a large amount of suspended inorganic particles. Therefore the origin of the high-turbidity water is considered to be deposited volcanic ashes from Miyake-shima.

Keywords : *Turbidity distribution, Miyake-shima Island, Volcanic ash, High-turbidity layer*

Introduction

An earthquake of the magnitude of 3 occurred in Miyake-shima Island on June 23, 2000. Mt. Oyama erupted on July 8 and 14, and the volcanic products (so-called volcanic ashes) were visibly observed. On August 18, volcanic smoke climbed higher than 5000 m, and an enormous quantity of volcanic ashes fell on Miyake-shima and its surrounding ocean area. Subsequent rainfalls washed away accumulated volcanic ashes from the coast to the surrounding ocean, causing discoloration of the ocean. The shallow water regions around Miyake-shima have bountiful marine resources such as spiny lobsters, abalones, agar weeds, etc. and fishery is one of the key industries. Because of these circumstances, there is a concern about the effects of sediments, which originate from volcanic ashes that have fallen into the ocean and ashes washed away from the island, on marine life of the surrounding ocean area.

In 1974 a comprehensive investigation of Nishinoshima-shinto Island, which was formed by the eruption of a submarine volcano, was carried out by Tokyo University of Fisheries. The report by MATSUIKE *et al.* (1975) is especially relevant to the present investigation. They investigated the turbidity of inner bay formed between Kyuto (old island) and Shinto

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(new island) of Nishinoshima and also the turbidity of the surrounding ocean area of the island. The results revealed that the water temperature of inner bay was 8℃ higher than that of the surrounding ocean water, and the amount of suspended matter was approximately 15 times larger. They also reported that a discolored ocean area, which was caused by the outflow of inner bay water to the surrounding ocean area, was observed within 0.5–0.6 nautical miles from the island.

NAKAO *et al.* (1978) investigated how the fallen ashes from the eruption of Usu Volcano affected the turbidity of Lake Toya. Their study involved an investigation of the sedimentation process of suspended matter. It was concluded that the suspended inorganic matter in the thermocline and in the middle water layer resulted from the following process: scouring of volcanic ash deposit by rain water, formation of muddy water and then turbidity current, intrusion of the turbidity current into the thermocline, and eventual settlement of ashes in the thermocline.

In the present investigation, we have studied detailed turbidity distributions in the surrounding ocean area of Miyake-shima after three months and also after four months from the time of Oyama eruption. The investigation is a part of the project by Tokyo University of Fisheries on "Influence of Miyake-shima Volcanic Activity on Fishing Environment".

Observation Methods

The observations were carried out aboard the RT/V Umitaka-maru of Tokyo University of Fisheries on October 17–20, and November 17–19, 2000. Eight observation stations (Stns. 1, 2, 3, 4, 5, 6, 7, and 8) were set up around Miyake-shima in October, and in November three additional observation stations (Stns. C1, C2, and C3) were set up to the east of the island (Fig. 1). In addition, four observation stations (Stns. K1, K2, K3, and K4) were set up every 10' in latitude between Miyake-shima and Izu-oshima as reference points. Measurements were performed for water temperature, salinity, fluorescence intensity, turbidity, water analysis, water color, and transparency. The water temperature, salinity, fluorescence intensity, and turbidity were measured with a CTD (OCTOPUS; ISHIMARU *et al.*, 1984) (Falmouth Scientific, Inc.). For the measurement of turbidity, an *in-situ* beam transmissometer with the path length 1 m and wavelength 527 nm was used. Water was sampled with 20 L volume Niskin bottles tied to the CTD; surface water was sampled with sampling buckets. The sampled water was used to determine the concentrations of suspended solid (SS) and suspended inorganic matter, and also to determine the particle size distribution. The concentration of SS was determined by filtering sample water through a Millipore HA filter (pore size, 0.45 μm), drying the filter cake at 60℃ for three days, and then weighing the residue. After determining the concentration of SS, we determined the concentration of suspended inorganic matter by heating the filter in a muffle furnace (550℃, one hour) and then weighing the residue. Particle size distribution was determined by freezing water samples on site, transporting them to the laboratory, thawing the samples, and then measuring the samples with a Coulter Counter Multisizer II (Beckman-Coulter Electronics, LTD.) in the range of 1.8 – 60 μm. The water color was determined by the Forel-Ule color scale and the transparency was determined with a Secchi disc (diameter, 30 cm).

Results and Discussion

Distribution of water temperature, salinity, and turbidity

Fig. 2 shows vertical profiles of water temperature and salinity for October and November. Water temperature and salinity of the surface layer for October (Fig. 2, top) are 23.3–24.4 ℃ and 34.0–34.1 psu, respectively. Both the water temperature and salinity do not change down to the depth of 50 m indicating a mixed layer. A thermocline is observed from the depth of 50 m to approximately 70 m. The temperature decreases gradually below the thermocline, reaching 15 ℃ at the depth of 150 m. On the other hand, the salinity increases gradually and reaches 34.5 psu at the depth of 60 m, and there is almost no change below that depth. The water temperatures and salinities for November (Fig. 2, bottom) have similar

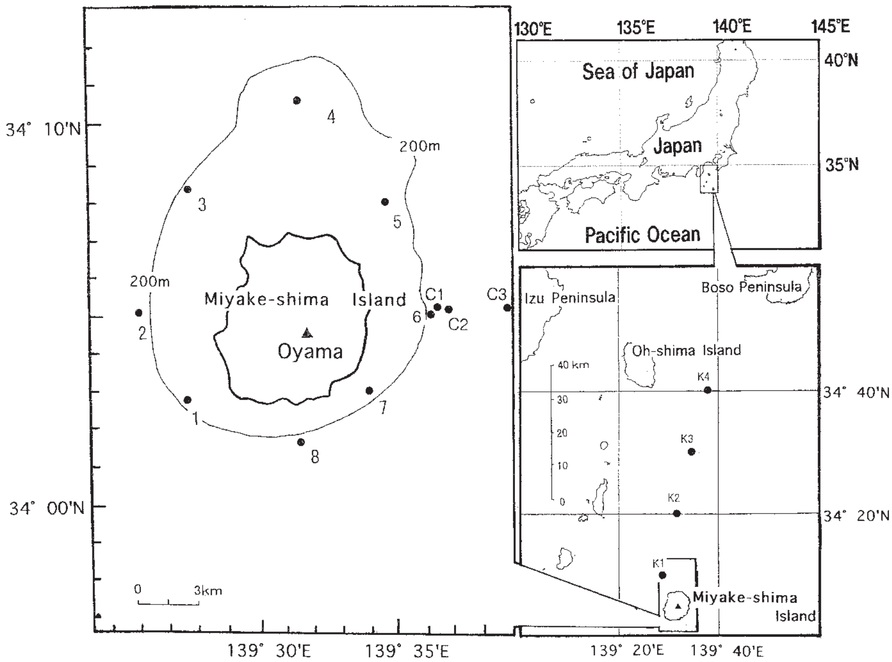

Fig. 1 Observation areas and the distribution of observation stations.

distribution patterns to those for October. The mixed layer, however, stretches by 10 m more to 60 m. Also the differences in water temperatures and salinities among different locations are greater than those for October. However, the water temperatures and salinities at eight observation stations around the island have nearly the same vertical profiles within each observation month.

The turbidity distribution around the island is discussed next. Discolored water area was not visibly detected in the surrounding ocean area of Miyake-shima in both October and November. Table 1 lists the transparency and the water color in the surrounding ocean area of the island; some data are missing because of nightfall. The transparencies and the water color for October are 19–31 m and 2–3, respectively, and those for November are 17–20 m and 2–3, respectively. In both the October and November observations, the transparency appears high from the west side to the north side of the island and it appears low on the other sides. The water color, however, has no dependence on the sea region.

Fig. 3 shows the vertical profiles of turbidity represented by beam attenuation coefficient for October and November. November data at Stn. 6 were obtained at 21:33. In October, rather large beam attenuation coefficients (0.45–0.60 m^{-1}) are observed near the surface at most stations. However, the beam attenuation coefficient drops steeply toward the depth of approximately 3 m. From that point down to the depth of 50 m, the beam attenuation coefficient gradually decreases but stays in the range of 0.2–0.3 m^{-1}. The beam attenuation coefficient reaches 0.16 m^{-1} around the depth of 100 m and stays close to a constant value below that depth at all stations. However, at Stn.6, which is located to the east of Miyake-shima, a high-turbidity layer at the depth of 60–90 m is observed with the beam attenuation coefficient of 0.35 m^{-1}.

The turbidity profiles for November show similar tendencies in October near the surface, however, from 3 m to the depth of 50 m, the beam attenuation coefficient stays almost constant in the range of 0.2–0.3 m^{-1}. The beam attenuation coefficient reaches 0.16 m^{-1} around the depth of 100 m and stays close to a constant value below that depth. One exception is seen at

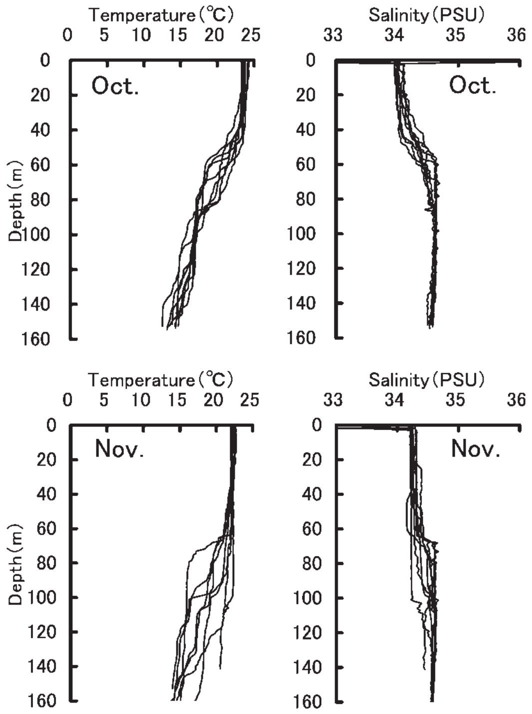

Fig. 2 Vertical profiles of water temperature and salinity for October and November.

Table 1. Transparency and water color for the ocean area around Miyake-shima for October and November.

Sta.		1	2	3	4	5	6	7	8
Oct.	Transparency	31	24	23	19	19	–	–	–
	Water color	3	2	2	2	–	–	–	–
Nov.	Transparency	–	–	–	20	–	17	18	19
	Water color	–	–	–	3	–	3	2	2

Stn. 3, which is located to the northwest of Miyake-shima. A high-turbidity layer at the depth of 60–90 m is observed with the beam attenuation coefficient of 0.54 m^{-1}. The depth of this high-turbidity layer is close to that of Stn. 6 for October.

Fig. 4 shows the vertical turbidity profiles observed in November around Stn. 6. Although a high-turbidity layer at the depth of 60–100 m of Stn. 6 is observed at 19:34, this layer is not observed two hours later at 21:33 (Fig. 4, top). In order to track this high-turbidity layer, turbidity profiles are studied at Stns. C1, C2, and C3 (Fig. 4, bottom). The beam attenuation coefficients at these three stations are around 0.2 m^{-1} from the surface to the depth of 150 m, and a high-turbidity layer is not observed. Therefore, it is considered that the distribution of high-turbidity water is localized.

Next, the vertical distributions of SS concentration are shown in Fig. 5. The SS concentration around Miyake-shima for October was in the range of 0.24–0.6 mg/l in the surface layer, and 0.23–0.38 mg/l at the depth of 50 m. The SS concentration at the depth of 75 m of Stn. 6 was very high (0.82 mg/l). For November the SS concentration in the surface layer was 0.22–0.49 mg/l, and 0.11–0.32 mg/l at the depth of 50 m. The SS concentration at the depth of 75 m of Stn. 3 was also high (0.71 mg/l). Thus, the distribution of the SS concentration corresponds well with that of the turbidity. Fig. 6 shows a relationship between the turbidity (beam attenuation coefficient) and the SS concentration. Their relationship is linear as shown. $Y=0.32X+0.14$, ($r^2=0.43$),

Where, Y is the turbidity (beam attenuation coefficient, m^{-1}), and X is the SS concentration (mg/l). A good correlation between the turbidity and the SS can be seen.

The turbidity of the surrounding ocean area of Miyake-shima was also studied with respect to the number of suspended particles. Fig. 7 shows the particle size distributions of November for the surface water of the surrounding ocean area of Miyake-shima (8 stations, solid lines) and of the sea area between Miyake-shima and Oshima (4 stations, broken lines). The particle size distributions for these two areas are different. That is, the particle size for the surface water around Miyake-shima spreads over a wide range (2–30 μm). The particle concentration especially for the sizes less than 5 μm is much higher for the surrounding area of Miyake-shima than that between Miyake-shima and Oshima. In addition, the concentration of particles number was ten times higher for the former than the latter.

Matsuike and Morinaga (1977) and also Matsuike *et al.* (1986) investigated the turbidity in the northwest Pacific Ocean. The beam attenuation coefficients for the high-current area of the Kuroshio are reported to be 0.11–0.12 m^{-1} (wavelength, 486 nm), and the beam attenuation coefficients for the Sagami

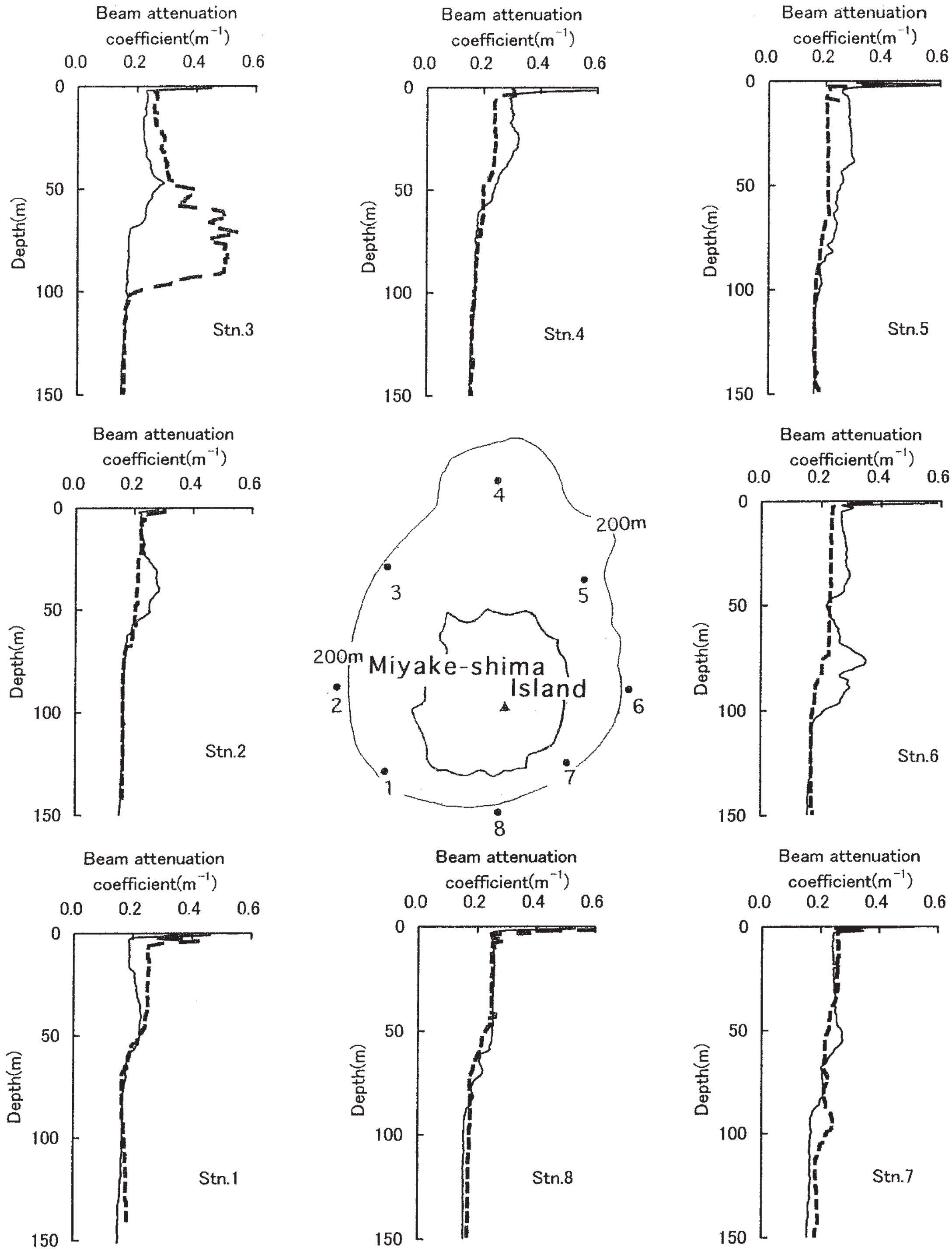

Fig. 3 Vertical profiles of turbidity for October (solid line) and November (broken line).

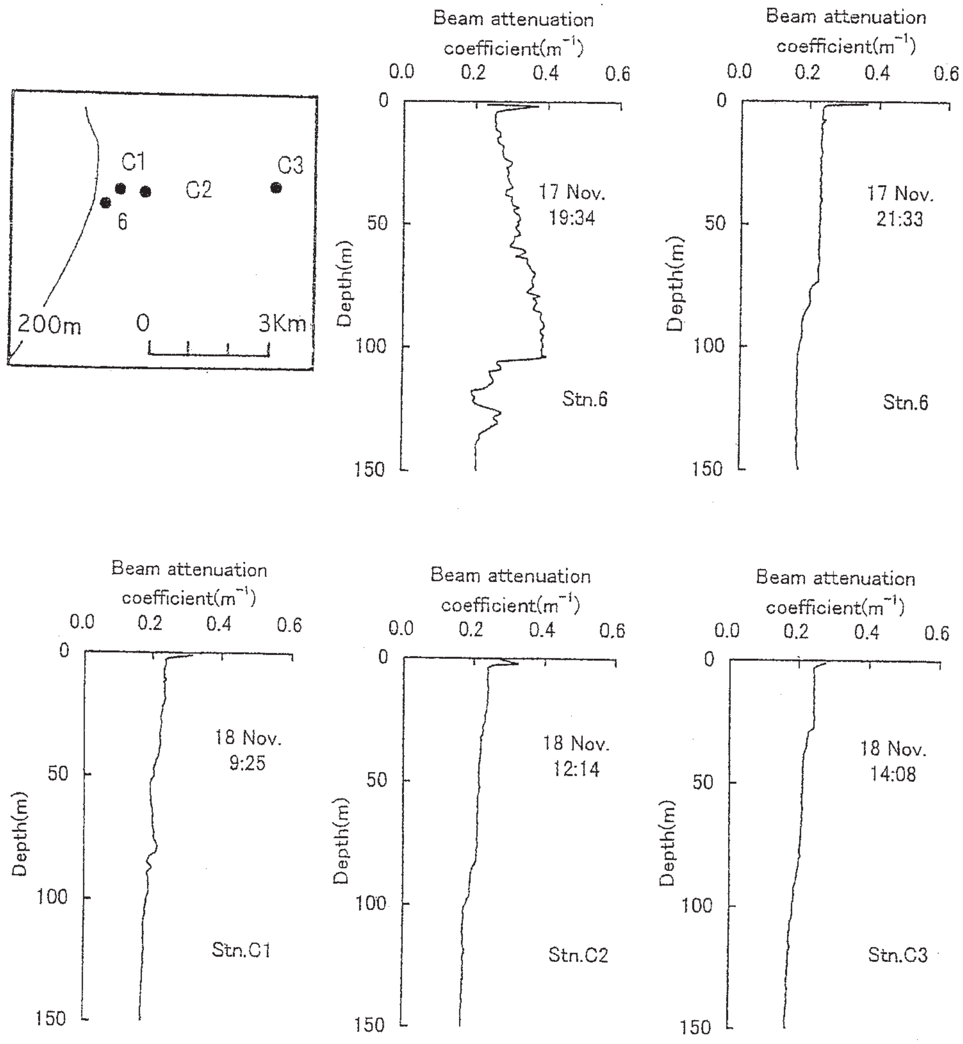

Fig. 4 Vertical turbidity profiles observed in November around Stn. 6.

Nada and its surrounding ocean area are reported to be 0.1–0.4 m^{-1} (wavelength, 486 nm). During the present investigation, the Kuroshio was flowing eastward at the distance of approximately 150 km south to Miyake-shima (Quick Bulletin of Ocean Conditions, 2000, Vol. 20 and 22, Hydrographic Department, Japan Maritime Safety Agency). Therefore, it is not considered that the Kuroshio affects the turbidity of the surrounding ocean area of Miyake-shima in the present observation. The measurement wavelength of the present investigation is different from the wavelength used in the investigation by the above-mentioned authors. However, the beam attenuation coefficients around Miyake-shima were in the range of 0.15–0.30m^{-1} (wavelength, 527 nm) except for the surface layer and the high-turbidity layer. Thus, the turbidity around Miyake-shima is considered to be similar to that of Sagami Nada. As mentioned above, the beam attenuation coefficients were 0.4–0.6 m^{-1} for some surface layers around Miyake-shima. These beam attenuation coefficients are somewhat higher than those of the Kuroshio and the Sagami Nada, and this phenomenon is considered to be the effects from the island. This phenomenon is also consistent with the

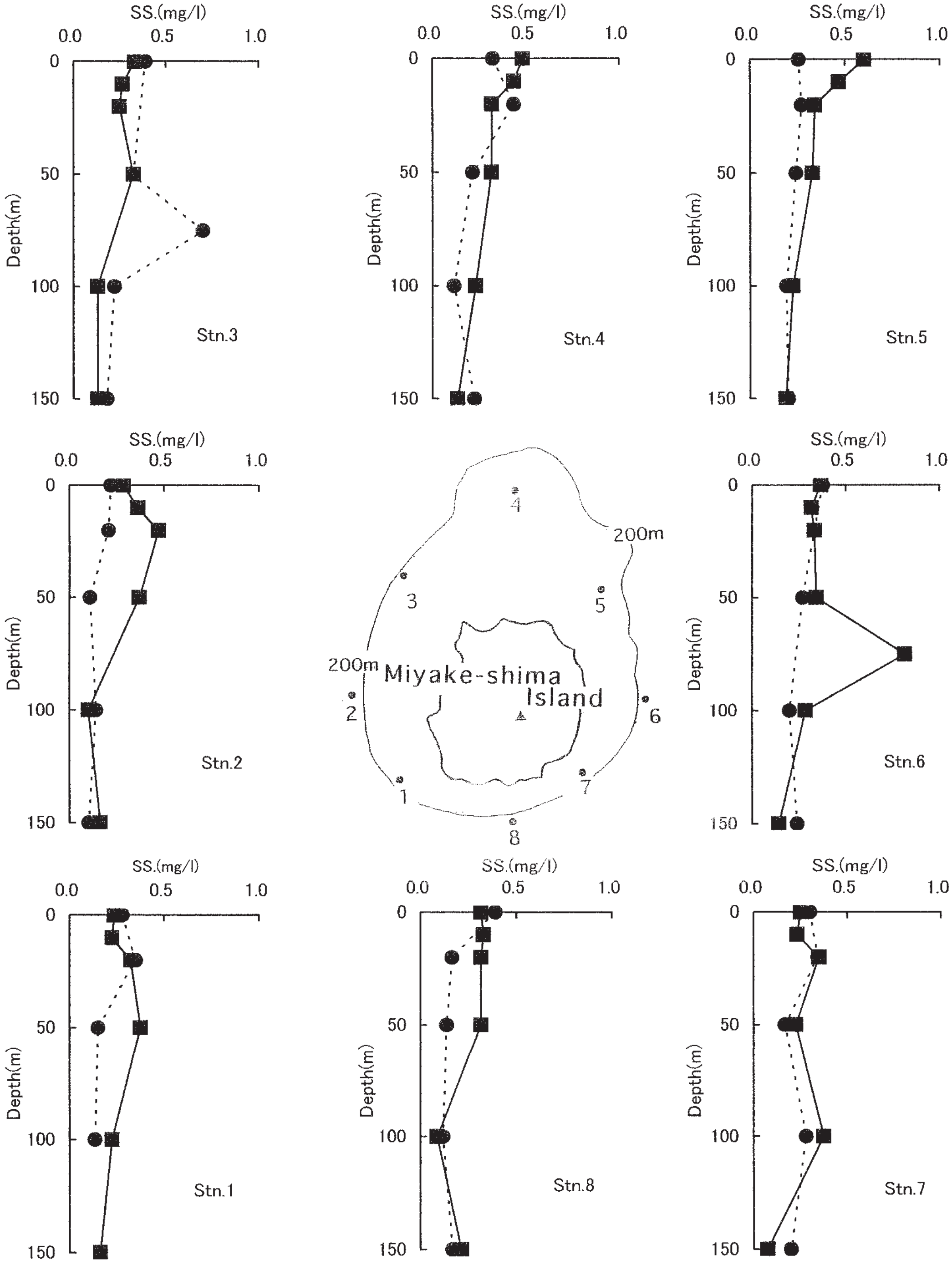

Fig. 5 Distribution of SS concentration. Solid line and dotted line indicate data for October and November, respectively.

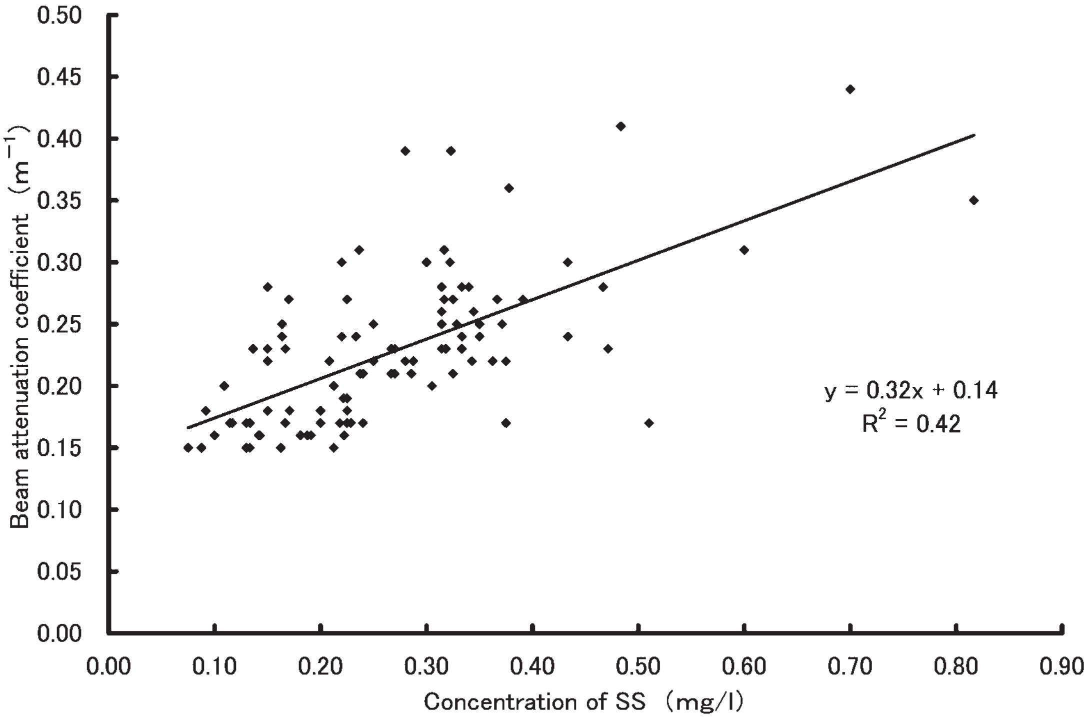

Fig. 6 Relationship between turbidity (Beam Attenuation Coefficient) and SS concentration.

observation that the concentration of the suspended particles less than 5 μm is approximately 10 times higher in the surface layer around Miyake-shima than in the surface layer of the sea area between Miyake-shima and Oshima (Fig. 7).

Characteristics of high-turbidity water

As described in the previous section, high-turbidity water layers were observed at Stn. 6 in October and at Stn. 3 in November at the depth of 60–90 m. The SS concentrations of this high-turbidity water were shown to be relatively high (0.71–0.82 mg/l). In this section we discuss the characteristics of the high-turbidity water in detail.

Fig. 8 shows the concentration distributions of suspended inorganic particles for October and November. The concentrations of suspended inorganic particles for October are 0.06–0.18 mg/l for the surface water, and 0.02–0.16 mg/l for the water at the depth of 50 m. And those for November are 0.04–0.27 mg/l for the surface water, and 0.04–0.25 mg/l for the water at the depth of 50 m. On the other hand, the high-turbidity layer observed at the depth of 75 m displayed a maximum concentration of 0.52 mg/l at Stn. 6 in October and 0.41 mg/l at Stn. 3 in November, respectively. The weight percentage of inorganic particles in the total suspended particles is calculated for October, becomes 21–31% for the surface water, but is very high (63.4%) for the high-turbidity layer water. For November, the percentage is 15–36% for the surface water at Stns. 1, 2, and 5, showing similar results to those of October, but is higher (55–70%) at other observation stations. The high-turbidity layer water at Stn. 3 for November has a high result (57.7%) like the case at Stn. 6 for October.

Next, the distributions of particle size are compared between the surface water and the high-turbidity layer water at the depth of 75 m. Fig. 9 shows the distribution of particle size for the surface water and the high-turbidity layer water at Stn. 3 for November. The particle volume concentrations for high-turbidity water are similar to that of the surface water

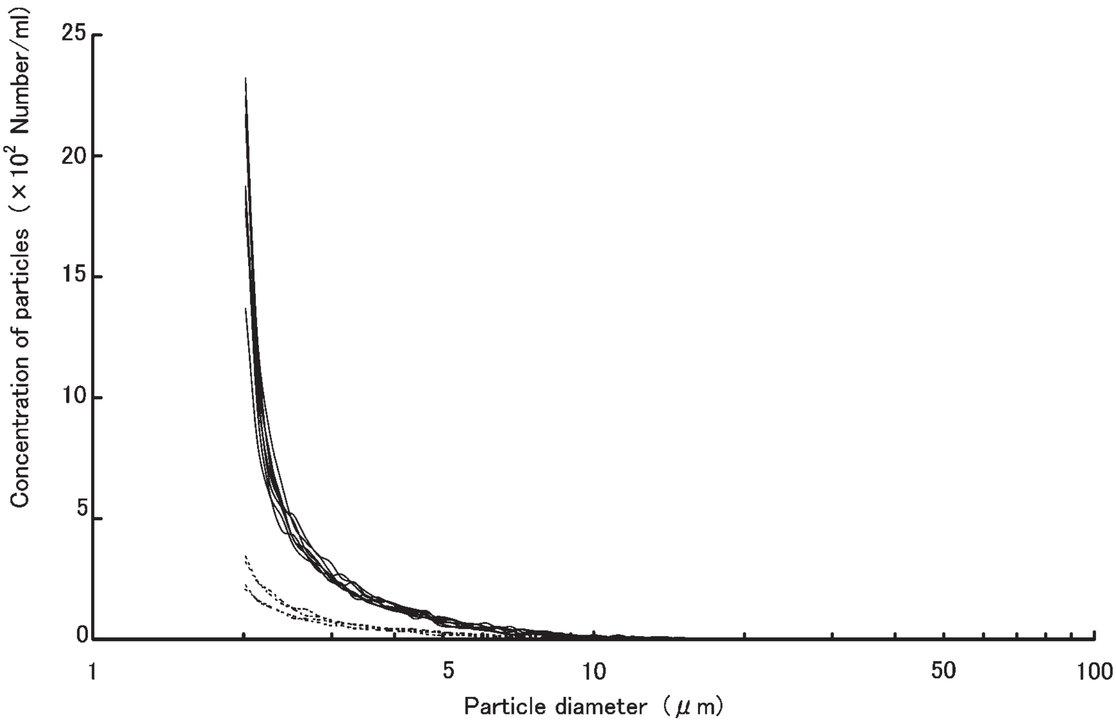

Fig. 7 Size distributions of particle number in the surface water for the surrounding ocean area of Miyake-shima (solid line) and for the sea area between Miyake-shima and Oshima (broken line) for November.

up to the particle size of 8 μm. However, the particle volume concentrations for high-turbidity water are higher for the particles with the size 8–14 μm than for the surface water. On the other hand, the surface water contains relatively larger particles (larger than 20 μm) than the high-turbidity water. Also the average particle size in the surface water (11.1 μm) is approximately equal to that of the high-turbidity water (9.7 μm).

The particles suspended in the high-turbidity water mainly consist of inorganic matter, and have the particle-size of 8–14 μm in diameter. Here, we calculate the sedimentation velocity (v) of the particles of the size 10 μm (D) by the following Stokes' equation;

$$v = \frac{1}{18} D^2 g \frac{\rho_s - \rho}{\mu}$$

where, g is gravitational acceleration, ρ_s is the density of particle, 2.5, ρ is the density of seawater, 1.023 g・cm^{-3}, and μ is the viscosity coefficient of seawater, 1.0×10^{-2} dyn・sec・cm^{-2}, respectively.

The sedimentation velocity in the mixed layer is estimated to be 8.04×10^{-3}cm/sec. Thus, it is found that the particles of the size 10 μm in the surface seawater takes about 8.6 days to reach the high-turbidity layer at the depth of 60 m.

Origin of high-turbidity water

In this section we discuss the relationship between the formation of the high-turbidity layer and the ocean constitution. Fig. 10 shows the vertical profiles of turbidity, water temperature, salinity, density (sig.-t), and fluorescence intensity at Stn. 6 for October and Stn. 3 for November; these are the time and locations when the formation of high-turbidity layers was observed. In case of Stn. 6 in October, the turbidity increases from the depth of 50 m, show a maximum at the depth of 75 m, and decreases below that. Seawater at the depth of 110 m is very clear. Also, the pycnocline with a gentle slope is seen from the depth of 50 m to 100 m. On the other hand, at Stn. 3 in

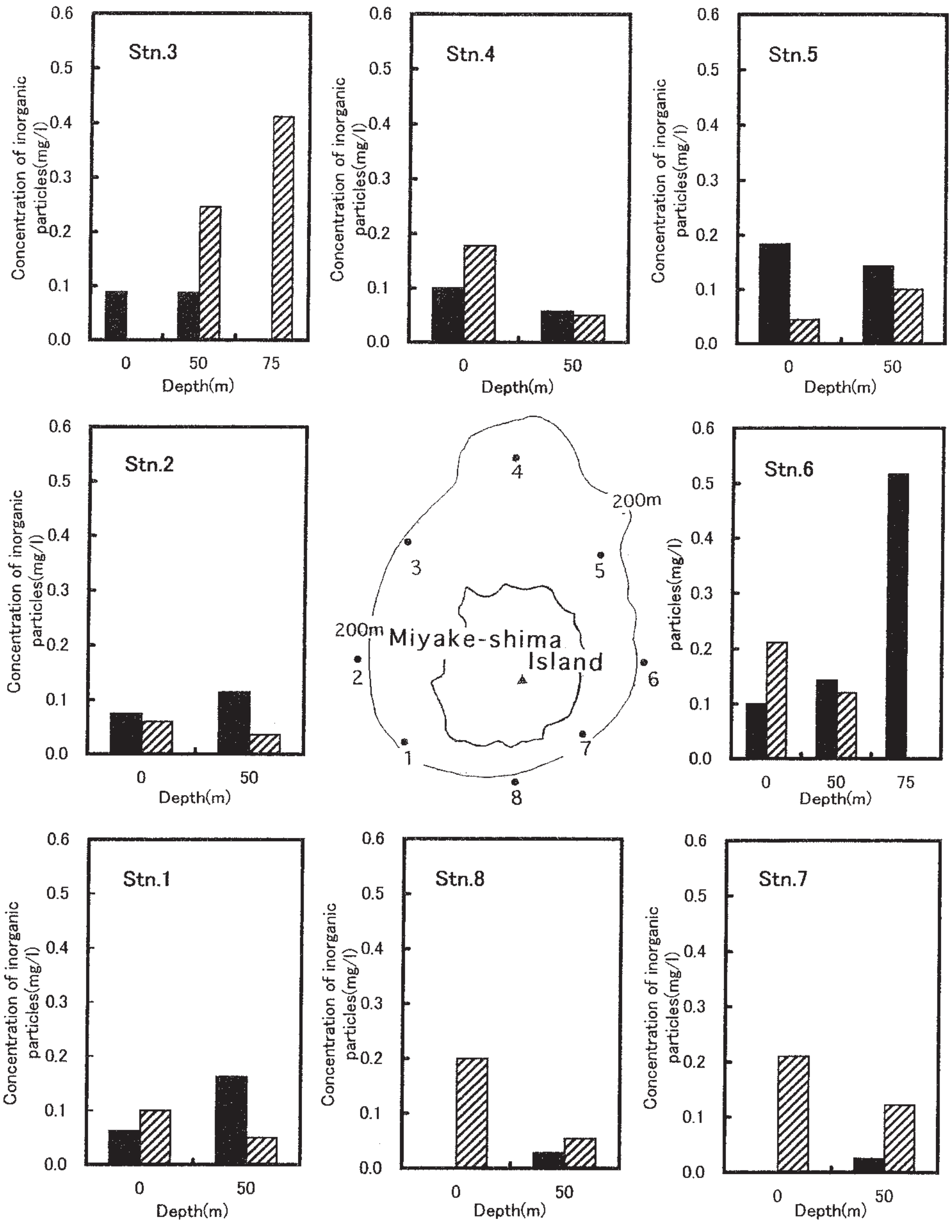

Fig. 8 Concentrations of suspended inorganic particles. Solid bars and striped bars indicate data for October and November, respectively.

The results are shown for the surface water and for the water at the depth of 50 m. The data are also included for the high-turbidity layer water at the depth of 75 m observed at Stn. 6 in October and at Stn. 3 in November. Observation data are missing for the surface water at Stns. 7 and 8 for October and at Stn. 3 for November.

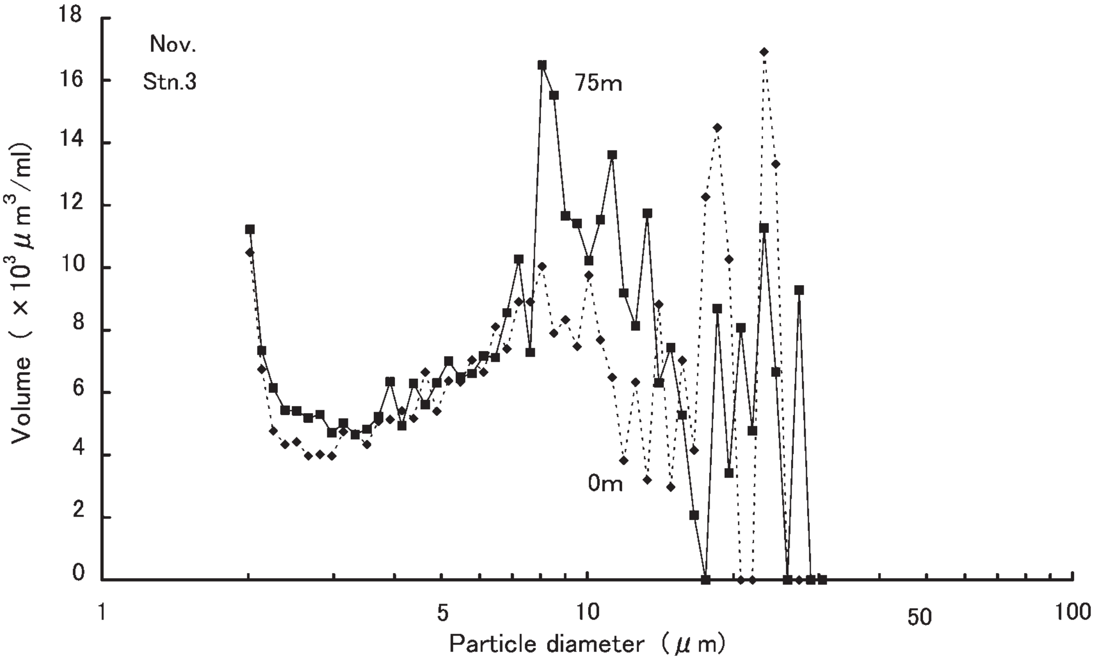

Fig. 9 Size distributions of particle volume at the depth of 0 m (broken line) and 75 m (solid line) at Stn. 3 for November.

November, the turbidity increases from the depth of 50 m, exist some maximum value between the depth of 60 m and 90 m, and decreases extremely deeper than the high-turbidity layer. The steep gradient pycnocline appears from the depth of 60 m to 100 m. For both October and November, the depth of the high-turbidity layer is found at the same depth where sudden changes take place in water temperature, salinity, and density.

JERLOV (1958) explained that suspended particles tend to settle, concentrate, and stay in the pycnocline because of a decrease in the sedimentation rate. NAKAO *et al.* (1978) reported that the concentration of the suspended matter, which is from the volcanic eruption, in Lake Toya displayed a maximum in the thermocline. It was explained that the muddy water, which contains volcanic ash deposits from the surrounding area, forms turbidity current, enters into the thermocline, and settles there at every rainfall. MIYAKE (1982) and MORINAGA (1983) observed similar phenomena in Funka Bay and the Antarctic Ocean, respectively. However, it is supposedly complicated to explain the phenomenon by the above mechanism if suspended particles are organisms (YAMAGUCHI and SHIBATA, 1981).

As shown in Fig. 10, the vertical profiles of turbidity and fluorescence intensity display different patterns at the depth of 60–90 m for both Stn. 6 and 3. The trend is especially noticeable at Stn. 6. As a result, the particles distributed at these locations could not consist of phytoplankton. In addition, the content of suspended inorganic particles in the suspended particles was 63.4% at Stn. 6 and 57.7% at Stn. 3 as described before. They are much higher than the values of approximately 20% in the water mass of open ocean (for example MATSUIKE *et al.*1983). Thus, it is confirmed that the content of inorganic particles is very high in the high-turbidity layer.

It is unlikely that inorganic suspended particles were carried to these locations from other places by ocean current because the Kuroshio was flowing eastward at the distance of 150 km south to Miyake-shima at the time of observation. Accordingly, the origin of inorganic suspended particles is considered to be from volcanic ashes due to the volcanic activity or from deposited ashes that were washed out together with clay and sand by rainfall. MATSUYAMA *et al.* (2002) presumed that the origin of particles in the high-turbidity layer is from fallen ashes because the high-turbidity water is distributed on the leeward side. For instance, the wind direction at Stn. 6 in October was from the northwest and at Stn. 3 in November was from the southeast. However, there was no eruption of the volcano on October and November, 2000. Also, the volcanic ashes did not almost fall.

MORIKAWA (1996) studied the intrusion process of muddy water at Lake Biwa and determined the size of particles in the high-turbidity water, which is formed in the pycnocline, to be 5–10 μm. In the present investigation, the observed particle size range of most populated particles in the high-turbidity water was 8–14 μm. This range of particle size agrees well with that of the high-turbidity water of Lake Biwa. This fact implies a possibility that the high-turbidity layer observed offshore Miyake-shima is formed by the intrusion of turbid water to the pycnocline.

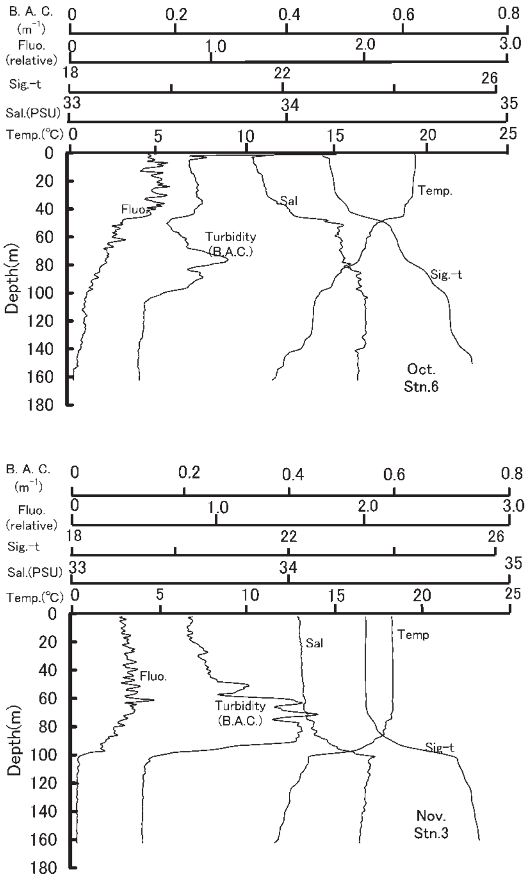

Fig. 10 Vertical profiles of water temperature, salinity, density (sig.-t), turbidity (Beam Attenuation Coefficient; B.A.C.), and fluorescence intensity at Stn. 6 (October) and at Stn.3 (November).

Based on the above discussion and the two reasons described below, we presumed that the suspended particles in the high-turbidity layer are deposited ashes that were washed out from the island together with clay and sand by rainfall. The first reason is that the high-turbidity water is localized to a horizontal direction, and the second is that there were rainfalls one week before of each observation (October 9–16, 49 mm; November 10–17, 84 mm).

In future we should investigate the process of outflow and the behavior of high-turbidity water by performing a space-time study for the shallow water area around Miyake-shima.

Summary

The turbidity distribution around Miyake-shima at three and four months after the eruption of Oyama was investigated.

1) The high-turbidity waters with the beam attenuation coefficients 0.35–0.54 m^{-1} were observed in the pycnocline at the depth of 60–90 m on the east side of the island in October and on the northwest side of the island in November.

2) The SS concentration of the high-turbidity water displayed extremely high values, 0.82 mg/l in October and 0.71 mg/l in November. The relationship between the turbidity and the SS concentration shows a good correlation.

3) The concentration of the suspended inorganic matter in the high-turbidity water also showed extremely high values, 0.52 mg/l in October and 0.41 mg/l in November. The weight percents of inorganic matter in the total suspended solids correspond to 63.4% and 57.7%, respectively.

4) For the particles with the size 8–14 μm, the particle volume concentration for the high-turbidity water was higher than that for the surface water at Stn. 3 in November.

That is, the high-turbidity water layer is formed in the vicinity of the pycnocline and mainly contains a large amount of suspended inorganic particles. Therefore the origin of the high-turbidity water is considered to be deposited volcanic ashes from Miyake-shima.

Acknowledgement

The present investigation is a part of the research project in Tokyo University of Fisheries, "Influence of the Miyake-shima Volcanic Activity on Fishing Environment". The authors express their sincere appreciation to the project leader, Professor Masaji MATSUYAMA, the investigators, and also the captain of RT/V Umitaka-maru, Professor Yasusuke TAKASU and his crew members of Tokyo University of Fisheries for their cooperation during the present investigation.

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