Seafloor Hydrothermal Deposits Exploration by Bathymetry and Backscattering Data Using Multibeam Echo-Sounder in the Higashi-Aogashima Caldera

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Abstract:
We develop an effective method for exploring seafloor hydrothermal deposits using acoustic apparatus. The important thing for seafloor hydrothermal deposits exploration is to carry out the efficiently detailed exploration after narrowing down a promising area from a vast area by wide-area exploration. Here, we aim to establish such a method, by examining methods for obtaining detailed bathymetric data and normalization of backscattering strength. Compared to conventional methods, data density is increased in both the transverse and traveling directions by narrowing the swath width and dropping the vessel speed. Also, normalization of submarine acoustic image is proceeded by applying the least square method from actual measurement focusing on the backscattering strength varying logarithmically with respect to the incident angle. Utilizing these techniques, we carried out a wide-area hydrothermal deposits exploration in the Higashi-Aogashima caldera. Accuracy of acquired wide-area bathymetry data had a difference of less than 0.1% against the area depth (about 700 m). In addition, normalized seafloor acoustic images were able to grasp the features of the sediment in the caldera. By narrowing the hydrothermal deposits candidate point, hydrothermal deposits were discovered from subsequent detailed exploration using an autonomous underwater vehicle and gravity corer. We are confident that these techniques will increase the efficiency of wide-area exploration of hydrothermal deposits.

Classification: Physical acoustics · Seabed acoustics
Keywords: Higashi-Aogashima caldera, hydrothermal deposits exploration, multibeam echo-sounder (MBES), seafloor acoustic image

1. Introduction
Many seafloor hydrothermal deposits have been discovered in the mid-Okinawa Trough and Izu-Ogasawara arc regions around Japan. These include the Izena hole,1) Myojin knoll caldera,2) and Bayonnaise knoll caldera.3) The seafloor hydrother-
Mal deposits contain useful metals such as gold, silver, copper, zinc and other rare metals. For this reason, they are attracting attention as a source of domestic natural resources for the next generation in Japan. Moreover, various studies have been conducted around the world towards commercialization and development of hydrothermal deposits. Although researchers have advanced the study of exploration methods for such deposits, a standard method has not yet been completely established. The important thing for seafloor hydrothermal deposits exploration is to carry out the efficiently detailed exploration after narrowing down a promising area from a vast area by wide-area exploration.

Recently, water column information analyzed by multibeam echosounder (MBES) has attracted attention as a wide-area method of exploration of seafloor hydrothermal deposits from an equipped with research vessel on sea surface. Plume detection in the water column is considered to react to the liquid droplets of carbon dioxide. While this method is a valid approach in the mid-Okinawa Trough, it is not applicable to the seafloor hydrothermal deposits area of the Izu-Ogasawara arc. Therefore, a method that does not rely on carbon dioxide detection is needed there for wide-area exploration of hydrothermal deposits.

In previous wide-area bathymetric surveys, it was common to create bathymetric maps of 50-m grids without much consideration of the characteristics of MBES. For the reason, this method is not efficient approach to narrow down detailed an exploration area from the wide-area exploration. Therefore, by narrowing the swath width in consideration of the acoustic properties of the MBES and obtaining detailed bathymetric data, we propose a method of efficient exploration from the wide area for hydrothermal deposits.

In addition, backscattering strength is measured at the same time as the bathymetry data using the MBES. An acoustic image of the seafloor is constructed by analyzing backscattering strength. Backscattering strength is known to vary depending on the angle of incidence and the sediment of the seafloor. Because the seafloor acoustic image reflects characteristics of the sediment, it can be classified by normalizing the dependence of the incident angle. While many researchers have already reported the normalizing dependence of incident angle and bottom sediment classification using side-scan acoustic images, a normalizing method for backscattering strength obtained from MBES has not yet been established.

We had two purposes in this paper. (a) To propose an efficient exploration method for hydrothermal deposits using detailed bathymetric data obtained from shipboard MBES carried out in the Higashi-Aogashima caldera. (b) To propose backscatter correction with respect to the incident angle using the least squares method. With actual measurement values from the MBES, we also considered the analysis method that reduces the variation of backscattering strength.

2. Study area and method
2.1 Higashi-Aogashima caldera

In this study, we chose the Higashi-Aogashima caldera as the exploration area. The submarine caldera is located about 360 km south from Tokyo, and about 12 km east from Aogashima-Island. The depth of the caldera floor is about 600–800 m, and the diameter is about 4.0×7.3 km. Heavy mineral samples were confirmed from seafloor sediments in this caldera in the past. However, detailed exploration to identify the hydrothermal activity area was not performed. Therefore, we conducted three research cruises to identify the hydrothermal deposits area, and carried out the
following exploration: (a) a wide-area bathymetric survey using a research vessel equipped with an MBES on the sea surface; (b) a bottom sediment sampling using a gravity corer (GC); and (c) a detailed bathymetric survey using an autonomous underwater vehicle (AUV) equipped with the MBES and approaching the seafloor.

2.2 Method of wide-area bathymetry

A shipboard MBES used for wide-area bathymetric survey is equipped on the bottom of the research vessel. The resolution of a conventional MBES depends on the width of the footprint, because resolution deteriorates as water depth increase. In recent years, however, newly developed hybrid models have been designed that can detect the sounding point by phase difference and reflection intensity. By narrowing the swath width, the new models can detect the phase difference from overlapping footprints, determine the incident angle (angle of arrival), and calculate a sounding point from the arrival time. Utilizing this feature, it is possible to acquire high-resolution data and further equidistant data in the transverse direction. For example, Table 1 shows the specifications of the MBES and the settings in the YK15-09 cruise. Conventionally, because data acquisition width uses the full width of the swath, the density of the transverse direction of the data is low. However, with this setting, the data density increases by narrowing the swath width and setting the survey line spacing to less than half of the data acquisition width. It was possible to acquire one sounding per ca. 2.6 m to the transverse direction with one swath (1,100 [m]/432 [soundings/swath]=2.55 [m/sounding]).

In addition to measuring while cruising at an average speed of 10 knots, it also possible to increase the density of data to the traveling direction by dropping the vessel speed. Here, assuming that the depth (slant range) is 750 m and the sound velocity is 1,500 m/s, the transmission interval is 1 Hz. In this case, surveying at 10 knots, the MBES sounds one swath per 5.1 m to the traveling direction. By contrast, surveying at 4 knots with the settings shown in Table 1, the MBES sounds one swath per 2.1 m to the traveling direction. Sounding 2 swaths per ping doubles the density of bathymetric data.

This setting in the 5-m grid is able to acquire about 2 soundings to the transverse direction and about 4 swaths to the traveling direction. In addition, because a survey line interval is less than half of bathymetric coverage, it is surveyed more than twice for each grid. In this way, it enhances the reliability of the data by increasing the sounding points.

2.3 Method of backscattering angle correction

The model of incident angle and bottom sediment regarding backscatter has already been defined. In particular, it is known that when the bottom sediment contains fine particles and has high density like silt or clay, it shows a strong reflection just under the sonar. On the other hand, the reflection weakens as the incident angle increases. The
backscattering strength $S_b(\theta)$ is represented by the following logarithmic function as a variable of incident angle $\theta$:

$$S_b(\theta)=10 \log_{10}\{\sigma_r(\theta)+\sigma_v(\theta)\}^{13}.$$ (1)

where

$\sigma_r(\theta)$ is dimensionless backscattering cross-section per unit solid angle per unit area due to interface roughness

and

$\sigma_v(\theta)$ is dimensionless backscattering cross-section per unit solid angle per unit area due to volume scattering from below the interface.

The scattering cross-sections are functions of the six parameters given in Table 2. However, particle size and distribution of the sediment are complex in the actual seafloor, and sampling the ground truth related to volume scattering is extremely difficult. Assuming that the seafloor surface is flat, we normalized the angle dependence by obtaining a correction curve according to a logarithmic function from the backscattering strength and reception angle recorded by the MBES. We focused on backscattering strength, varied logarithmically with respect to incident angle, and defined the coefficients $a$, and $b$ assuming for convenience in formula (1) from the logarithmic curve $S(\theta)$ shown below using the least squares method:

$$S(\theta)=a \log_{10} \theta - b.$$ (2)

It is calculated by the least square method extracting a value of each 25 ping back and forth for a ping of calculation object. The average between the actual measured backscattering strength and the symmetrical curve to the value of $S(\theta)$ at the reference angle (set to 20 degrees) was calculated as a normalized value.

3. Result

3.1 Process until discovery of seafloor hydrothermal deposits

3.1.1 Preliminary exploration and wide-area bathymetry

The bathymetric survey was carried out using the research vessel with MBES. Bottom sediment sampling was also carried out by the GC at the central part of the caldera as a preliminary exploration (KKKyot13-01 cruise). In order to identify the sampling position, the global acoustic positioning system (GAPS) was fixed on the 10 m of the GC. The GAPS (iXBlue Inc., 0.2% accuracy of slant range) is a USBL system that integrates GNSS and an inertial navigation system. Figure 1 shows a regional map around the caldera and a bathymetric map with the sampling point obtained in this survey. Heavy mineral analysis on the acquired sediment was carried out, and a few sulfide minerals of hydrothermal origin were discovered in the sediment. Therefore, the possibility of hydrothermal activity was indicated inside the caldera, and a wide-area bathymetric survey for all areas of this caldera was carried out at the next exploration (YK15-09 cruise). High-quality data was sur-

| Symbol | Definition |
|--------|------------|
| $\rho$ | Ratio of sediment mass density to water mass density |
| $\nu$ | Ratio of sediment sound speed to water sound speed |
| $\delta$ | Ratio of imaginary wavenumber to real wavenumber for the sediment |
| $\sigma_2$ | Ratio of sediment volume scattering cross-section to sediment attenuation coefficient |
| $\gamma$ | Exponent of bottom relief spectrum |
| $\omega_2$ | Strength of bottom relief spectrum (cm$^4$) at wavenumber $2\pi/\lambda = 1$ cm$^{-1}$ |
veyed by carrying out high-density measurement, as shown in Table 1. Figure 2 shows the entire seafloor topography in the Higashi-Aogashima caldera. The detail seafloor topography of the entire area in the Higashi-Aogashima caldera was shown first time in this cruise.

3.1.2 Detailed bathymetric survey by the AUV

The topographical conditions of the hydrothermal deposits discovered in the past were unique terrain, such as the slope of the caldera wall, the mound, and ridge-like terrain features. From the acquired wide-area bathymetry data, we planned survey lines on the detailed map to target such terrain with the AUV in the YK15-09 cruise. The detailed survey was conducted using the SeaBat7125 (Teledyne Reson Inc.; frequency, 400kHz; sounding, 512 soundings/swath) with the AUV approaching the seafloor. Figure 3 shows a bathymetric bird’s-eye view generated from the acquired data.

The chimney-like terrain shown in Figure 3(a) was located on the southeast slope of the central cone in Figure 2(a). The mound had a height of about 20 m and a width of about 40 m; moreover, there was a chimney-like terrain of 20–30 m height above the mound. The cone-shaped unique terrain shown in Figures 3(b) and (c) was found on the southeast slopes of the caldera wall in Figure 2(b) and the northeast side of the floor in Figure 2(c).
3.1.3 Confirmation of hydrothermal deposits by sampling

Since the chimney-like terrain indicating hydrothermal activity were found, the bottom sediment sampling was performed by the GC at the southeast side slopes of the central cone and the southeast side slopes of caldera wall in the KKKyot15-02 cruise. The GAPS was fixed on the GC as in the preliminary exploration. As a result, massive sulfides including chalcopyrite, galena and sphalerite were collected. These minerals are known to be generated by hydrothermal activity of more than 150–350°C.\(^{15}\) This fact explained the existence of hydrothermal deposits.

3.2 Seafloor acoustic image analysis

Figure 4 compares the seafloor acoustic image by raw backscattering strength and processed backscattering strength in the Higashi-Aogashima caldera. Backscattering strength was processed in the following order: (1) electric noise reduction using a graphic user interface (electric noise detection was carried out using MBES post-processing dedicated software [HIPS and SHIP ver8.1, CARIS, Canada]). To display the cross-section of one swath for each sounding point, data inconsistent with
the adjacent data were erased; (2) backscattering angle correction (This result describes in detail in Chapter 4.2.) and (3) filtering by the standard deviation (SD; standard deviation was calculated from the corresponding backscattering strength of all the sounding points in the 5-m grid; values greater than $2\sigma$ were eliminated). By overlaying the bathymetric slope map, a seafloor acoustic image was rendered so that the relief of the terrain could be visually represented.

The trend of bottom sediment in the Higashi-Aogashima caldera showed that a weak-intensity area, likely silt or clay, is widespread on the southern and northwestern caldera floor. In addition, a strong-intensity area, likely hard sediment, dots the southeast side of the central cone and eastern slopes of the caldera.

4. Discussion
4.1 Checking the survey grid data

The sounding points acquired the MBES have some variability. In order to survey high-accuracy bathymetry, it is necessary to increase sounding points and adopt the average value of the sounding point as grid data. The average data number was 12.5 points per pixel for the wide-area bathymetry in the Higashi-Aogashima caldera shown in Table 1. Based on this we verified the density of the points per pixel as reasonable or not. To confirm the accuracy of this method of bathymetric survey,
we compared the main bathymetric grid data in the north-south direction of the survey line to that in the east-west direction of the survey line. By crossing the survey line, each data gained independence. Figure 5 shows the depth difference of the two grid data. Because depth error is likely to occur by the “omega” effect\(^{16}\) when a research vessel tracks a steep slope, there was a difference between the depth values in part of the area. However, the difference was within 2 m for most of the verification area. The depth difference was 0.41 m on average, with a 1.18 m SD for the entire area compared. This difference was less than 0.1% of the area depth (about 700 m), and so this verification proved that the survey setting had high repeat accuracy. Acquiring such data allowed us to interpret topography in detail by wide-area exploration, and led to the discovery of hydrothermal deposits with pinpoint accuracy. In addition, high-quality wide-area bathymetry also contributed to the safe navigation of the AUV.

4.2 Normalized seafloor acoustic image

Next, we discuss the result of backscattering angle correction. Figure 6 shows an example of a data correction measuring a flat and silty seafloor. Under such conditions, the seafloor acoustic image with normalized influence of the angle is also even and has no variation. The SD of backscattering strength before the correction was large (3.24 dB). After correction, however, the SD of backscattering strength was small (1.62 dB), and the seafloor acoustic image could normalize the angle dependence of strength.
To consider the analysis results in the Higashi-Aogashima caldera, in Figure 4(a), a strong reflection just under the sonar like a trace-tracking line in the north-south direction was confirmed. By contrast, in Figure 4(b), the influence of the incident angle just under the sonar as removed, and the seafloor acoustic image was normalized.

5. Conclusion

This paper presents a method for creating bathymetric maps for wide-area exploration using a shipboard MBES. Generally, bathymetric maps using shipboard MBES are processed with the resolution of the footprint. Because the method in this paper allowed us to survey high-resolution bathymetry of the deep sea from the surface, we were able to utilize the AUV effectively, and discovered seafloor hydrothermal deposits. There are previous studies of sediment classification with acoustic images using side-scan sonar on an AUV in hydrothermal deposits areas. In future, we plan to quantify the characteristics of different textures using seafloor acoustic images, and want to consider detection methods for peculiar characteristics of hydrothermal deposits. By applying that study, we expect to develop a method of acoustic image analysis of hydrothermal deposits for wide-area exploration. We also aim to detect quantitative image features using a combination of various textural analysis results. By establishing these techniques, we are confident that wide-area exploration of hydrothermal deposits will become more efficient.

Fig. 5 Comparison of main survey and checking survey grid data. The main survey line navigated in the north-south direction, and the checking survey line in the east-west direction. Although depth error often occurs on steep slopes, the result show good repeat accuracy at most parts of the verification area.
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