T Waves Associated with Submarine Volcanic Eruptions in the Marianas Observed by Ocean Bottom Seismographs

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In September and December of 1989, swarms of T waves were observed by ocean bottom seismographs (BSOBS) off the Boso Peninsula of Japan, by a SOFAR hydrophone array near Wake Island, and by a station at Rangiroa. Using arrival times observed by these networks, the source location of the T waves was determined to be in the northern Marianas, where submarine eruptions had been observed frequently in recent years.

The T waves were not accompanied by corresponding body waves. The T waves had shorter duration (from a few to ten seconds) and higher prominent frequency than those of tectonic earthquakes which also occurred in the northern Marianas. The amplitude variation of the T waves observed by BSOBS showed a different pattern from those from tectonic earthquakes. This is a manifestation of a difference in the spectral contents between them. The spectra of these T waves showed conspicuous harmonic peaks. These characteristics are similar to those of volcanic T waves as previously reported. Therefore we concluded that they are excited by submarine volcanic eruptions.

From the detailed analysis of the T wave events, this volcanic activity is considered to proceed through three stages: the first which was not so explosive, the second which was composed of intermittent explosive eruptions, and the third which was small and similar to the first. The observed fundamental frequencies of the T waves varied with time. This could be caused by changes in the eruption site or in the size of the area where reverberations occurred.

1. Introduction

Swarms of T waves (underwater acoustic waves) were observed in September and December of 1989, by ocean bottom seismographs of the Japan Meteorological Agency, by a SOFAR (sound fixing and ranging) hydrophone array near Wake Island of

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T waves were discovered for the first time on the seismograms at land stations (Linehan, 1940). Owing to the advancement in underwater acoustics and the deployment of hydrophone networks around the Pacific Ocean, T waves have become known as acoustic water waves traveling through the low velocity layer (the SOFAR channel) in the sea water (e.g., Ewing and Worzel, 1948; Pekeris, 1948).

Japan Meteorological Agency (JMA) established permanent ocean bottom seismograph observation systems off the south coast of Tokai and off the south coast of Boso Peninsula. These systems have been providing useful seismic data for the determination of hypocenters of earthquakes in the sea area. Since they are installed on the sea bottom, they often detect T waves (Hamada, 1985). In this paper, we examined the usefulness of ocean bottom seismographs for the detection of T waves and investigated characteristics of the swarms of T waves using waveform data obtained by JMA's ocean bottom seismograph, those by Wake SOFAR hydrophones and those by RSP network.

2. Instruments

The permanent ocean bottom seismographs (OBS) were installed off the south coast of the Tokai area in 1978 and off the south coast of the Boso Peninsula in 1985. Their data have been used for surveillance of the seismicity around the Tokai–Kanto area in Japan. The detailed instrumental design and installation of these OBS's are explained by Meteorological Research Institute (1980) and Fujisawa et al. (1986). The T waves analyzed in this paper were observed only by the OBS off the Boso Peninsula (hereafter we will abbreviate the OBS as BSOBS).

BSOBS consists of four stations whose locations are shown in Fig. 1. Each station has three components of a short period seismometer (one vertical and two horizontal components). The horizontal components of seismometers are orthogonal to each other and one of them is oriented almost parallel to the cable axis shown by a thick solid line in Fig. 1. The natural frequencies of seismometers are 3 Hz at BS1 and 4.5 Hz at BS2–BS4. Three component displacement waveforms and a vertical velocity waveform are obtained at each station. Seismic signals are transmitted continuously through an FM-FDM system to the coastal station and are telemetered from there to the JMA headquarters in Tokyo. They are processed and are recorded on optical disks and pen recorders by the Earthquake Phenomena Observation System (EPOS; Yokota and Yamamoto, 1989) in the JMA. The sampling frequency of the digital data acquisition system is 100 Hz for each data component. A total frequency response of BSOBS system is shown in Fig. 2. The system has a nearly flat response from 2 to 20 Hz.

Wake hydrophone array is located near Wake Island and consists of eleven hydrophones; six of these are on the ocean floor in a 40 km pentagonal arrangement (one of the elements is at the center of the pentagon) and five are in the SOFAR channel. These data are recorded on a digital magnetic tape system and on drum recorders. The system has recorded many T waves associated with tectonic earthquakes and has been used for a number of studies of earthquakes in the Pacific (e.g., Walker et al., 1992).
Fig. 1. Locations of the ocean bottom seismographs of JMA, Wake hydrophone array, and PMO station, which is on Rangiroa Island, of RSP network. A triangle indicates the source location of the swarms of T waves determined in the present study. The epicenters of tectonic earthquakes whose T waves are analyzed are also shown.

The data used in this paper are from three SOFAR hydrophones (Fig. 1). Their frequency response is also shown in Fig. 2.

RSP network in French Polynesia, which consists of seismic stations on islands around Tahiti, has also recorded many T waves associated with tectonic earthquakes...
and submarine volcanic eruptions. The data are used for studies of seismicity and submarine volcanism (e.g., Talandier and Okal, 1987). The T waves studied in this paper were recorded at PMO station on Rangiroa Island (Fig. 1).

3. Source Location of the T waves

In September 21–22, December 22–24, and December 26–27 in 1989 (JST), BSOBS observed strange waveforms. Their apparent velocity was 1.4–1.5 km/s and they were thought to be T waves which traveled from the SSE direction. But the corresponding P waves and S waves were not identifiable. During the same period Wake SOFAR hydrophone array and RSP network also observed T waves. The apparent propagating direction at Wake array was estimated as from the west. Examples of the records of T waves observed by BSOBS, Wake SOFAR hydrophones and a seismometer at PMO of RSP network are shown in Fig. 3. Undoubtedly, these are the records of the same event that occurred somewhere in the western Pacific. From the observed arrival times at these networks, we determined the source location of these T waves. Using corrected water sound velocity data, the source location was determined as 20.3°N, 144.9°E. The absolute location error might be rather large but the relative error must be within 10 km because the reading error at each station is within several seconds. Since no variation in the travel times could be observed during the activity, the location of the source seems to be identical through the period within the relative error.

Another JMA’s permanent ocean bottom seismograph system off the south coast of Tokai (Fig. 1) did not record the present T wave events. Tokai area is possibly a shadow zone for the T waves from the northern Marianas because the T waves attenuate effectively when they pass the shallow sea region of the Izu–Ogasawara Islands.

4. Comparison to T Waves Associated with Tectonic Earthquakes

In this chapter, we compare the T waves of the 1989 swarm events to those asso-
Fig. 3. Examples of records of T waves on September 21 observed by BS4, Wake hydrophones, and PMO.

ciated with tectonic earthquakes. For the comparison, we used T wave records from two tectonic earthquakes which occurred in the northern Marianas. Hypocenters of the earthquakes used are shown in Fig. 1. The travel paths of the T waves are similar to those of the T waves studied in this paper.

Waveforms and running spectra of T waves associated with these earthquakes are shown in Fig. 4(A) and (B). Those of the swarm of T waves analyzed in this paper are shown in Fig. 4(C). P and S waves were observed in advance of the T waves associated with the tectonic earthquakes though they are not shown in the figure. In the case of the earthquake in Fig. 4(B), two T phases can be identified. As the arrival time of the latter phase agrees with the origin time of the earthquake but that of the other phase is more than 2 min earlier, these two phases seem to be one generated just above the hypocenter and another generated in a region some distance away from the epicenter. The present swarms of T waves were composed of many T waves whose durations were within 20 s. On the other hand, the T waves associated with tectonic earthquakes are composed of spindle-shaped wave-packets and their durations are longer (1–2 min) than the present T waves. The spectra of the T waves from tectonic earthquakes are mainly composed of low frequency components. On the other hand, the swarms of T waves contains higher frequency components. The spectra of the swarms of the T waves have several peaks which are arranged at regular intervals. Such band-shaped
spectra are often observed in a certain kind of volcanic quakes and tremors (e.g., Kamo et al., 1977), while the T waves from tectonic earthquakes do not have such harmonic spectra.

Figure 5 shows amplitude variations among four stations of BSOBS for T waves from one of the 1989 swarm events and from the two tectonic earthquakes. It is obvious that there is a difference in the pattern of the variation between the swarm events and the tectonic earthquakes. The amplitudes for T waves from the two tectonic earthquakes show similar variations and the amplitudes are almost the same at the four stations, whereas the amplitude of the T wave from the swarm events shows a significant variation. The amplitude of the T wave from the swarm observed at BS4, located at the shallowest depth (658 m), is largest among the four stations and about ten times larger.

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Fig. 5. Amplitude variations of T waves among the four stations of BSOBS.

Fig. 6. Frequency dependence of the ratio of T wave amplitude observed at BS2 to that at BS1 for the 1989 swarm events.

than that at BS1, located at the deepest depth (4,011 m). Ratios of the T wave amplitude from the swarms observed at BS1 (depth = 4,011 m) to that at BS2 (depth = 2,090 m) are shown in Fig. 6 for several frequency bands. Around the frequency of 2 Hz the amplitude ratio is almost 1, but the amplitude ratio becomes larger as the frequency becomes higher. The difference in amplitude variations between T waves from tectonic earthquakes and the present swarms of T waves are thought to be caused by the difference of their spectral contents.

Below, we will demonstrate how the difference in frequency contents affects the depth variation of T waves amplitudes by using a theoretical calculation. Theoretical aspects of T waves have been studied by many workers (e.g., Pekeris, 1948; Ewing and Worzel, 1948). Sato (1978) gave numerical solutions for T waves trapped in the SOFAR channel. A pressure wave \( p \) which propagates along the horizontal axis \( x \) in vertically heterogeneous water is represented as

\[
p = P(z) \exp(i\xi x - i\omega t),
\]

where \( P(z) \) is obtained from the equation,

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\[ \frac{d^2 P(z)}{dz^2} - \frac{1}{\rho} \frac{d\rho}{dz} \frac{dP}{dz} \left( \frac{\omega^2}{c(z)^2} - \xi^2 \right) P = 0, \]

where \( \rho \) is the density of water and \( c \) is the sound velocity of water. A numerical solution for a realistic underwater sound velocity model is shown in Fig. 7. It is obvious that the energy of underwater waves concentrates around the depth of 900 m, where the sound velocity takes its minimum (the SOFAR channel), especially for higher frequency components. This explains well why the present swarms of T waves, rich in high frequency components, show the largest amplitudes at BS4 which is the closest to the SOFAR channel. T waves generated by tectonic earthquakes have less high frequency components, therefore the energy does not concentrate near the SOFAR channel.

Fig. 7. A theoretical pressure distribution of a T wave in a realistic underwater sound velocity model, whose velocity profile is shown to the left. The pressure is normalized to that at the sea bottom.

Fig. 8. Velocity amplitude-frequency relation of the T waves observed by BSOBS (BS4) from December 22 to 23. \( n \) and \( N \) indicate frequency and cumulative frequency, respectively.
Figure 8 shows the amplitude-frequency relation of the T wave events observed at BS4 for the period from 06 h on December 22 to 06 h on 23. In the figure, the events with amplitude larger than $1 \times 10^{-4}$ cm/s are shown. More than 1,000 events were observed in this period. In general, the amplitude-frequency relation of earthquakes is expressed as

$$n(A) = aA^{-m},$$

where $A$ is the amplitude, $n(A)$ is the number of earthquakes which have amplitudes of $A$ to $A + dA$, and $a$ and $m$ are constants (Ishimoto and Iida, 1939). The $m$-value is known to be about 2 for the tectonic earthquakes. Also for the present T wave events, the $m$-value obtained is about 2 for the amplitude-range of $0.2 - 1.5 \times 10^{-3}$ cm/s, but the cumulative frequency distribution, indicated as N in Fig. 8, is not linear, and bends at the amplitude of $1.5 \times 10^{-3}$ cm/s. Such upward convex type of amplitude-frequency curve suggests that the swarm of T waves has an upper bound in magnitude, that is often observed for volcanic earthquakes and volcanic explosion-quakes (e.g., Seino, 1983).

As mentioned above, the source of the T waves was located at northern end of the Marianas, the south of Uracus Island (Farallon de Pajaros). Bloomer et al. (1989) identified many submarine volcanoes around the Marianas from narrow-beam bathymetry maps and from selected dredge samples. Their study indicates that many of these volcanoes are active. According to the report of the Smithsonian Institution Scientific Event Alert Network (SEAN, 1989), at least 19 volcanic eruptions have taken place since 1864, and discolored water has been often observed in recent years around Uracus Island. Also in the activity of 1985, T-phase events were recorded by the station at Rangiroa (PMO) where the 1989 swarms of T waves were also observed as mentioned earlier. The source location error of the present T waves is large, but the estimated epicenter is very close to the site of the most recent documented volcanic activity near Uracus Island, where a 3 km zone of discolored water was observed in September 1985 near the 1969 eruption site.

Walker et al. (1985) and others indicated that acoustic water waves associated with volcanic eruptions are accompanied by no seismic body waves and that their waveforms were composed only of strong, impulsive phases of short duration. The characteristics of the present swarms of T waves coincide with their results and the amplitude-frequency relation of the T waves indicates that they have an upper bound in magnitude as in the case of a certain volcanic events.

Therefore, it is reasonable to conclude that the swarms of T waves treated in this paper were associated with submarine volcanic eruptions in the northern Marianas though they were not testified by any visual observations.

5. Waveforms and Spectra of the T Waves

In this section we describe characteristics of waveforms and spectra of the present volcanic T waves in more detail.

Examples of records of the T waves at BS0BS are shown in Fig. 9. In the activity of September, various kinds of waveforms are observed and some of them show long
duration of fluctuating intensity, looking like volcanic tremors. On the other hand, in the activity of December 22–24, impulsive events with similar waveforms of large amplitude are intermittently observed. In the second activity of December, signals smaller than those in the earlier two stages are observed. Examples of records of the T waves observed at one of Wake SOFAR hydrophones are shown in Fig. 10. Similar
Fig. 11. An example of spectra (top) and waveforms (bottom) of a volcanic T wave event on September 21 obtained at four stations of BSOBS.

Fig. 12. Comparison of the spectra of T waves obtained by BSOBS and Wake hydrophones. The spectra were obtained by stacking those observed by three stations of each array. Spectra of the events that occurred on September 21 (left) and December 22 (right) are shown.

to the observations at BSOBS, events with rather continuous waveforms are observed in September and intermittent events with similar waveforms are observed in December 22–24.

Examples of waveforms and spectra observed by BSOBS are shown in Fig. 11. The spectra were obtained by the fast Fourier transform (FFT) method using 20 s long data. The T waves contain frequency components higher than 3 Hz, and spectral peaks at frequencies of about 4 Hz and 8–9 Hz are obvious. Although the power levels are somewhat different among the four stations, the two peak frequencies are commonly observed.

Typical examples of spectra of the T waves obtained by BSOBS and Wake SOFAR hydrophones are shown in Fig. 12. They were obtained by stacking the spectra for the data of each array. In the case of the BSOBS data, we stacked the spectra for three stations except BS1 (the deepest station) whose spectra are rather different from those of the others. Although apparent shapes of the stacked spectra are different from each
Fig. 13. Spectra of T waves obtained by BSOBS (left), BSOBS spectra modified by the frequency response of Wake hydrophones (center), and spectra obtained by the Wake hydrophones (right). Spectra of the volcanic events on December 22 are shown.

Fig. 14. Spectra obtained by BSOBS (top) and PMO station (bottom) for the volcanic T waves on December 22, 1989.

other, peak frequencies are common to the two arrays. High frequency components contained in the apparent spectra of Wake array data are more pronounced than those at BSOBS. This is because BSOBS has a flat response in the frequency range from 2 to 20 Hz while Wake array does not (Fig. 2). For the purpose of easy comparison, we modified the spectra for the frequency response curve by multiplying the spectra obtained at BSOBS by the ratio of frequency response of Wake to that of BSOBS. As shown in Fig. 13, we can obtain almost the same shape of spectra for these arrays in spite of a more than 3,000 km difference in their travel paths.

An example of the spectra obtained at PMO is shown in Fig. 14. The peak frequency at 6–7 Hz can be identified but the other peak frequencies which are obtained for BSOBS are not clear for PMO. It seems that the signal obtained at PMO has been distorted and the peaks have become obscure. This distortion might be caused not only by the remoteness of PMO (more than 8,000 km distant from the source) but also
The temporal variation of spectra of the volcanic T waves observed by BSOBS is shown in Fig. 15. They were obtained by stacking the spectra observed at BS2–BS4 using 20 s data. The spectra of events in proximity to each other are very similar but the arrangement of peak frequencies varied with time. At the early stage, peaks at frequencies of 4–5 Hz and 8–9 Hz are conspicuous. These two peak frequencies are retained in the activity of September. However, in the first activity of December, band

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Fig. 16. An example of particle motion diagrams of the volcanic T wave observed by the BSOBS. Displacement components of BS4 are shown. X and Y are horizontal components, and Z is the vertical component. The direction of X is almost parallel to the cable axis (almost NNW).

widths of peak frequencies become narrower and the spectra take complex patterns. It can be interpreted as a change of the fundamental frequency. In the second activity of December, the similar spectra to those in September were observed. Since the spectral feature is common between BSOBS and Wake hydrophone array, the temporal variation can be attributed to some changes in the source region. Detailed discussion will be made in the following section.

Because BSOBS is composed of three component seismographs, we can obtain information on the particle motions of T waves. An example of a particle motion diagram is shown in Fig. 16. The polarization of the trajectory is prominent in the horizontal plane, and that in the vertical radial plane indicates prograde elliptic motions. Hamada (1985) investigated the particle motions of T waves associated with tectonic earthquakes observed by the ocean bottom seismographs off the south coast of Tokai which is another OBS system of JMA. He obtained the same results and inferred that prograde motions are the effect of unconsolidated materials of considerable thickness beneath the sensors. The present study supports that the prominent polarization and prograde particle motions must be a general property of T waves observed by ocean bottom seismographs.

6. Discussion

Underwater acoustic waves excited by submarine volcanic eruptions have been studied by several scientists. Ewing et al. (1946) speculated that some of underwater sounds observed by SOFAR hydrophones might be from submarine volcanic activities, and suggested that detection and location of submarine volcanoes would be one of the applications of the SOFAR monitoring. The first detailed study on the underwater sounds associated with submarine volcanic activities was done by Dietz and Sheehy.
Table 1. Comparisons of T waves generated by submarine volcanic eruptions with those by tectonic earthquakes.

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<th>Submarine eruption</th>
<th>Tectonic earthquake</th>
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<tbody>
<tr>
<td>Seismic body wave</td>
<td>Not observed</td>
<td>Observed</td>
</tr>
<tr>
<td>Duration</td>
<td>Short (within 20s)</td>
<td>Long (1-2 min)</td>
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<tr>
<td>Spectral content</td>
<td>High frequency (more than 3Hz) and harmonic</td>
<td>Low frequency (around 2Hz) and not harmonic</td>
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(1954). They studied underwater sounds associated with the 1952 eruption at Myojin Reef and investigated the time sequence of the activity. Snodgrass and Richards (1956), Norris and Johnson (1969), and others also detected submarine volcanic eruptions with SOFAR hydrophones and demonstrated that the SOFAR observation is very useful for the detection of submarine volcanic activities.

Characteristics of T waves from submarine eruptions and those from tectonic earthquakes are summarized in Table 1. One of the characteristics of seismic records of T waves from submarine volcanic eruptions is the absence of corresponding seismic body waves. Also in the case of the submarine eruptions analyzed in this paper, no seismic body waves could be identified in the records of BSOBS, Wake hydrophone array and RSP network. Actually, seismic body waves must be excited by submarine volcanic eruptions. For example, during the 1989 submarine eruption off the east coast of the Izu Peninsula, large amplitude volcanic tremors were observed by seismographs around the Kanto–Tokai area of Japan and seismic waves were identified at stations more than 300 km distant from the eruption site (Yamasato et al., 1991; Ukawa, 1993). But in the case of more distant observations such as those discussed here, seismic body waves are attenuated and only the sound trapped in the SOFAR channel can be detected.

The second characteristic of T waves from submarine eruptions is waveforms of short duration (within 20s at BSOBS). Ewing and Worzel (1948), who investigated the transmission of SOFAR signals using the ray theory, showed that the duration of the signal is correlative to the distance from the source. The 2–3s duration of the waveforms of the volcanic T waves of December observed by Wake SOFAR hydrophones, more than 2,000 km distant from the source, can be interpreted as the response from an impulsive pressure pulse at the source. On the other hand, as shown in Fig. 10, the durations of T waves observed by Wake hydrophone array in September are nearly 10s and are rather longer than those in December. The change in the durations of the T waves might indicate that somewhat continuous eruptions occurred in September and intermittent explosions did in December. Some volcanic T waves have long duration (reaching up to an hour) of fluctuating intensity (Okal et al., 1980). Talandier and Okal (1984) speculated that such eruptions, which they called ‘quiet eruptions,’
are caused by degassing of lava or boiling of the sea water. The activity of September might be of intermediate nature between the quiet eruptions and explosive eruptions.

Another waveform characteristic of T waves from submarine volcanic eruptions is their spectral contents. The T waves generated by volcanic eruptions contain high frequency components more than those by tectonic earthquakes and have obvious harmonic spectra as shown in Fig. 4(C). Those of tectonic earthquakes, on the other hand, have no harmonic spectra (Fig. 4(A), (B)). The absence of high frequency components in T waves from tectonic earthquakes can be the reflection of the source spectra and of the attenuation of body waves which generate T waves.

Harmonic spectra similar to that of the T waves presently discussed have been observed for T waves from submarine eruptions of other volcanoes (Norris and Johnson, 1969). Johnson and Norris (1972) investigated T waves from submarine volcanic eruptions at Myojin, and they demonstrated that harmonic spectra, which they called spectral banding, varied when surface venting explosions occurred. They further ascribed the spectral banding to resonance of the water between the sea surface and the irregular summit of the volcano. If the spectral banding is due to some resonance near the source, the fundamental frequency of the resonating T waves should be determined by the water depth or the geometry of the source area. The observed difference in the arrangement of peak frequencies between those in the activity of September and those in the first activity of December indicates a change in fundamental frequencies and is possibly due to a change of the eruption site. Such change can also be explained by an expansion of the area in which the sea water reverberates as a consequence of the eruptions: the T wave magnitudes of individual explosions were generally larger for the events in December.

From our detailed analysis of the T wave events, the submarine volcanic activity at the northern Marianas in 1989 is considered to proceed through three stages. The volcanic eruption started in September. The first eruption was not so explosive and observed T waves had rather long durations. The second activity took place in December 22–24. The activity was of an intermittent explosiveness. The spectra of the T waves differed from those in September, indicating that the eruption site had changed or that a larger body of sea water than that in September was put into reverberation by the explosions. The third activity on December 26 and 27 was similar to that in September; it was not explosive and was weaker than those in the earlier two stages.

7. Conclusions

We analyzed swarms of T waves that were originated in the Marianas in 1989 and were observed by the ocean bottom seismographs of the JMA (BSOBS), the SOFAR hydrophone array of Wake Island and PMO station of RSP network of Tahiti.

We compared the waveforms and spectra of the T waves with those excited by tectonic earthquakes whose epicenters are in the vicinity of those of the T waves. The T waves had shorter duration (from a few to ten seconds) and higher prominent frequency than those of tectonic earthquakes. The amplitudes of T waves from tectonic
earthquakes observed by BSOBS were almost identical at all four BSOBS stations while a large part of the energy of the T waves from the swarm events was concentrated at stations near the SOFAR channel. This is a manifestation of a difference in the spectral contents between them. The observed characteristics coincide with those of volcanic T waves previously reported. Therefore we concluded that they were excited by submarine volcanic eruptions.

The waveforms of the T waves were continuous in September and had changed to be impulsive in December. This can be due to some difference in the mechanism of the eruptions. The spectra of the volcanic T waves showed conspicuous harmonic peaks and their fundamental frequency varied with time. Since the observed spectral features were almost the same between BSOBS and Wake SOFAR array, this variation could be attributed to a change in the eruption site or the size of the area where reverberation of acoustic waves occurred.

This volcanic activity is considered to proceed through three stages. In September, volcanic eruption started but it was not so explosive. The subsequent activity in December 22–24 was more explosive. A larger area than that in September might be involved for the reverberation of sea water or the eruption site might differ from that in September. The third activity in December 26–27 was similar to that in September and smaller than those in the earlier two stages.

The present study has shown that the observation by ocean bottom seismographs is useful for the detection of submarine volcanic eruptions.

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