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Continuous seismic monitoring of Nishinoshima volcano, Izu-Ogasawara, by using long-term ocean bottom seismometers

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Abstract

Nishinoshima in Izu-Ogasawara started erupting in November 2013, and the island size increased. Continuous monitoring is important for study of the formation process. Since it is difficult to make continuous observations on a remote uninhabited island, we started seismic observations near Nishinoshima using ocean bottom seismometers (OBSs) from February 2015. Our OBSs have a recording period of 1 year, and recovery and re-deployment of OBSs were repeated to make continuous observations. The OBSs were deployed with distances of less than 13 km from the crater. Events with particular characteristics were frequently recorded during the eruption period and are estimated to correlate with the release of plumes from the crater by comparison with temporal on-site records using a video camera and microphones. We estimated the number of events using the amplitude average of records to monitor volcanic activity. There were approximately 1800 detected events per day from February to July 2015. The number started to decrease from July 2015, and reached less than 100 per day in November 2015. The surface activity of the volcano was estimated to have ceased in November 2015. Characteristic events began re-occurring in the middle of April 2017. The number of events reached approximately 1400 events per day at the end of May 2017. Seafloor seismic observations using OBSs are a powerful tool for continuous monitoring of island volcanic activity.

Keywords: Nishinoshima, Volcanic eruption, Continuous seismic monitoring, Ocean bottom seismometer (OBS)

Introduction

Nishinoshima is positioned on the volcanic front of the Izu-Ogasawara volcanic arc and lies approximately 1000 km south of Honshu island in Japan (Fig. 1). Nishinoshima was a small island, 650 m in length and 200 m in width, until 1973. The island is on the crater rim of a huge volcano, which has height of about 4000 m above the deep sea floor and a base diameter of 30 km. Before the 1973 eruption, the island had a relatively flat topography and andesitic rocks were found in the island (Ossaka 1973). Nishinoshima volcano had no historical record of eruption until 1973. A submarine volcano close to Nishinoshima was estimated to start eruption in April 1973

(Ossaka 1973). A new island was created by accumulating large lava flows and ejecta in September 1973 (Ossaka 1974). The new island merged with the existing island of Nishinoshima in June 1974 and activity terminated (Iizuka et al. 1975). Ejecta from the 1973 eruption sampled on the new island was also andesitic (Ossaka et al. 1974, Umino and Nakano 2007). After the 1973 eruption, discolored water appeared near Nishinoshima sporadically, and the area of the island decreased due to erosion.

In November 2013, a submarine volcano eruption close to Nishinoshima was confirmed (Ono et al. 2015). At the finding of the eruption, a new island was found approximately 500 m south of Nishinoshima. The new island was 100 × 70 m (Ono et al. 2015). The eruption was estimated to start from at least early November 2013, because a thermal anomaly was detected in this area in satellite images (Maeno et al. 2016). Shortly after, a lava flow appeared from the crater, and the new island

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increased in size. Finally, the new island was connected with the existing Nishinoshima by lava flows in late December 2013 (Ono et al. 2015). Lava effusion continued for more than 1 year, and the new island had an area of 2.6 km² in March 2015 (Maeno et al. 2016). The Japan Coast Guard (JCG) reported the cessation of the Nishinoshima volcano eruption in November 2015. The area of Nishinoshima reached approximately 2.7 km². During the activity, the active crater was positioned in the center of the new island and did not change position. Scoria and ash from the 2013 activity were obtained, which were also andesite (Saito et al. 2014). In April 2017, it was confirmed that the Nishinoshima volcano resumed erupting and extruded lava flows.

To understand the formation process of a new volcanic island, it is important to monitor volcanic activity. However, it is difficult to make observations on an uninhabited island such a large distance from populated land, such as Nishinoshima that is 130 km from the closest habited island, Chichi-jima in the Ogasawara islands. Aerial observations and images from satellites can be useful for understanding volcanic activities on uninhabited islands. For Nishinoshima, observations by airplane were conducted 1-month intervals, and the data from aerial observations and satellite images were used for analyses (Maeno et al. 2016). However, these are not continuous observations. Although it is possible to monitor volcanic activity using infrasonic waves from a remote island (Nishida and Ichihara 2016), continuous observations are difficult to obtain due to meteorological effects. Continuous observations close to the island are essential to identify detailed activities. Since landing on Nishinoshima during eruption was dangerous, access to the new island is prohibited, and deploying observational equipment on the island was impossible. Seafloor observations close to submarine volcanoes and volcanoes on islands using ocean bottom seismometers (OBSs) can monitor activity because there is no need to install them on land (e.g., Nishizawa et al. 2002). Existing OBSs have relatively short recording period, usually a few months, which is a disadvantage for continuous monitoring. However, monitoring submarine volcano or volcanoes on an island for a long period requires frequent OBS replacement. Recently, long-term OBSs (LT-OBSs) were developed (Kanazawa et al. 2009), which can record seismic signals continuously with a recording period of 1 year.

We began seismic observations using LT-OBSs from February 2015, when the eruption was occurring continuously. The main objective was to monitor the activity of Nishinoshima volcano continuously using seismic methods. In this study, we describe seafloor seismic monitoring of Nishinoshima volcano using LT-OBSs and present

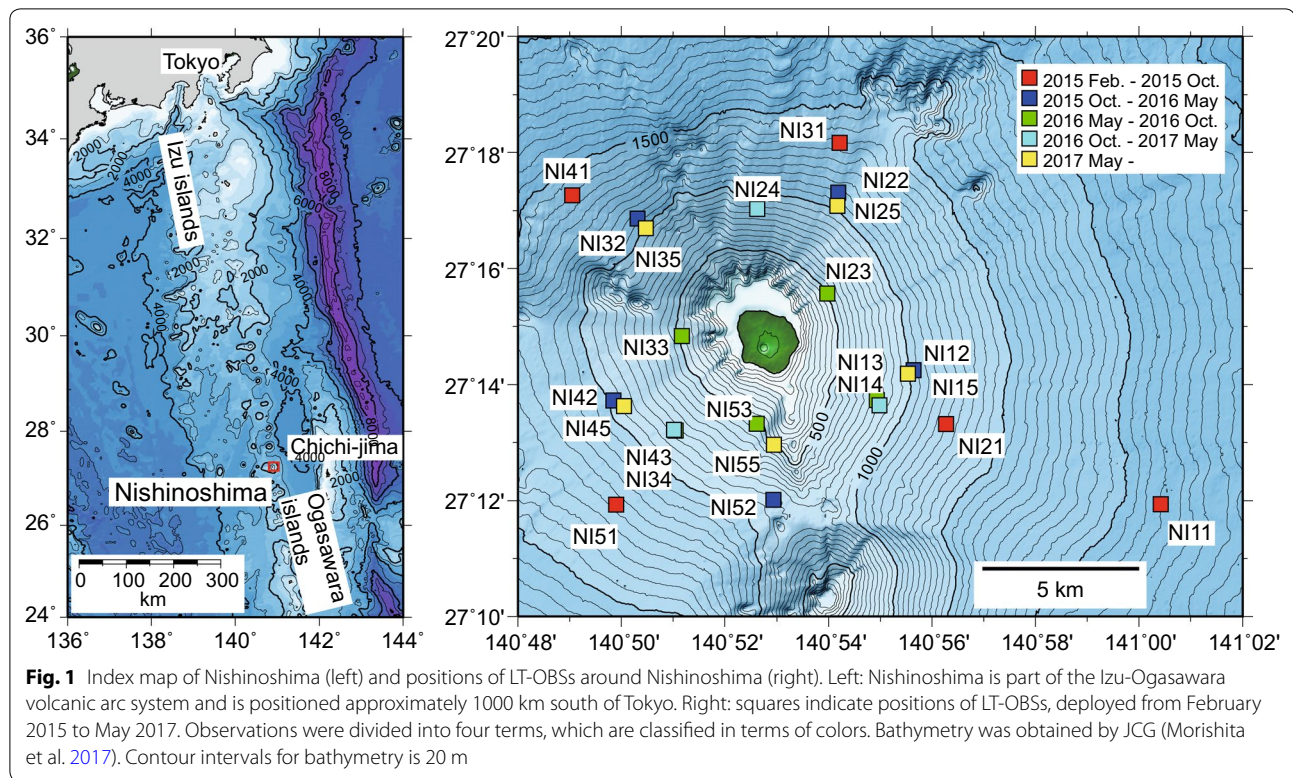
Nishinoshima volcanic activity observations from February 2015 to May 2017.

Observations

The LT-OBS system was developed to continuously observe seismic events on the seafloor for 1 year (Kanazawa et al. 2009). A titanium alloy sphere, 50 cm in diameter, contains a seismic sensor, recorder, and batteries. The seismic sensors have a velocity-proportional response with a natural frequency of 1 Hz. Three component sensors are mounted on a leveling system. Signals from the seismometers are converted to digital data continuously. The sampling frequency is 100 or 200 Hz. The converted data are stored to hard disks or memory cards. Power to all electric circuits is supplied from lithium battery cells. Although the number of battery cells depends on the intended duration of recording, approximately 50 battery cells are needed for 1 year of observations. The LT-OBS is equipped with an acoustic release and communication system. The most important function of the acoustic system is to release a weight for recovery. Another function of the acoustic system is communication between the seafloor and surface. The recording unit on the OBS can be controlled from the interrogator onboard, for example, starting or stopping recording, leveling the sensor, and checking the recording unit status.

The first deployment around Nishinoshima was carried out by the R/V *Kairei* belonging to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in February 2015. We deployed four LT-OBSs at a distance of about 8 km from a central crater of Nishinoshima where water depths are about 1400 m and a LT-OBS at a distance of about 13 km (the first-term observation). Before the first deployment, approaches of distances less than 6 km were prohibited. Infrasonic and video observations were performed on the R/V *Kairei*. Three microphones (Hakusan, SI104) were installed on the deck and recorded with data loggers (Hakusan, LS8800) at 200 Hz. For time synchronization, Global Positioning System (GPS) times displayed on the infrasonic data logger were filmed using a video camera at the end of the observation.

In October 2015, the deployed LT-OBSs were recovered by the R/V *Keifu Maru* belonging to the Japan Meteorological Agency (JMA), and five LT-OBSs were installed to continue observations (the second-term observation). This second set of LT-OBSs was placed at a distance of 5 km from the crater at a water depth of about 1000 m, because the distance restriction for approach had changed to 4 km. In May 2016, the S/V *Shoyo* belonging to the JCG retrieved the five LT-OBSs and deployed five LT-OBSs (the third-term observation).



When the LT-OBSs were deployed for the third-term observation, we were able to approach the crater at a distance of 1.5 km. Therefore, the LT-OBSs were deployed close to Nishinosima. The LT-OBSs were deployed at depths from 500 to 800 m. In October 2016, these five LT-OBSs were recovered by the R/V *Shinsei Maru* belonging to the JAMSTEC. Because the eruption of Nishinosima volcano had ceased at the end of 2015, we decided to decrease the number of deployed LT-OBSs. Three LT-OBSs were installed to continue observations (the fourth-term observation). When LT-OBSs were deployed for the fourth-term observation, there was no activity on Nishinosima volcano. Three LT-OBSs were deployed at a distance of 4 km from the crater, and their water depth was approximately 800 m, where a quiet environment was expected. Installation in shallow water depth causes low signal-to-noise ratios in seismic records due to sea surface conditions. Three LT-OBSs were recovered by the R/V *Keifu Maru* belonging to the JMA in May 2017. In April 2017, aerial observation confirmed that Nishinosima volcano had resumed erupting. We deployed five LT-OBSs at a distance of 5 km from the crater (the fifth-term observation) at water depths of approximately 1000 m. As of August 2017, monitoring using LT-OBSs has continued. The seismic monitoring near Nishinosima using LT-OBSs is summarized in Fig. 1.

Analyses of LT-OBS data

First, the data stored in the recorders were copied to hard disks on computers for data processing and archiving. Timing of data from each OBS was adjusted to GPS time using time differences between the GPS time and an internal clock in each OBS, which were measured just before deployment and after recovery. Finally, data from each OBS were combined into a single file in 1-hour segments.

All LT-OBSs for the first-term observation frequently recorded characteristic events from the beginning of the records. The early part of the events dominates waves with a high frequency of a few-Hz and large-amplitude waves with a period of a few seconds follows (Fig. 2). Characteristic events were recorded throughout the records of the first-term observation, the early part of the second-term observation, and the late part of the fourth-term observation. In contrast, few ordinary earthquakes were recorded by the LT-OBSs. Characteristic events were also reported by Okada et al. (2016). These characteristic events have good S/N ratio in a frequency range from 4 to 8 Hz. The event durations were < 1 min in a frequency band of 4–8 Hz.

The record section of the characteristic event shows that the arrival time of the event on the furthest OBS from Nishinosima (NI11) is the latest and amplitude is smallest (Fig. 2). In addition, arrival times and amplitudes

are similar for other OBSs with almost identical distances from Nishinoshima. We picked up arrival times of the events on February 28, 2015 for each OBS on computer display (Urabe and Tsukada 1991), and located the events (Hirata and Matsu'ura 1987). A homogeneous velocity structure with P-wave velocity of 4 km/s was adopted for the location. Although it is difficult to pick arrival times precisely, especially S-wave arrivals, the epicenters of the events were concentrated near the volcano crater on Nishinoshima (Fig. 2).

On February 27, 2015, infrasound and video observations were performed on the R/V *Kairei* during the deployment of the LT-OBSs. Infrasound was observed during the plume release from the crater. We selected visual data just above the crater from the video and determined the luminance based on their collection times (Fig. 3). When Nishinoshima volcano emitted plumes, a black region traveled toward the upper right. During the infrasound and video observations, one OBS (NI11) was deployed and began the observations. We compared the events recorded by NI11 with infrasound data (1–7 Hz) and visual data of the volcano (Fig. 3). For comparison, infrasound and seismic data times were shifted in consideration of the sonic and seismic speeds in seawater. The wave packets in the LT-OBS records with bandpass filter of 4–8 Hz seem to correlate with the plume emissions (Fig. 3).

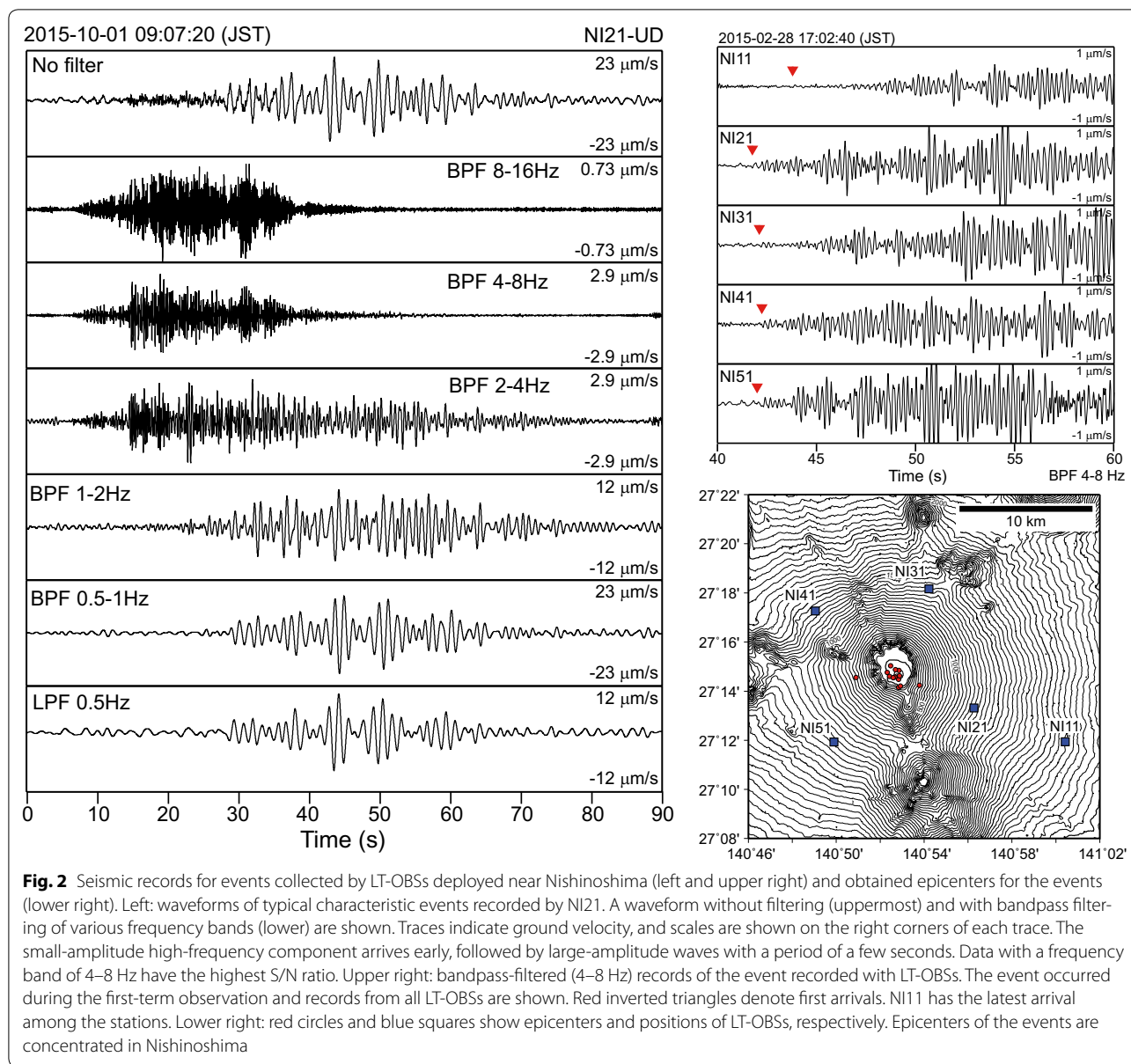
We estimated the number of characteristic events that were considered to be related to plume release using the Short-Term Average (STA)/Long-Term Average (LTA) trigger method. The method was applied to records from more than three LT-OBSs. First, a bandpass filter of 4–8 Hz was applied to all records and we adopted the parameters of the STA/LTA method as follows: 2-s STA window, 40-s LTA window, 1.5 STA/LTA ratio, 3-s trigger duration, 4-s re-trigger time. Events were identified by more than three triggers at the same time, and a continuous trigger was interpreted as one event. We changed the STA/LTA ratio parameter for each observation period due to a change in configuration of the LT-OBS network; all other parameters were identical for all terms. For the first-term observation, STA/LTA ratio was set to 1.5. We detected 363,367 events from February 27, 2015 to October 3, 2015 (the first-term observation). During the second-term observation (from October 4, 2015 to May 5, 2016), 27,544 events were identified. For the second term, we changed the STA/LTA ratio to 2.0. For the third-term observation (from May 5, 2016 to October 20, 2016), 8192 events were detected with an STA/LTA ratio of 1.6. We identified 39,618 events for the fourth-term (from October 19, 2016 to May 26, 2017) using an STA/LTA ratio of 1.6. Figure 4 shows examples of detecting the events using the STA/LTA method. We also calculated the trigger length for each event and measured the

maximum amplitude for 1 h on the vertical component. In addition, visual inspection using the waveform of the OBS records was useful for recognizing seismic activities. We calculated the averaged absolute values of vertical component in the seismograms for time windows of 1 s and plotted all processed data for one LT-OBS for each term. The resulting graphs were examined to confirm events detected using the STA/LTA method.

Results and discussion

The LT-OBSs around Nishinoshima recorded characteristic events, and epicenters of the events were estimated near the Nishinoshima volcano using hypocenter locations. Takagi and Nagaoka (2017) performed short-term seafloor observations using short-period OBSs from June to September 2015. Their OBSs recorded many events with the same characteristics as those events recorded with the LT-OBSs. They located hypocenters of the events using the envelope correlation method (Obara 2002) and reported that almost all hypocenters were positioned under Nishinoshima and depths were estimated to be less than 1.5 km (Takagi and Nagaoka 2017). Based on comparing LT-OBS records with infrasound and visual observations from research ships about 6 km from the crater, the characteristic events corresponded to plume emissions from the crater. From these results, we conclude that characteristic events represent the emission of plumes from the Nishinoshima volcano (explosion). Okada et al. (2016) also estimated that characteristic seismic signals were related to volcanic eruption activity by comparing the occurrence of the characteristic seismic signals and visual observation of eruptions. The events relating to plume emission spanned a wide frequency range. Because the data with a bandpass filter from 4 to 8 Hz had the best signal-to-noise (S/N) ratio (Fig. 2), we detected events using this frequency band and the STA/LTA method. Event detection using the STA/LTA method was compared with the waveform (Fig. 4). A red bar in Fig. 4 means that a detection was triggered; the detection using the STA/LTA method was consistent with the waveform. We counted the number of red bars in 1 day. The number of detected events is believed to represent volcanic activity on Nishinoshima island.

Okada et al. (2016) reported that N-type events were frequently observed by the OBS positioned at Nishinoshima–Minami Knoll. These events were characterized by a slow decrease in amplitude with a monotonic vibration. Because magnitudes of N-type events were estimated to be very small, the N-type, or tornillo events were recorded by only a single OBS. Because our detection of the characteristic event needs to be observed by at least three OBSs simultaneously, there was little possibility of detecting an N-type event.



Under this interpretation, we plot the temporal variation in the accumulated number of detected events per day, average duration of detected events per day, and maximum amplitude of 1-hour records (Fig. 5). The number of events detected using the STA/LTA method is thought to be related to volcanic activities on Nishinoshima because there were few ordinary seismic events, such as local earthquakes. We interpret the temporal change in the number of characteristic events as reflecting the variation in volcanic activity.

From the beginning of our seafloor observations, February 2015, to June 2015, the number of detected events was constant at approximately 1800 per day.

From the middle of July 2015, the detected number rapidly decreased, and duration of events lengthened. The decrease in events was also observed in the short-term OBS observations conducted by JMA from June to September 2015 (Takagi and Nagaoka 2017). The maximum amplitude increased from the beginning of observations to May 2015, and stabilized. The maximum amplitude started to decrease from the end of September 2015. At the end of October 2015, the number was reduced to less than 300 per day. Although the number temporarily increased at the beginning of November, the number of detected events reached less than 100 per day after the end of November. We confirmed that

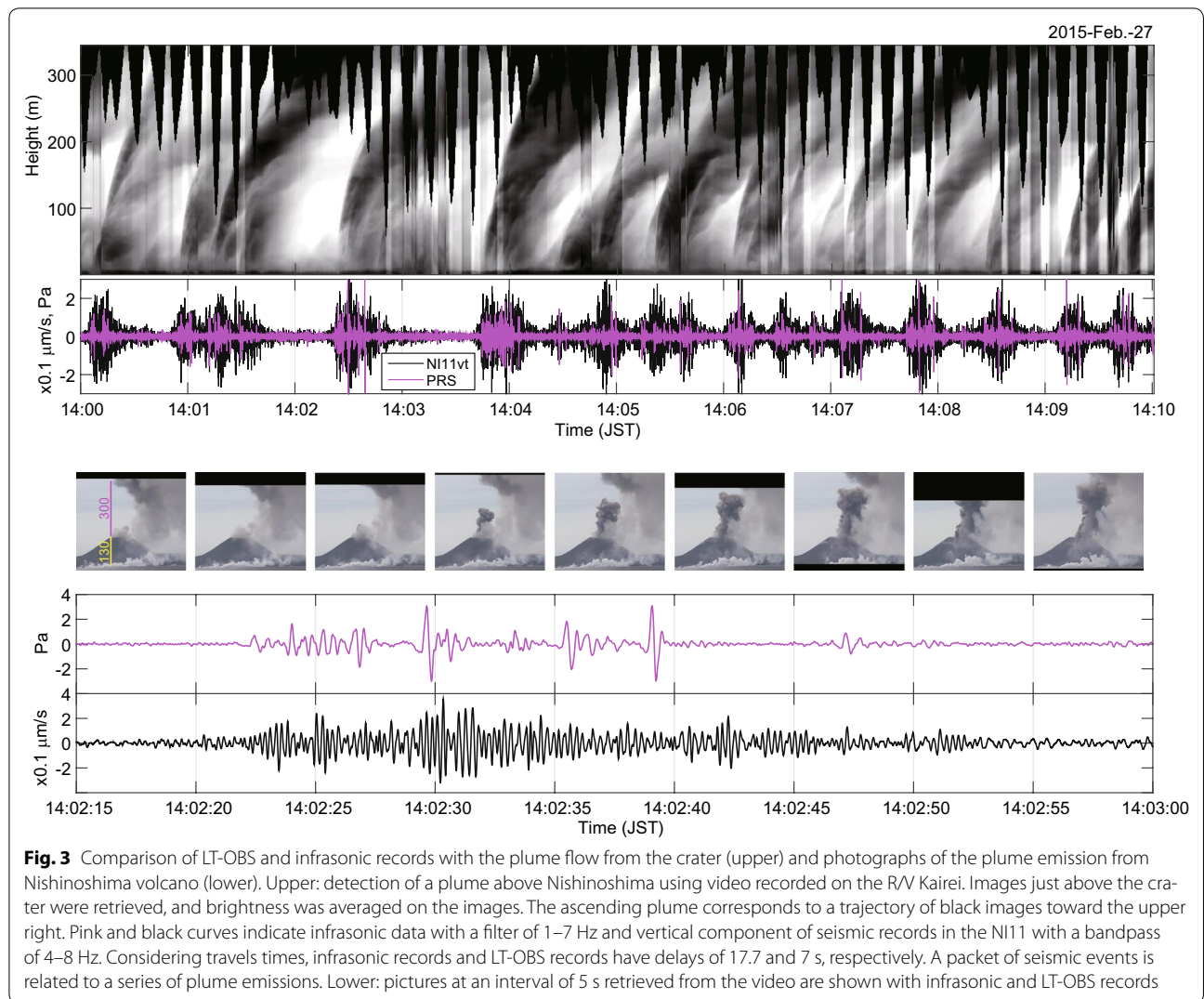
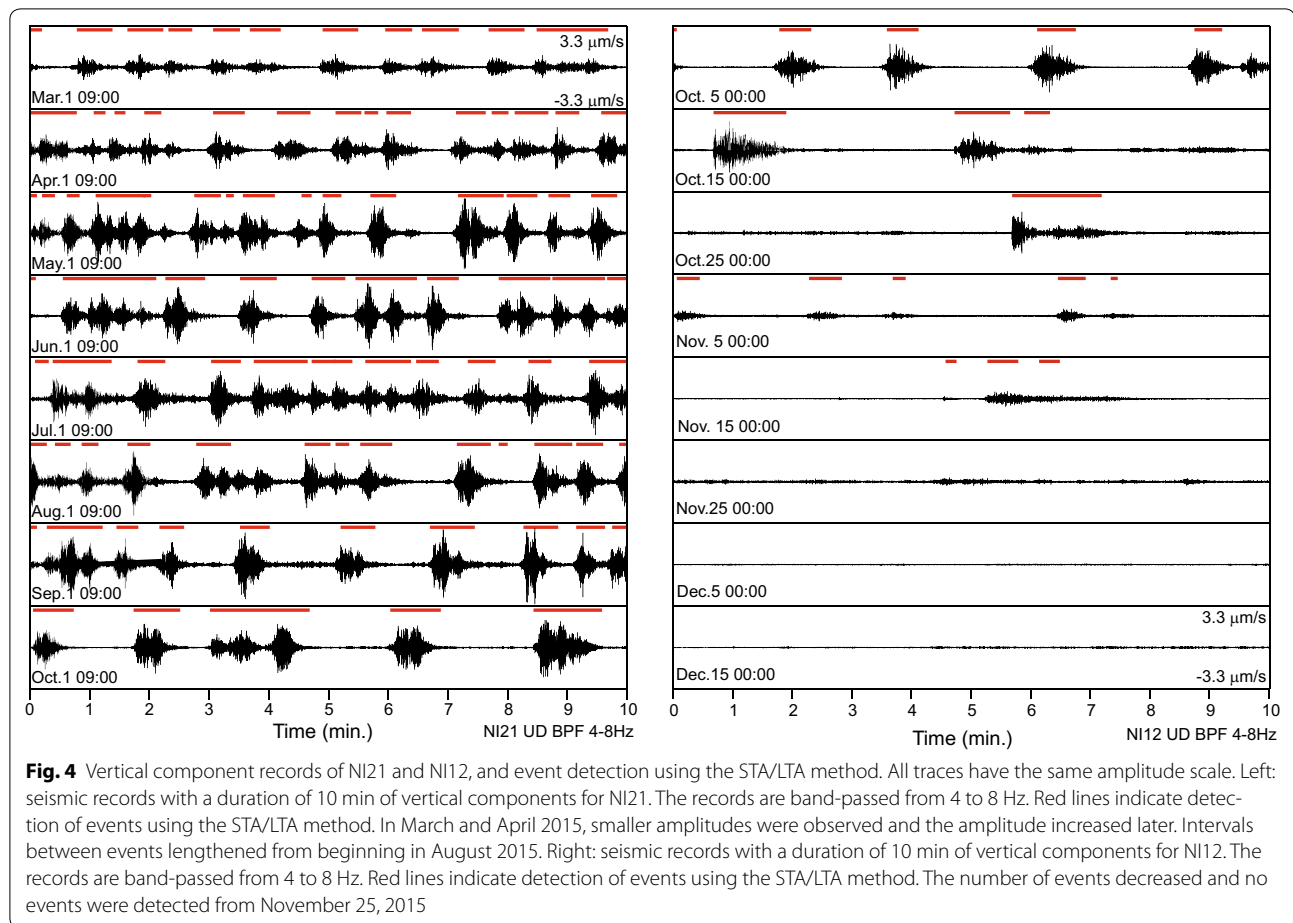


Fig. 3 Comparison of LT-OBS and infrasonic records with the plume flow from the crater (upper) and photographs of the plume emission from Nishinoshima volcano (lower). Upper: detection of a plume above Nishinoshima using video recorded on the R/V Kairei. Images just above the crater were retrieved, and brightness was averaged on the images. The ascending plume corresponds to a trajectory of black images toward the upper right. Pink and black curves indicate infrasonic data with a filter of 1–7 Hz and vertical component of seismic records in the NI11 with a bandpass of 4–8 Hz. Considering travels times, infrasonic records and LT-OBS records have delays of 17.7 and 7 s, respectively. A packet of seismic events is related to a series of plume emissions. Lower: pictures at an interval of 5 s retrieved from the video are shown with infrasonic and LT-OBS records

frequent occurrence of characteristic events caused a temporary increase in the number of detected events by visual inspection of the waveform plots. The maximum amplitude in the 1-hour records decreased from the November 2015, which corresponded to a loss of detection. The surface activity of Nishinoshima volcano was estimated to have declined from the end of July 2015. Aerial observation on November 22, 2015 found that there was no volcanic activity on Nishinoshima. A rapid decrease in the detected events was consistent with the aerial observation. We infer that the volcanic activities on Nishinoshima started to decline from July 2015 and

temporarily increased at the beginning of November 2015. Then the surface activity of Nishinoshima volcano ceased at the end of November 2015.

There was little activity from the middle of November 2015 to April 2017. Aerial observation on April 22, 2017, reported the volcano on Nishinoshima began erupting again. The number of detected events rapidly increased from the middle of April 2017 and reached approximately 1400 events per day. The LT-OBSs recorded many events with the same characteristics as the activity during the 2015 eruption from the end of April 2017. This rapid increase is interpreted to be rapid growth in Nishinoshima



volcano activity, and the May 2017 activity is estimated to correspond to the activity in the summer of 2015.

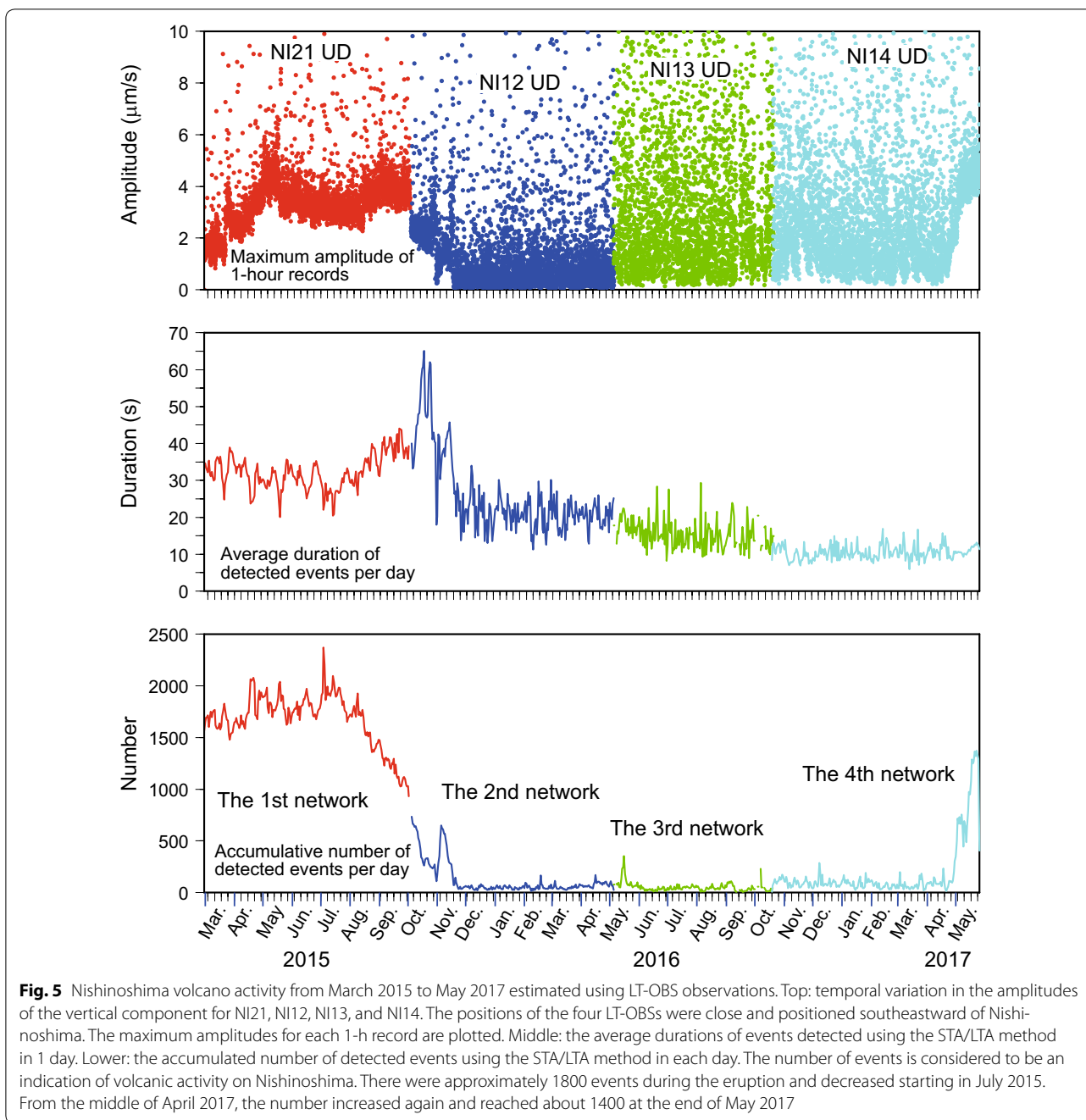
Conclusions

From November 2013, Nishinoshima volcano began erupting and a new island formed. We started seismic observation using LT-OBSs from February 2015 to monitor volcanic activity, and repeated deployments and recoveries to maintain continuous observations. Until May 2017, the observations are repeated four times. All LT-OBSs were deployed near Nishinoshima with distances less than 13 km. The LT-OBSs frequently recorded characteristic events from the beginning of the observation.

High-frequency components of a few Hz dominated in the early part of events, followed by large-amplitude waves with a period of a few seconds. Event durations were < 1 min on a band of 4–8 Hz. We located

hypocenters of these events using the first arrival times, and epicenters were located close to the crater. In February 2015, infrasound and video observations were performed by the R/V Kairei. Comparing the events recorded by a LT-OBS deployed during the infrasound observation period with infrasound data (1–7 Hz) and pictures of the crater, the events in the LT-OBS records are considered to correlate with plume emissions.

We counted the number of the events using the STA/LTA method in records from more than three LT-OBSs. All records for the method were bandpass-filtered from 4 to 8 Hz. Parameters used in the STA/LTA method were the same for each observation period except the STA/LTA ratio. We detected 363,367 events from February 27, 2015 to October 3, 2015. In the second observation period, 27,544 events were identified. The number of detected events reached approximately 1800 per day in July 2015. The detected number began to decrease from



July 2015, and the duration of events lengthened. In November 2015, the number reached < 100 per day. In November 2015, the surface activity for Nishinoshima volcano began a dormancy period that lasted until characteristic events began occurring in mid-April 2017. The number of events reached approximately 1400 events per day at the end of May 2017. Sea floor seismic observations of activity in May 2017 are in agreement with those

from the summer of 2015. In summary, seafloor seismic observations using OBSs are useful for continuously monitoring volcanic activity on a remote island.

Additional file

Additional file 1. Detection, location of characteristic events and comparison with aerial observations.

Abbreviations

GPS: global positioning system; JAMSTEC: Japan Agency for Marine-Earth Science and Technology; JCG: Japan Coast Guard; JMA: Japan Meteorological Agency; LT-OBS: long-term ocean bottom seismometer; OBS: ocean bottom seismometer; R/V: research vessel; STA/LTA: short-term average/long-term average; S/V: survey vessel.

Authors' contributions

MS played a leading role in this study, performed observations, data processing and analysis, and completed the manuscript. MI and SS identified a relationship between the event and eruption using visual observations and event location. MI, TY, MT, HS, YN, AT, TM, TO, and AN contributed the repeat observations using LT-OBSs around Nishinoshima. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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