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Research paper

Constraints on the source mechanism of harmonic tremors based on seismological, ground deformation, and visual observations at Sakurajima volcano, Japan

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Abstract

Vulcanian-type eruptive activity has occurred from the summit crater of Sakurajima volcano, Japan, since 1955. Over this period, harmonic tremors have commonly occurred either several hours after swarms of B-type earthquakes (herein termed HTB: Harmonic Tremor following B-type earthquake swarm) or immediately after explosive eruptions (herein termed HTE: Harmonic Tremor after an Eruption). In this study, we analyzed the spectra and particle motions of HTBs and HTEs. Both HTBs and HTEs have spectra with peaks at fundamental frequencies and higher frequencies that are integer multiples of the fundamental frequencies. The peak frequencies of HTBs remained within a certain range, whereas those of HTEs showed a gradual increase. The spectra of an HTB that occurred on 20 July 1990 had stable fundamental frequencies of 1.46–1.66 Hz and at least 9 peaks of higher modes; in contrast, the HTE that occurred 3 minutes after an explosive eruption at 11 h 15 m (JST) on 11 October 2002 showed clear frequency gliding from 0.8 to 3.7 Hz in the fundamental mode. The peak frequencies of higher modes of the HTE also showed an increase corresponding to the shift of the fundamental mode towards a higher frequency. Particle motion analysis mainly identified Rayleigh waves from the prograde elliptical motion at the deepest borehole station (HAR) and retrograde motions at the other shallower stations. Love waves were dominant at the stations north and south of the crater. The distribution patterns of Rayleigh and Love waves of HTBs are similar to those of HTEs. The nature of the dominant surface waves of both HTBs and HTEs suggest that the sources of harmonic tremors are located at a shallow depth, corresponding to a gas pocket in the uppermost part of the volcanic conduit. Differences in the temporal characteristics of the HTB and HTE spectra reflect the internal condition of the gas pocket: HTBs are associated with inflation of the conduit, whereas HTEs occur following an eruption, associated with deflationary ground deformation. HTBs are caused by resonance of the gas pocket embedded beneath the lava dome. Although HTEs occur within the open conduit, the small size of vents enables resonance within the bubbly magma conduit. The positive gliding of dominant peaks toward higher frequencies is interpreted to result from shortening of the bubbly magma conduit due to a rise in the bubble nucleation level; this rise results from the re-pressurization that accompanies the ascent of magma from deep within the reservoir.

Keywords: harmonic tremor; Sakurajima volcano; frequency gliding; particle motion; surface waves

1. Introduction

Harmonic tremors have been observed at a number of volcanoes with long-term eruptive activity, including Sakurajima in Japan, Langila in Papua New Guinea, Arenal in Costa Rica, Mt. Erebus in Antarctica, Lascar in Chile, and Mt. Semeru in Indonesia. Harmonic tremors are characterized by spectral peaks with a regular frequency interval, composed of a fundamental frequency and its overtones. Temporal changes in the fundamental frequency have been recognized at several volcanoes. For example, the fundamental frequency of a harmonic tremor that occurred on 24 February 1975 at Sakurajima volcano increased gradually from 0.5 to 1.3 Hz over a period of 12 minutes (Kamo et al., 1977). Similar increases have been reported from Langila volcano (from 1 to 1.6 Hz; Mori et al.,

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1989) and Arenal volcano (from 1.9 to 3.2 Hz; Benoit and McNutt, 1997; and from 0.5 to 3.2 Hz; Hagerty et al., 2000). In contrast, decreases have been reported from Mt. Erebus volcano in May 1998 (from 3 to 1 Hz over a period of ~10 minutes), and gliding or stepped decreases at Arenal volcano (Lesage et al., 2006). In addition to increasing and decreasing trends, it is sometimes observed that the fundamental frequency of harmonic tremors fluctuates within a certain range. For example, the fundamental frequency of the harmonic tremor at Sakurajima on 23 June 1975 fluctuated in the range of 0.9–1.8 Hz for 16 hours (Kamo et al., 1977). Fluctuations have also been recorded in the range of 0.5–1.7 Hz at Mt. Semeru (Schlindwein et al., 1995) and 0.55–0.70 Hz at Lascar volcano (Hellweg, 1999).

Previous studies have analyzed the particle motions of harmonic tremors in estimating wave types. The dominant directions of particle motions occur in both the longitudinal and transverse directions within the crater of Sakurajima volcano (Nagamune, 1975). Furthermore, Kamo et al. (1977) reported that polarization patterns differ among different modes and that simple wave types could not be determined due to the variety of vibration patterns. A similar variety of particle motions has been observed at Lascar volcano, where the particle motion of the harmonic tremors could not be interpreted as a simple wave type (P, SV, SH or Rayleigh waves) in fundamental mode and its overtones (Hellweg, 1999).

Although Benoit and McNutt (1997) demonstrated that the S-wave was included in the harmonic tremor recorded at Arenal volcano on 25 April 1994 (based on the linearity of the wave and its polarization direction of particle motion), Hagerty et al. (2000) reported that the particle motion is elliptical rather than being consistently composed of a simple wave type. The inconsistent nature of particle motion patterns among different stations, as well as temporal changes in the patterns and differences among modes, mean that previous analyses of the particle motion of harmonic tremors failed to identify simple wave types.

Models of the source mechanisms for harmonic tremors have been proposed based on analyses of the tremors themselves. The spectral characteristics of a harmonic tremor recorded at Mt. Semeru reflected the repeated triggering of sources (Schlindwein et al., 1995). Benoit and McNutt (1997) proposed a source model of the resonance of a 1D vertical conduit for a harmonic tremor recorded at Arenal volcano, while Hellweg (2000) proposed three physical source models (eddy shedding, slug flow, and soda bottle) and discussed the relationships among fundamental frequency, power spectrum, and fluid dynamics variables such as conduit size, kinematic viscosity of the fluid, and flow velocity.

Most of the models described above are largely based on spectral characteristics: little consideration has been given to the characteristics of particle motion. In addition, most of the previous studies on harmonic tremors obtained seismograms from temporary observations or analyzed short-term sections of long-period activity. The characteristics of harmonic tremors have yet to be related to volcanic activity.

Sakurajima volcano has erupted continuously from the summit crater of Minamidake since 1955; more than 7800 vulcanian explosions occurred between 1955 and the end of 2006. In terms of the time sequence of seismicity preceding eruptive activity, A-type earthquakes occur first, followed by swarms of B-type earthquakes several days before an increase in

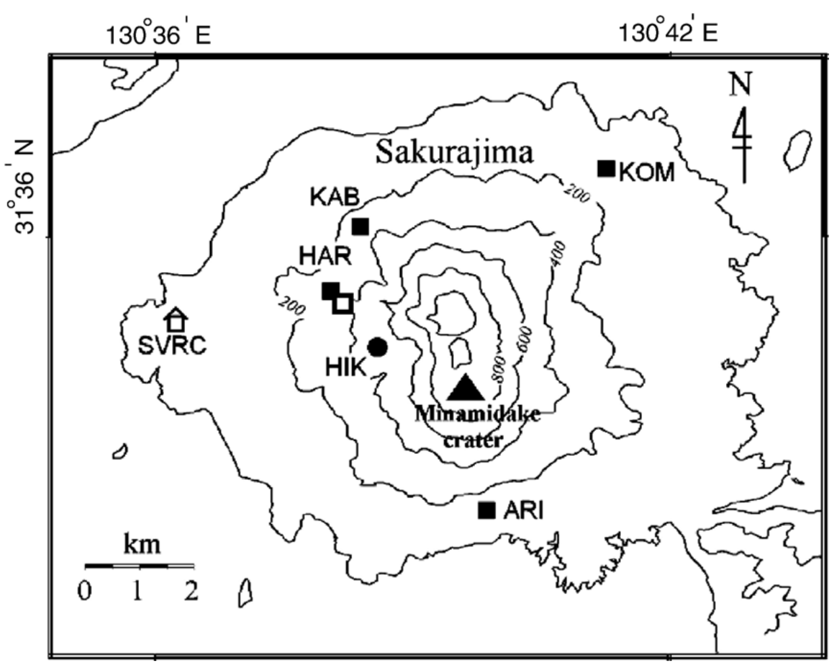

Fig. 1. Locations of the seismic stations used in this study. Solid squares and circle denote boreholes and a ground-based seismometer, respectively. The triangle indicates the location of the summit crater of Minamidake, and the open square indicates the underground tunnel in which the water-tube tiltmeters and extensometers are installed. SVRC: Sakurajima Volcano Research Center, from where seismic records are registered.