Report 4

Seismic signature of fluid motion in a shallow conduit system beneath Aso volcano, Japan

Mare Yamamoto, Hitoshi Kawakatsu
Earthquake Research Institute, University of Tokyo, Tokyo, Japan

Satoshi Kaneshima, Noriaki Takagi
Department of Earth and Planetary Sciences Kyushu University, Fukuoka, Japan

Yasuaki Sudo
Aso Volcanological Laboratory, Kyoto University, Kumamoto,Japan

From temporary deployments of seismic arrays and a dense seismic network at Aso volcano, Japan, we determine the location and the source mechanism of short-period (0.5-1 sec) tremors which often occur in synchronization with long-period (15 sec) tremors. The source of the short-period tremors are located at the top part of a crack-like conduit which generates the long-period tremors, and the result of moment tensor inversions indicates a cylindrical deformation at the source. We thus attribute these short-period tremors to the flow induced vibration at a junction between a deep crack-like conduit and a shallow cylindrical conduit. Our results suggest these two phenomena at different frequency bands are generated by a fluid motion in a single conduit system.

1. Introduction

Aso volcano is one of the most active volcanoes in Japan, and located in central Kyushu (Figure 1). The volcano consists of a large elliptical caldera and several central cones. It erupts in Strombolian style repeatedly with intervals of 5-10 years, and recent activities take place at the youngest central cone named Naka-dake, which is composed of seven craters aligned in the northwest-southeast direction. The last magmatic activities occurred in the beginning of 1990s at the first crater located at the northernmost of the chain of craters, and after that its surface activities has been restricted to the continuous fumarolic activities at the crater.

At Aso volcano, various types of volcanic tremors have been observed after the pioneering work by *Sassa* [1935]. These tremors include the long period tremors (LPTs) with a period of 15 sec and the short period tremors (SPTs) with a period of 0.5-1.0 sec [e.g., *Kawakatsu et al.*, 2000]. Although it has long been reported that these tremors often occur in synchronization with each other [e.g., *Sassa*, 1935; *Kikuchi*, 1974; *Churei*, 1985], the relationship between these tremors has not been well understood.

In this paper, to obtain more detailed image of SPTs and to understand the relationship between tremors, we study the source location and the source mechanism of SPTs. We first locate the source of SPTs using data obtained by short period array observations, and then determine the source mechanism using data obtained by a dense short period seismic network.

2. Seismic observations

To constrain the source of SPTs, in November, 1999, we deployed two seismic arrays at west and north of the first crater of Naka-dake (Figure 1: hereafter called West array and North array, respectively). Each array was set at a distance of about 700 m from the first crater, and consisted of 29 stations deployed along concentric semicircles. Respective aperture of arrays was 160 m for the West array and 200 m for the North array. Stations at the center and on the outermost semicircle of each array were equipped with Lennartz LE-3D three component velocity seismometers with a natural period of 1 sec, and all other stations were equipped with Mark Products L-22D vertical component velocity seismometers with a natural period of 0.5 sec. At each of the stations, output from the seismometer was recorded by DataMark LS8000SH data logger with a sampling rate of 100 Hz. The position of each station was determined using the quick static GPS, and relative station position was measured precisely enough for the subsequent analyses. The clock of each data logger was locked with GPS timing signals, and kept enough accuracy throughout the observation. We conducted the array observation in three nights from November 24 to 26 to avoid human noises, and obtained record of total length of 33 hours. Detail of the array observations is also described in *Takagi et al.* [2006] in which the nature of high frequency tremors (3-10 Hz) is studied by these array observations.

In addition to data from the array observation, we also use data from the ASO98 experiment (*Sudo et al.*, 2002). The ASO98 experiment was a controlled-source seismic experiment conducted in November, 1998, where total of 296 temporary seismic stations were deployed around the central cones of Aso volcano. Most of the stations were equipped with the same seismometer and the data logger as used in our array observation in 1999. Although the main scope of the ASO98 experiment was to constrain the subsurface structure of the volcano, SPTs were also clearly recorded at more than 70 stations within about 1 km from the first crater.

3. Short-period (0.5-1 sec) tremor

Figure 2 shows an example of 20-minute-long seismogram at the center of the North array and enlarged view of SPTs. As shown in the figure, on the observed raw seismogram, high frequency (3-10 Hz) continuous tremors dominate, and SPTs occur intermittently with an interval of a few minutes. These SPTs are accompanied by LPTs observed in the broadband record, and each SPT consists of a decaying signal with a period of around 0.5 sec which lasts for a few cycles. Such characteristics of SPTs are common between events, and the similarity of waveforms is still high even before-and-after a one-year-long interval as seen in the figure. This fact seems to suggest a non-destructive process as the source of SPTs.

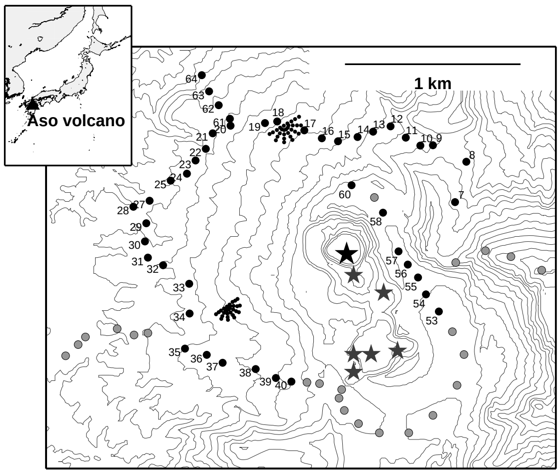

Figure 1. Aso volcano is located in central Kyushu, Japan, and one of the central cones Naka-dake is composed of seven craters (starts) aligned in the NW-SE direction. We deployed two semi-circular short period seismic arrays represented by dots at north and west flank of Naka-dake in 1999. A part of the ASO98 network is shown as black and dark circles, and we use stations in black in our inversion of source mechanism of SPTs.

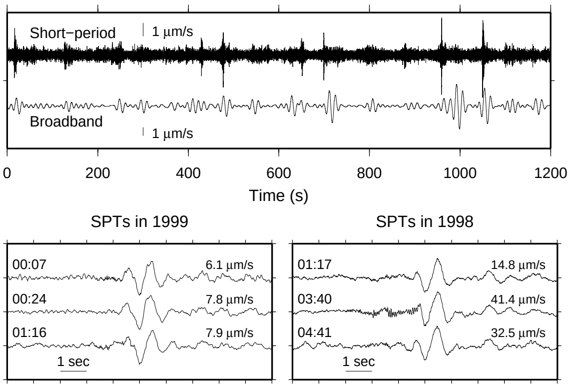

Figure 2. Top panel shows a 20-minute-long seismogram starting at 04:00 on November 27, 1999 observed at the center of the North array and bandpass filtered (0.03-0.1 Hz) seismogram observed at a broadband station close to station 36 in Figure 1. These two traces show frequent occurrence of SPTs appeared as spikes in the short-period record, and simultaneous occurrence of SPTs with LPTs appeared in the broadband record. Bottom two panels show examples of SPTs observed in 1999 and 1998. Waveforms of SPTs show high similarity between events.

3.1 Source location

To locate the source of SPTs, we use the semblance method [*Neidell and Taner*, 1971]. Since the distances between a roughly estimated hypocenter and each array are several times larger than the aperture of the array, the effects of the curvature of a wave front is not so significant [e.g., *Almendros et al.*, 1999]. We thus first constrain the epicenter of SPTs under the assumption of plane wave propagation, and then refine the estimation of location including depth assuming spherical wave propagation. We set a three-dimensional grid of size of 50×50×100 m around the epicentral region estimated by the plane wave analyses within the depth range of -100 to 1500 m from the ground surface, and compute semblance values for all the pseudo-sources on the grid assuming a spherical wave in a homogeneous isotropic medium. We use medium velocity of 1.0-3.5 km/sec, and compute the propagation delay for every velocity step of 0.01 km/sec. After a computing semblance for each array, we determine the source location by averaging the semblance values obtained from the two arrays.

Figure 3 shows the result of the analysis. The source is located a few hundred meters southwest of the first crater and at a depth of about 600 m. Although the resolution of depth is not high partly due to the relatively small aperture of the arrays, the estimated source region is almost consistent with the top of the crack-like conduit detected as the source of LPTs [*Yamamoto et al.*, 1999].

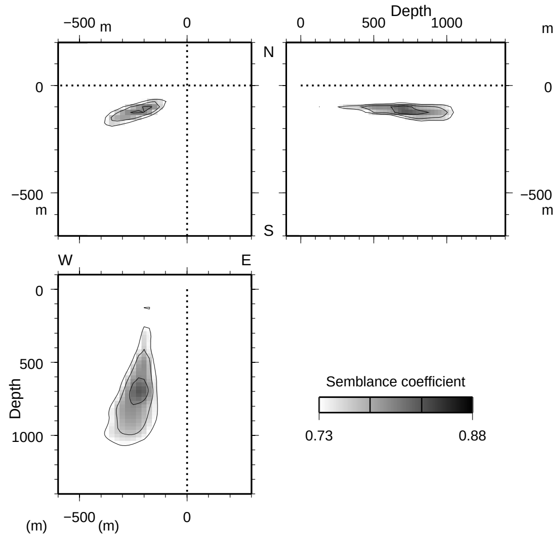

Figure 3. Three panels show the projection of the distribution of averaged semblance coefficients on NS-EW, NS-Depth, EW-Depth planes. Semblance coefficients are represented as the darkness of the shade, and grids with semblance coefficient larger than 0.73 are plotted with contour lines of every 0.05. The coordinate origin in the figure corresponds to the horizontal location of the first crater and the elevation of the center of the West array.

3.1 Source mechanism

To further understand the physical process and the nature of SPTs, we next analyze the source mechanism of SPTs using a point source inversion method. In the analysis, we use data from the ASO98 experiment, and determine the mechanism of SPTs with consideration of independent source time functions for moment tensor components and the effect of topography.

We use the linear inversion method of *Ohminato et al.* [1998], and determine the source time function for each component of the moment tensor such that the variance reduction between observed and synthesized bandpass filtered (0.33-5 Hz) velocity seismograms is maximized.

Green's functions used in the inversion are computed by the finite difference method of *Ohminato and Chouet* [1997]. We use the digital elevation map published by Geographical Survey Institute of Japan, and the topography of Aso volcano is approximated by a staircase composed of cubic cells with a size of 10 m. The velocity structure inside the volcano is assumed to be one-dimensional with depth, and we use a linear velocity gradient of 2 km/s per 1 km based on the result of *Tsutsui et al.* [2003].

Since the number of stations is large enough and the azimuthal coverage around the source is sufficient, we randomly select 30 stations with good signal quality from the stations surrounding the crater, and perform inversions using several different data sets. Based on the fact that the coherence of waveforms recorded in 1998 and 1999 are fairly high, in the following analyses, we assume the source location of SPTs is not changed during this period, and use the epicenter of SPTs obtained by the array analysis and a depth of 600 m from the ground surface.

Figure 4 shows the results of inversions for three different data sets of a SPT at 01:17, November 26. The results of the inversions are stable and consistent each other except slight difference in the later parts. Fitting of the observed and synthetic waveforms is also shown in the figure for the data set #1. In each solution, the diagonal components of the moment tensor clearly dominate, and the off-diagonal components that slightly precede diagonal components are also resolved.

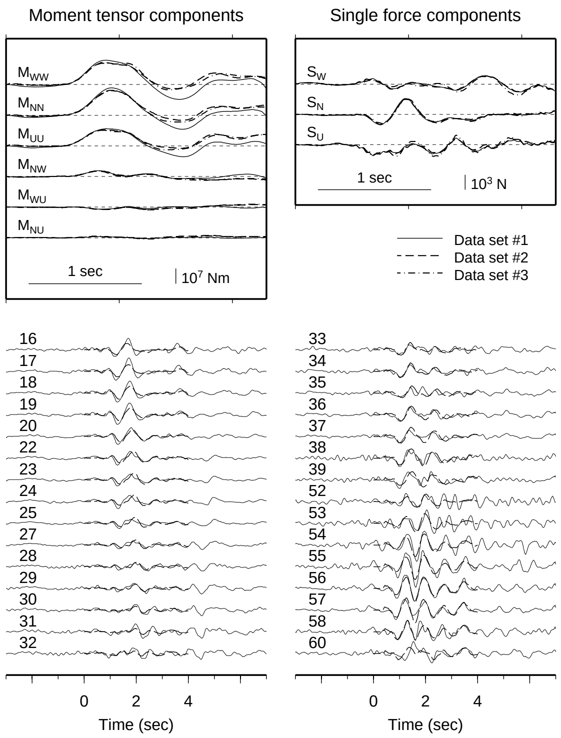

Figure 4. Top panel shows results of moment tensor inversions of a SPT on 01:17, November 26. Inversions using three different data sets show consistent results, and the results suggest that the source mechanism of SPTs consists of a radial deformation and a slight shear faulting. Bottom panel shows the waveform match between observed (solid lines) and synthesized (dashed lines) waveforms. Synthetic waveforms are calculated using the inversion result for the data set #1.

4. Discussion

The ratio of three eigenvalues of the obtained moment tensor is about 2:2:1 with a minimum value corresponding to the eigenvector pointing to the nearly vertical direction. Thus the volumetric component in the moment tensor may represent a radial deformation of the sidewall of a nearly vertical cylindrical source. This kind of source mechanism has been also observed at other volcanoes and it is interpreted as an expansion and/or contraction of volcanic conduits. The moment of the volumetric component is about $(2, 2, 1) \times 10^7\,\mathrm{Nm}$ from our inversions, and it corresponds to a volumetric change of $4.8 \times 10^{-3}\,\mathrm{m}^3$ assuming Lame's constants of $\lambda = \mu = 4.2 \times 10^9\,\mathrm{Nm}$. Here we use an expression of the moment tensor for an infinite cylindrical source whose eigen values are $\Delta V \cdot (\lambda + \mu, \lambda + \mu, \lambda)$ [e.g., *Fukuyama and Takeo*, 1990] where ΔV is the volume change of the unconfined volume [e.g., *Kawakatsu and Yamamoto*, 2007]. The amount of the volumetric change is fairly small, and the result may suggest SPTs are generated by an influx of fluid pressure and fluid itself with small bulk modulus into the cylindrical source region.

P and T axes of the shear fault component suggest a dislocation on a fault trending north-south or east-west. Considering the existence of a crack-like conduit aligned along the chain of the craters and the stress field around Aso volcano, it may be natural that the shear dislocation occurs in north-south direction.

Single force components are also involved in obtained solutions. However, the contribution of the single forces is relatively small, since the calculated Green's functions show that the surface motion due to a single force of $10^3\,\mathrm{N}$ is about one order smaller than the one due to a moment tensor component of $10^7\,\mathrm{Nm}$. Such small amplitude of single force components may be below the resolution limit of our inversion. However, numerical tests indicate that the single force components are resolvable from our data, and thus the weak single forces seem to reflect a real property of the source mechanism of SPTs. This fact may suggest that the fluid in the source region has relatively low viscosity and the exchange of linear momentum between the source volume and the Earth through the viscous drag force is not so effective.

Figure 5 schematically illustrates a conceptual model we have constructed for the SPT source and the volcanic conduit system beneath Aso volcano from the results of geophysical observations: There exists a conduit system of a magma chamber, a reflector void, and a crack-like conduit (LPT source) beneath the volcano [*Sudo and Kong*, 2001; *Tsutsui and Sudo*, 2004; *Yamamoto et al.*, 1999] that transports gases and heat from the deep part to the surface. At a depth of about 600 m, the crack-like conduit narrows down to a cylindrical conduit extending toward active fumaroles at the ground surface. In this conduit system, the continuous flow of gases exists. The flow may cause some flow instabilities, such as the density wave oscillation [e.g., *Iwamura and Kaneshima*, 2005], and the resultant pressure perturbation in the crack-like conduit excites the vibration of the entire crack-like conduit which is observed as LPTs. The resonant oscillation of the crack and the accompanied fluid motion may build up a pressure excess at the top of the crack-like conduit, and cause the outward opening of the cylindrical conduit which generates a vibration observed as a SPT.

The results of this study suggest that tremors with different frequency bands that have been separately studied are driven by fluid dynamics in a single conduit system. Further quantitative study including the simulation of the triggering mechanism of LPTs may reveal the behavior of the total system beneath the active volcano, and shed new light on the transport system beneath volcanoes.

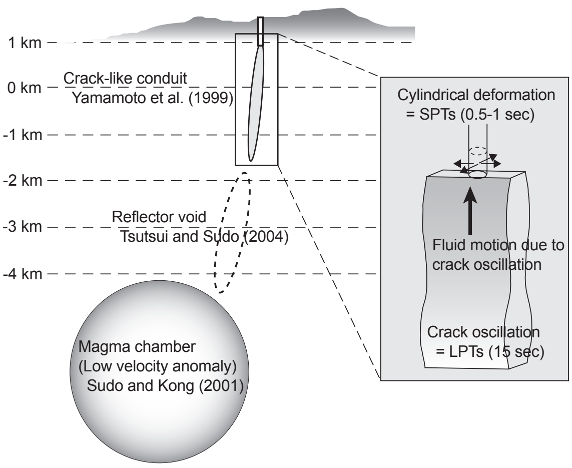

Figure 5. A conceptual model for SPTs source and the volcanic conduit system beneath Aso volcano. Reflector voids and a crack-like conduit compose an open-conduit system from a postulated magma chamber to the surface crater. Coupled fluid motions in the conduit system generate both SPTs and LPTs.

Acknowledgments

We are grateful to T. Ohminato, M. Kato, A. Okabe, T. Nakajima, J. Oikawa, and M. Sako for their support in the field.

References

Almendros, J., J. M. Ibanez, G. Alguacil, and E. Del Pezzo (1999), Array analysis using circular-wave-front geometry: an application to locate the nearby seismo-volcanic source, *Geophys. J. Int.*, *136*(1), 159–170, doi: 10.1046/j.1365-246X.1999.00699.x.

Churei, M. (1985), Particle motion properties and amplitude-frequency distribution of volcanic long-period tremors of Aso volcano, Kyushu, *Bull. Volcanol. Soc. Jpn.*, *30*, 71–80.

Fukuyama, E., and M. Takeo (1990), Analysis of the near-field seismogram observed during the eruption of Izu-Oshima volcano on November 16, 1987 (in Japanese), *Bull. Volcanol. Soc. Jpn.*, *35*, 283–297.

Iwamura, K., and S. Kaneshima (2005), Numerical simulation of the steam-water flow instability as a mechanism of long-period ground vibrations at geothermal areas, *Geophys. J. Int.*, *163*(2), 833–851, doi:10.1111/j.1365-246X.2005.02749.x.

Kawakatsu, H., and M. Yamamoto (2007), Volcano Seismology, in *Treatise on Geophysics*, vol. 4, edited by H. Kanamori, Elsevier.

Kawakatsu, H., S. Kaneshima, H. Matsubayashi, T. Ohminato, Y. Sudo, T. Tsutsui, K. Uhira, H. Yamasato, H. Ito, and D. Legrand (2000), Aso94: Aso seismic observation with broadband instruments, *J. Volcanol. Geotherm. Res.*, *101*(1-2), 129–154, doi:10.1016/S0377-0273(00)00166-9.

Kikuchi, S. (1974), On the long-period volcanic micro-tremors observed at Mt. Aso, *Bull. Disaster Prev. Res. Inst., Kyoto Univ.*, *17B*, 29–47.

Neidell, N. S., and M. T. Taner (1971), Semblance and other coherency measures for multichannel data, *Geophysics*, *36*(3), 482–497, doi: 10.1190/1.1440186.

Ohminato, T., and B. A. Chouet (1997), A free-surface boundary condition for including 3D topography in the finite-difference method, *Bull. Seismol. Soc. Am.*, *87*(2), 494–515.

Ohminato, T., B. A. Chouet, P. Dawson, and S. Kedar (1998), Waveform inversion of very long period impulsive signals associated with magmatic injection beneath Kilauea volcano, Hawaii, *J. Geophys. Res.*, *103*(B10), 23,839–23,862.

Sassa, K. (1935), Volcanic micro-tremors and eruption-earthquakes (part 1 of the geophysical studies on the volcano Aso), *Mem. Coll. Sci. Kyoto Univ.*, *18*, 255–293.

Sudo, Y., et al. (2002), Seismic exploration, ASO98, in Aso volcano (in Japanese), *Bull. Earthq. Res. Inst., Univ. Tokyo*, *77*, 303–36.

Sudo, Y., and L. S. L. Kong (2001), Three-dimensional seismic velocity structure beneath Aso volcano, Kyushu, Japan, *Bull. Volcanol.*, *63*(5), 326–344, doi:10.1007/s004450100145.

Takagi, N., S. Kaneshima, H. Kawakatsu, M. Yamamoto, Y. Sudo, T. Okura, S. Yoshikawa, and T. Mori (2006), Apparent migration of tremor source synchronized with the change in the tremor amplitude observed at Aso volcano, Japan, *J. Volcanol. Geotherm. Res.*, *154*(3-4), 181–200, doi:10.1016/j.jvolgeores.2006.02.001.

Tsutsui, T., and Y. Sudo (2004), Seismic reflectors beneath the central cones of Aso volcano, Kyushu, Japan, *J. Volcanol. Geotherm. Res.*, *131*(1-2), 33–58, doi:10.1016/S0377-0273(03)00315-9.

Tsutsui, T. et al. (2003), 3-D seismic velocity structure beneath the edifice of central cones of Aso volcano (in Japanese), *Bull. Volcanol. Soc. Jpn.*, *48*(3), 293–307.

Yamamoto, M., H. Kawakatsu, S. Kaneshima, T. Mori, T. Tsutsui, Y. Sudo, and Y. Morita (1999), Detection of a crack-like conduit beneath the active crater at Aso volcano, Japan, *Geophys. Res. Lett.*, *26*(24), 3677–3680, doi: 10.1029/1999GL005395.