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Pressure Waves derived from Eruption Movie Images of Sakurajima Volcano

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Synopsis

We analyzed some eruption movies of Sakurajima and Suwanosejima volcanoes. Propagation of pressure waves produced by these eruptions were clearly recognized as changes in luminance using an image processing of movies, even for the case that we could not see them by bear eyes. The apparent speeds of propagation were around 340-570 m/s at Sakurajima. Furthermore, information on wavelengths of pressure waves has been investigated quantitatively to estimate the source conditions of volcanic explosions; such as time-spatial dimension of the waves.

Keywords: Sakurajima volcano, image processing, Vulcanian explosion, visualized pressure wave

1. Introduction

It is known that atmospheric pressure waves are produced by volcanic eruptions. In last decades, these waves have been observed around volcanoes using low frequency microphones all over the world. Results of the observations were attributed to identification of eruptive or non-eruptive activities, as well as to determination of accurate locations of eruptive vents (Okada et al., 1990; Ripepe and Marchetti, 2002). Other successes of understanding source processes of eruptive mechanisms or dynamics were inferred from a theoretical point of view (Buckingham and Garcés, 1996; Vergniolle and Brandeis, 1996).

Propagation of these pressure waves, in particular shock waves, excited by explosive eruptions have been occasionally visualized as “flashing arc” (Perret, 1912) or as the disappearance of pre-existing clouds and/or the formation of cloud (Nairn, 1976; Ishihara, 1985; Yokoo et al., 2004). Perret (1912) interpreted flashing arc as the change of the refractive index of the air. In contrast, others interpreted that these phenomena were induced by the phase change of H_2O due to compression phase of shock waves and following rarefaction phase.

Velocities of their propagation were estimated to be ~600 m/s based on the shape of the condensation cloud at Ngauruhoe (Nairn, 1976), and to be 300-440 m/s for the clouds spreading out with time at Izu-Oshima (Yokoo et al., 2004). On the other hands, Ishihara (1985) estimated them 440-550 m/s to trace the disappearance position of the clouds at Sakurajima.

Besides, Yokoo and Taniguchi (2004) developed a method to detect pressure waves from eruption movies using image processing. As a result, they succeeded to visualize pressure waves within the ash-laden plume at Aso volcano, though the phenomenon was too weak to be recognized directly by bear eyes.

For confirmation of usefulness of their method, we analyzed some eruption movies of Sakurajima and Suwanosejima volcanoes. In this paper, we mainly describe the results of Sakurajima; both of estimated apparent velocities to propagate and spatial dimensions of atmospheric pressure waves. And then, we presume source information of the volcanic explosion. In addition, for the case of weak eruption, the result of a Suwanosejima eruption is also reported in Appendix.

2. Eruption Movies of Sakurajima

Table 1 Characters of pressure waves determined from the movie images

No.	Date & Time	P^a [Pa]	$V_{pw}{}^b$ [m/s]	$v_{comp}{}^b$ [m/s]	$v_{rare}{}^b$ [m/s]	$\lambda_{comp}{}^c$ [m]	$\lambda_{rare}{}^c$ [m]
A05	1982/05/23 11:28	140			574 (±21)		>280
A09	1982/06/07 11:26	90	342 (±28)	354 (±20)		150	
A23	1982/12/15 11:25	110	459 (±22)	441 (±12)	464 (±14)	175	>390
A83	1987/12/08 10:40	320			514 (±14)		>210
A98	1988/01/07 18:15	230			364 (± 7)		250

[a] Amplitude of pressure wave recorded at HAR, 2.7 km apart from the summit crater.

[b] Propagation speed of pressure wave (V_{pw}) and that of compression and rarefaction phase of the wave (v_{comp}, v_{rare}).

[c] Lengths of compression and rarefaction phases of pressure wave

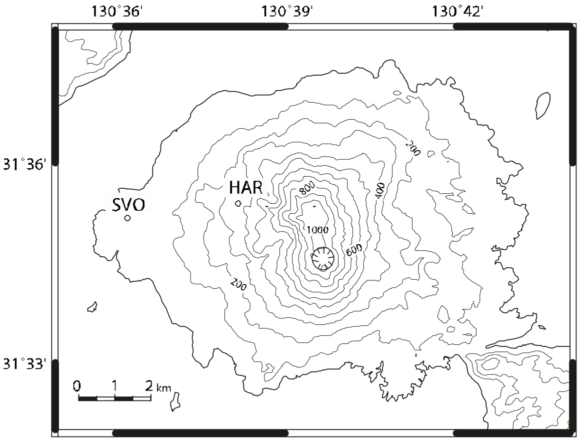

Fig. 1 Index map of Sakurajima. A TV camera and a microbarograph were installed at SVO and HAR, respectively.

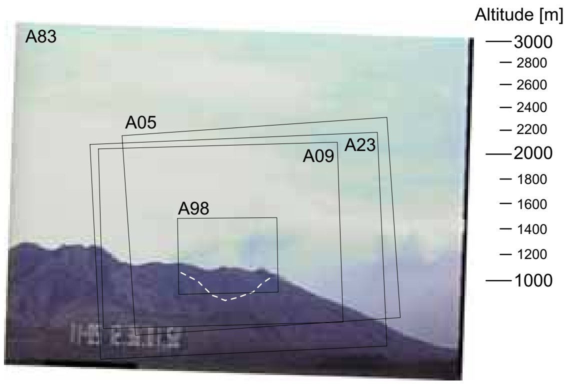

Fig. 2 Field-of-views of the movies for each eruption listed in Table 1. A white dashed line indicates the profile of the crater.

volcano

Sakurajima volcano located at southern Kyushu has erupted more than 8000 times since 1955 at a summit crater (Fig. 1). The eruption type of Sakurajima is called a Vulcanian explosion. A mechanism of this type of explosion is proposed as a bursting of a gas pocket just beneath the crater (Tameguri et al., 2002). At the time of bursting, a strong air-shock is emitted from the crater. An observed general waveform at Sakurajima volcano is composed of an impulsive compression phase and a following longer rarefaction phase (Iguchi and Ishihara, 1990; Garcés et al., 1999).

In early 1980s, Sakurajima Volcano Observatory, DPRI, Kyoto University, constructed a monitoring system for eruptions by combining a TV camera with seismometers. This system succeeded to capture flashing arcs associated with explosive eruptions (Ishihara, 1985).

Five eruption movies analyzed here were selected from archived movies taken by this system, as shown in Table 1 and Fig. 2.

3. Image Processing and Result of Analyzing

Firstly, movies recorded on U-matic video tapes were converted to digital files with VGA sized resolution (640 pix×480 pix) and 30 fps. Then, an operation of a geometric transformation with linear interpolation using near 4 points was conducted (Jähne, 2002).

For deriving characters of pressure waves, we paid attention to luminance data of the images (Yokoo and Taniguchi, 2004). The data of luminance, Y, is an index of brightness on digital images and it is calculated from the color data of RGB (8bit×3) for each pixel by following equation:

$$Y = 0.299 \times R + 0.587 \times G + 0.114 \times B$$

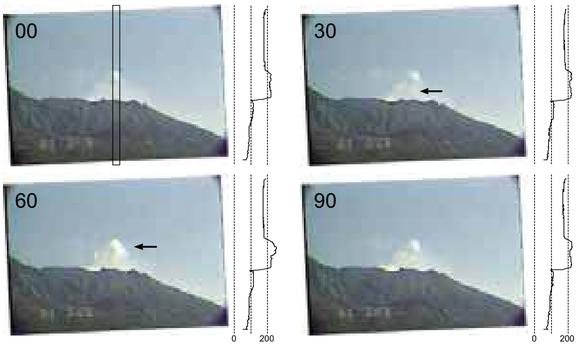

Fig. 3 Four snapshots of the A23 eruption with 1.0 sec intervals (frames #00, #30, #60, and #90). Vertical luminance profile along the rectangular zone, as indicated in the frame #00, is illustrated at the right side of each snapshot.

The index Y is generally corresponding to a gray scale of an image. That is, smaller and larger values mean darker and brighter colors on digital images, respectively (0-255; black to white).

Here, we picked the image of the eruption on Dec. 15, 1982 (A23 in Table 1) up for explaining the nature of a visualized pressure wave (Fig. 3). Before the eruption, there were white clouds just above the crater (frame# 00). One second later, some parts of them were turned to darker (#30) and then flushed with white color at the upper (#60). It quickly returned to the state before the eruption (#90). Thus, the visualized pressure wave was recognized as going upward from the crater.

To make this phenomenon quantitatively by the image processing, we focused on a rectangular zone of 20 pix width, as indicated in Fig. 3. Then, average values of luminance Y for all horizontal lines in this zone are calculated for each frame.

The sequential change of averaged luminance in the zone was illustrated in Fig. 4a. It was clearly recognized that both of a darker and a bright ones propagated upward in the range of 1100-1450 m. The luminance change at the altitude of 1400 m resembled the pressure change have been recorded by an infrasonic microphone (Iguchi and Ishihara, 1990; Fig. 4b). Namely, the dark and bright portions corresponded to the compression and rarefaction phase of the pressure wave, respectively.

Duration of a compression phase of the wave was found about 0.4 sec and it did not change much value for each altitude (Fig. 5a). On the other hand, that of a following rarefaction phase became longer and longer than the preceding compression one as altitude being higher (about 0.5-2.0 sec).

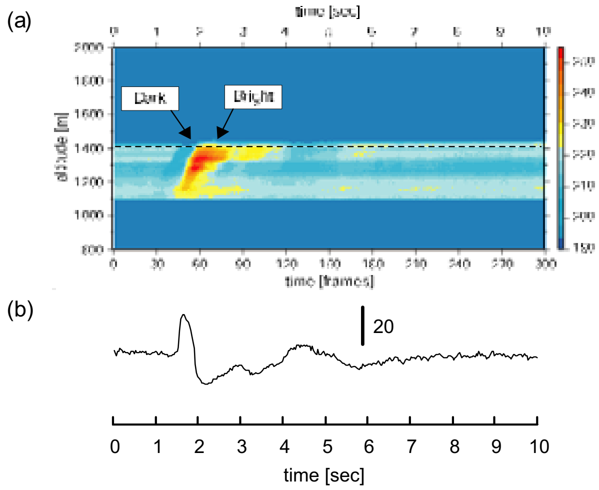

Fig. 4 (a) Sequential luminance data during 10 sec from approximately 1 sec before the onset of the A23 eruption. (b) Luminance change at the altitude of 1400 m. Decrease in luminance is plotted upwards.

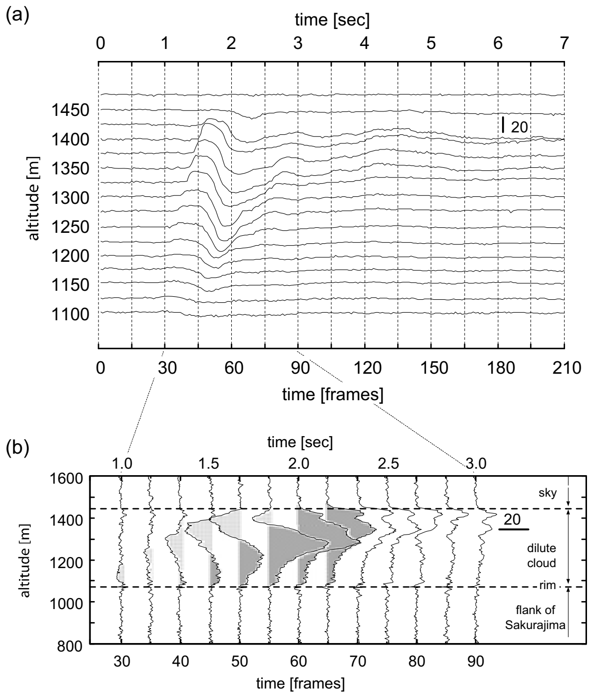

Fig. 5 (a) Luminance changes with time at the altitudes ranging from 1100 to 1475 m. (b) Profiles of changes in luminance. Difference of luminance data between each frame and the first frame (#00). Increase in luminance is plotted rightwards.

To estimate the propagation speed of this wave, we checked the three times in luminance changes every 5-8 m altitudes; (a) the time starting to be darker, (b) the time of the primary negative peak, and (c) the secondary positive peak. As a result, the velocities of (a), (b), and

(c) were estimated as 459 m/s (±22 m/s), 441 m/s (±12 m/s), and 464 m/s (±14m/s), respectively (Table 1). All of them were significantly higher than the speed of sound in the air (~335 m/s).

Moreover, we subtracted the luminance data of the first frame #00 from that at each frame for the purpose of getting information on spatial-dimension (a kind of wave length). The compression phase of the wave was about 175 m at frame #45, and the rarefaction phase was >390 m at #60 (Fig. 5b).

Results of the analyses for other eruptions were also listed in Table 1. Apparent propagation speeds of the waves were faster than the sound velocity of the air. The spatial scales of the compression phases were about 150 m and those of the rarefaction phases were about 150 m and two times longer than the compression's.

4. Discussion

One of our interests is source conditions of gas pocket causing the volcanic explosion. In order to get some information on that, we calculated average velocities of pressure waves at the distance of 250-600 m from the source using 1D spherical explosion model (Saito and Glass, 1979; the code was provided by Prof. T. Saito). This range of distances was equivalent to that of altitudes of 1100-1450 m from the crater bottom, within which the waves of A23 eruption were visualized on the movie. We assumed that the explosion source was composed of 500°C H_2O vapor degassed from magma and the outside was the air for the calculation.

In Fig. 6a, the relationship between internal pressure and velocity was illustrated for each radius of the source; 5 m, 10 m, 15 m, 20 m, and 25 m. If we adopt a pressure of the explosion source to be 140-280 bars which were estimated from ejection speeds of ballistics (Iguchi et al., 1983; Ishihara, 1985; 1990), a radius of that would be deduced for 10-15 m. This evaluated value was roughly consistent with the size of red-growing part in the lava dome which had disappeared by the explosion, and the pressure source of the explosion estimated from the data of ground deformation (Ishihara, 1990).

The waveform of pressure waves at 550 m distance was calculated with parameters mentioned above, and illustrated with the luminance change from the movie in Fig. 6b. The duration of the calculated compression phase almost coincided with that of the luminance change. However, the following phase did not have so

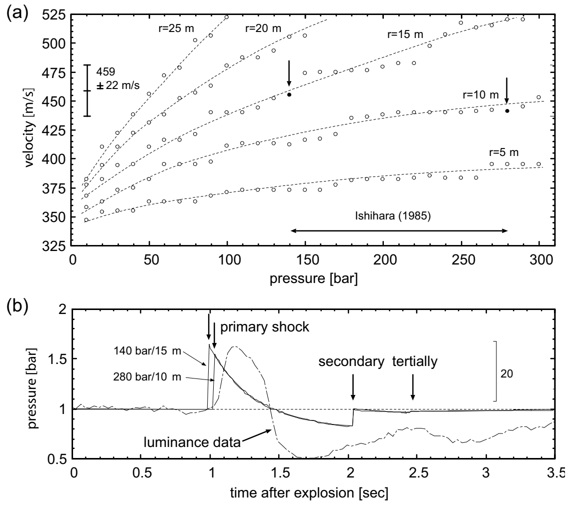

Fig. 6 (a) Relationship between internal pressure and average velocities of pressure waves at the range of distance from 250 to 600 m calculated from 1D spherical explosion model. *r* denotes the radius of pressure source. (b) Comparison between calculated waveforms of pressure waves at 550 m from the source and observed luminance change 550 m above the crater bottom, as shown in Fig. 4b.

good agreement. We think that this may be mainly caused by simplicity of the explosion model we used here; e.g., an instantaneous release of a high-pressurized gas.

5. Summary

We re-examined some characters of atmospheric pressure waves associated with Vulcanian eruptions at Sakurajima more quantitatively by an image processing. The apparent propagating speeds of the waves were faster than the sound velocity of the air (342-574 m/s). We also found that a spatial scale of a compression phase was about 150 m and that of a rarefaction phase was two times more than the former. The method to combine an image processing of eruption movies with a numerical simulation of propagation of pressure wave would make a contribution to modeling of volcanic explosions and physical parameters of explosive sources

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Appendix

Here, we report a brief result of analysis for the weak pressure waves excited by a small eruption at Suwanosejima.

Suwanosejima volcano is a volcanic island located about 200 km southwards from Kyushu. On Aug. 10, 2005, a few tens of eruptions were occurred in the daytime. An eruption occurred at 16:11:02 was the largest one, but the peak pressure of this eruption was observed 8.4 Pa at a station 620 m apart from the vent.

Before the eruption, there were quite dilute steam above the crater (Fig. A1a). The first volcanic cloud (jet)

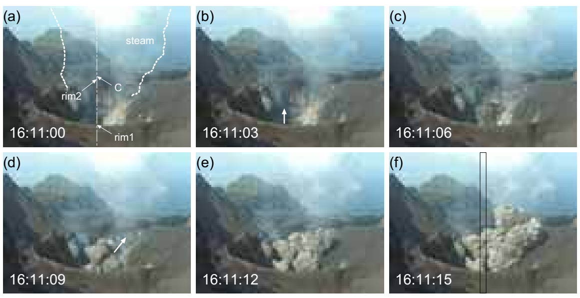

Fig. A1 Sequential images of 16:11 eruption on Aug. 10, 2005, with 3 sec time intervals.

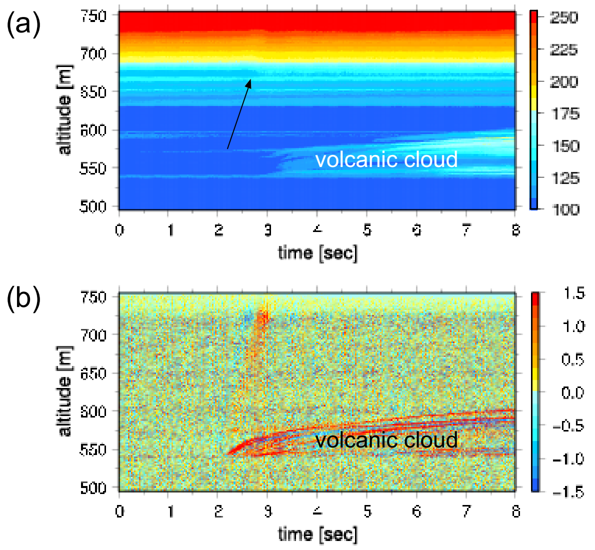

Fig. A2 (a) Luminance change in a 20 pix width zone at the center of the image (Fig. A1f), started from 16:11:00. (b) Differences between the luminance of two consecutive frames. Bluish and reddish colors denote darker and blither before each one frame, respectively.

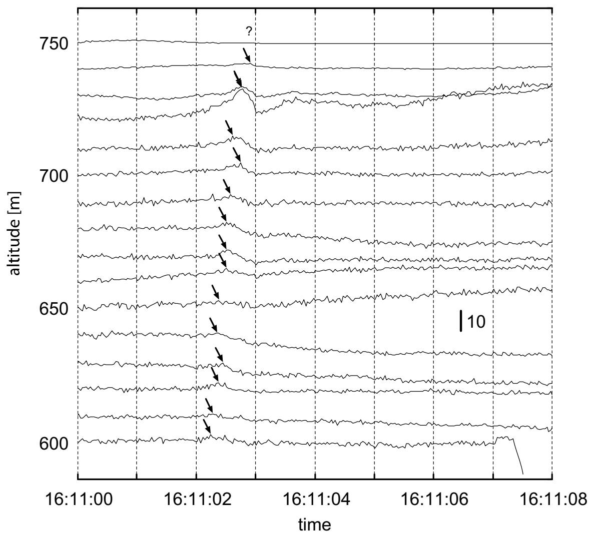

Fig. A3 Luminance data at each altitude. Note that decrease in luminance is plotted upside.

could be seen as a vertical emission within the crater (Fig. A1b) and about 7 sec later the secondary cloud with ballistics began to rise up toward an inclined direction (Fig. A1d).

It was very difficult to recognize propagation of a pressure wave associated with this eruption from the normal image.

Using the method of image processing described in text we found the slight changes in luminance data at the upper part of the image (Fig. A2a), although they were much weak compared with Sakurajima eruptions (Fig. 4a). Therefore, we calculated difference of the luminance between two consecutive frame's data (Yokoo and Taniguchi, 2005). Then, propagation was recognized in the altitude ranging from 550 m to 750 m (Fig. A2b).

We estimated an apparent speed of propagation using luminance change with time at each altitude in the vertical rectangular zone shown in Fig A1f. The estimated speed of velocity was about 228 m/s based on the upward migration of 42 peaks of luminance (Fig. A3a), which was slower than the sound speed of the air.

火山噴火映像から抽出した圧力波の特徴について

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要旨

桜島火山の噴火映像に対して画像処理・解析を行った。その結果，圧力波が伝播する様子やその時空間特性を定量的に把握することが可能となった。また，球状衝撃波伝播の計算結果と比較することで，火山爆発源の物理諸パラメータについての簡単な検討を行った。

キーワード:桜島火山，画像処理，ブルカノ式噴火，圧力波，可視化