Earthquakes series preceding very long period seismic signals, observed during the 2000 Miyakejima volcanic activity

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Received 19 November 2002; revised 14 February 2003; accepted 12 March 2003; published 18 April 2003.

[1] Unusual earthquakes series were observed one to two hours before a very long-period (VLP) seismic pulse that happened once or twice a day, during the 2000 activity of Miyakejima volcano, Japan. The series on July 11 and 12 have particularly a clear feature. The time intervals of the earthquakes in the series decrease at a constant rate in the manner of geometric progression. The maximum amplitude of each earthquake is initially almost constant, but linearly decreases with time from few minutes before the occurrence of a VLP pulse. Hypocenters of these earthquakes are below the south-western region of the crater, and near the sea level in depth. We interpret these earthquakes series as repetition of a gradual stress accumulation, and release under the variable critical stress level. The critical stress level is first constant, but linearly decreases later. *INDEX TERMS:* 1734 History of Geophysics: Seismology; 1749 History of Geophysics: Volcanology, geochemistry, and petrology; 7280 Seismology: Volcano seismology (8419). **Citation:** Kobayashi, T., T. Ohminato, and Y. Ida, Earthquakes series preceding very long period seismic signals, observed during the 2000 Miyakejima volcanic activity, *Geophys. Res. Lett.*, *30*(8), 1423, doi:10.1029/2002GL016631, 2003.

1. Introduction

[2] Miyakejima is an active volcanic island in the volcanic chain running parallel to the Izu-Ogasawara trench. It has frequently erupted basaltic magma. The most recent activity in 2000 involved a great depression of the summit area and several summit eruptions in the newly formed crater or caldera. During the period from July 9 to August 18 when several dominant eruptive activities are included, very long period (VLP) seismic pulses having the pulse width of about 50 seconds were observed once or twice a day [*Kumagai et al.*, 2001]. The mechanism of VLP pulses is explained as follows. In the process of the caldera collapse, the piston in the conduit episodically moves down to the magma reservoir and a VLP pulse is excited by a sudden pressure increase at each piston injection event. At the same time when a VLP pulse occurred, a tilt-step was also recorded [*Ukawa et al.*, 2000].

[3] The interesting series of earthquakes were observed as a precursory seismic activity of the VLP pulse [*Ukawa et al.*, 2000; *Fujita et al.*, 2001]. Each of these series started one to two hours before a VLP pulse and stopped with its occurrence. In this paper, we investigate characteristics of these earthquakes series called hereafter "pre-swarm".

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0094-8276/03/2002GL016631

2. Data

[4] For the analysis of the pre-swarm earthquakes series, we used seismograms of 3 broadband and 15 short-period seismometers. All these seismometers are of three components. Locations of the seismic stations are shown in Figure 1. The broadband seismometers deployed by Earthquake Research Institute, University of Tokyo had a natural period of 120 seconds (CMG-3T, Guralp Ltd). The short-period (1 sec) seismometers were operated by the Tokyo Metropolitan Government. 5 of them were in the island of Miyakejima and 10 of them were in nearby islands within 40 km from Miyakejima. Output signals of the broadband and the short-period seismic sensors are continuously digitized by digital recorders (LS800WD, Hakusan Co.) with resolutions of 24 bits, and by the digitizers (manufactured by Meisei Co.) with 12 bits, respectively. The sampling frequency of all the data is 100 Hz.

3. Characteristics of Pre-Swarms

[5] Figure 2a shows an example of pre-swarm seismograms observed at KAS station, preceding the VLP pulse at 11:51 (JST) on July 11, 2000. As approaching to the VLP pulse, the time intervals of the pre-swarm earthquakes gradually decrease. The maximum amplitudes of the earthquakes are initially nearly constant, and then suddenly start decaying rapidly few minutes before the occurrence of the VLP pulse. The magnitudes of earthquakes, which were determined from the relation between the amplitudes and hypocentral distances [*Watanabe*, 1971], are between 1 and 2. Individual earthquakes in the pre-swarm have quite similar waveforms from the onset to the coda (Figure 2b), although their amplitudes vary from event to event. The amplitude and timing of pre-swarms were characterized by a clear trend in the first few cases, but the trend was gradually obscured later. In this paper, we analyze the pre-swarms having clear characteristics, which are associated with VLP pulses at 2:11 and 11:51 on July 11, and at 0:34 and 13:04 on July 12. Hereafter, these pre-swarms are referred to as pre-swarm 1, 2, 3, and 4, respectively. We divide each pre-swarm into two parts. The first part is called zone I and is characterized by a nearly constant amplitude of earthquakes, while the second part, called zone II, is characterized by rapid amplitude decay (see Figure 2a).

[6] The time intervals of earthquake occurrence during each pre-swarm are subjected to a simple rule. Closed circles in Figure 3 show the occurrence interval as a

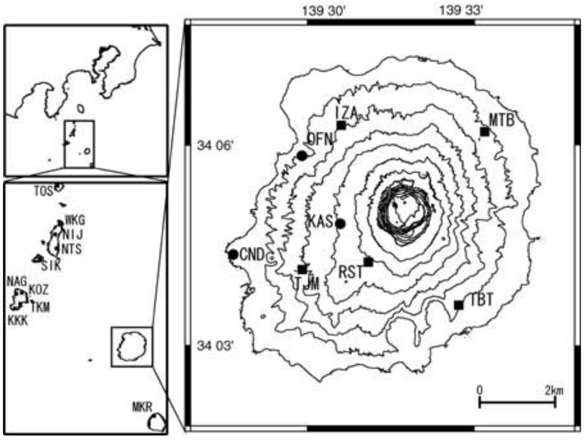

Figure 1. Seismic stations in Miyakejima and nearby islands. Solid circles and solid squares show broad-band and short-period seismometers, respectively. The contour map shows Miyakejima after the eruptions, which is drawn by using Geographical Survey Institute Technical Data for GIS.

function of the occurrence time for the pre-swarms 1 to 4. They indicate that the time intervals decrease linearly with time. We fit a line

$$d_i = \alpha t_i + \beta \tag{1}$$

to the data, where $t_0, t_2, \ldots,$ and t_N are the origin time of $N + 1$ earthquakes, and $d_i = t_i - t_{i-1} (i = 1, 2, \ldots, N)$ is the time interval between ith and $i - 1$th earthquakes, and α and β are constants. Introducing $\gamma = 1/(1 - \alpha)$, equation (1) leads to

$$d_i = d_1 \gamma^{i-1} \tag{2}$$

The time sequence of earthquakes in a pre-swarm thus makes a geometric progression with the initial value d_1 and the common ratio γ. The VLP pulse occurs when d_i being zero. The values of γ from pre-swarm 1 to 4 are 0.49, 0.61, 0.81, and 0.94, respectively, showing an increasing trend.

[7] Open circles in Figure 3 show the change of maximum amplitudes of the pre-swarm earthquakes with time. Maximum amplitudes are nearly constant in zone I, but decrease almost linearly in zone II, as shown by the broken line in Figure 3.

4. Hypocenters

[8] We determined hypocenters of the pre-swarms earthquakes using the Bayesian approach [*Hirata and Matsu'ura*, 1987]. In our study, S-wave arrival times were obtained only from broadband seismograms, because the S wave records were usually saturated in the short-period seismograms. We used a velocity model composed of 5 layers. From the top, the velocities are 1.5, 2.2, 3.6, 6.0 and 6.7 km/s, and the thicknesses are 0.1, 0.4, 2.0, 10.0 and 10.0 km. This model is based on the velocity structure obtained by the *Tokyo Metropolitan Government* [1990] with an additional slow-velocity layer of 1.5 km/s at the top. This slow-velocity layer was introduced because other basaltic volcanoes along the Izu volcanic chain have similar low velocity layers near the surface. This layer was actually effective to prevent some hypocenters from being above the ground level. The horizontal and vertical uncertainties are a few hundred meters, and 1 to 2 km, respectively. Figure 4 shows well determined hypocenters of 35 earthquakes that occurred during the pre-swarms 1 to 4. Hypocenters are located beneath the south-western region of the crater, and the depths are about sea level. There is no systematic difference in hypocenter distribution, among the 4 pre-swarms. In order to obtain the focal mechanisms, we used three events with high signal to noise ratio. Their focal mechanisms are similar to one another. If we assume a fault motion as the source mechanism, the solution is a normal fault having the strike between 50° and 70° from the north, and dip angle of 20°. This solution is not unique. Other source mechanisms, such as CLVD solution, cannot be excluded due to poor station coverage. The source region of the VLP pulses has not yet been determined definitely. A shaded area in Figure 4 indicates the source region inferred from the particle motions. The location is roughly consistent with the result inferred from the waveform analysis [*Kumagai et al.*, 2001]. Although the depth of VLP pulses has large uncertainties, it is suggested that the pre-swarms occurred above the source region of VLP pulses.

5. Discussion

[9] As has been noted, these pre-swarms have the following four main features.

[10] (1) Time intervals of occurrences of earthquakes gradually decrease in the manner of geometric progression.

[11] (2) Maximum amplitudes are almost constant initially, but decrease linearly with time starting a few minutes before the occurrence of the VLP pulse.

[12] (3) Hypocenters of pre-swarms are below the south-western region of the crater and near the sea level in depth, being located above the source region of VLP pulses.

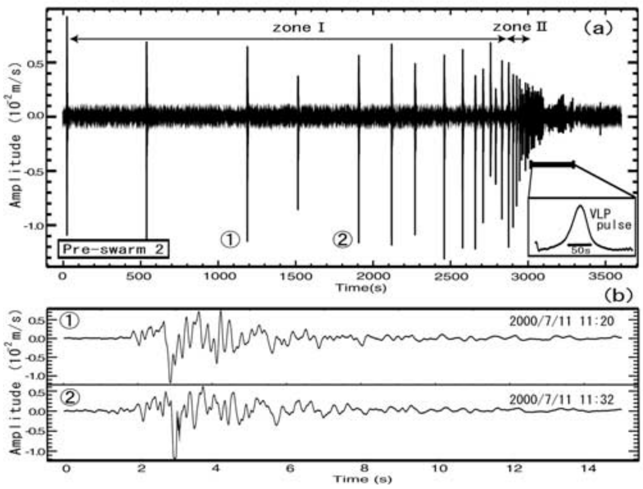

Figure 2. (a) Pre-swarm seismic signals observed at KAS station on July 11, 2000. The record is vertical-component of velocity. The VLP pulse, which is low-pass filtered at 10 sec, is shown in the inset at the bottom right corner. (b) Two examples of vertical component of waveforms of individual earthquakes in the pre-swarm shown in Figure 2(a).

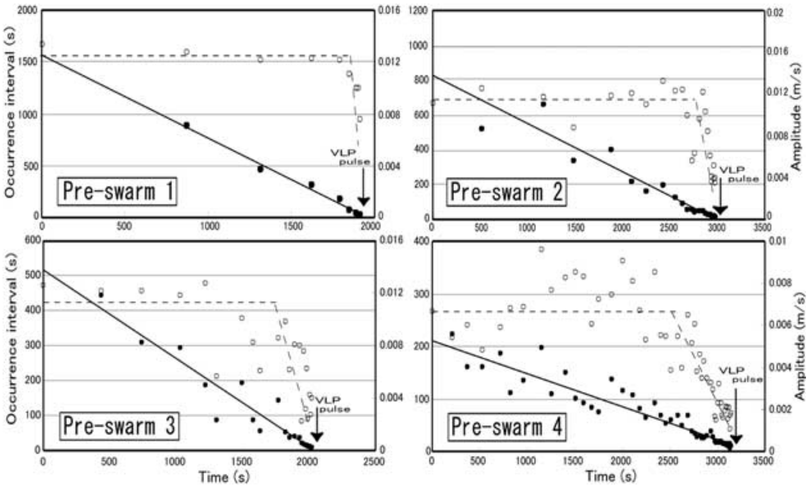

Figure 3. Time intervals (closed circles) and the maximum amplitudes (open circles) of pre-swarm earthquakes as functions of time. Left axis indicates time interval and right axis indicates maximum amplitudes. The number of earthquakes for pre-swarm 1, 2, 3, and 4 is 9, 25, 22, and 50, respectively.

[13] (4) Individual earthquakes in the pre-swarms have almost similar waveforms.

[14] Temporal character (1) of the pre-swarms reminds us of the characteristic behavior of foreshocks of tectonic earthquakes or acoustic emission (AE). It is known that the number of foreshocks of tectonic earthquakes as well as AE in the laboratory experiments increases toward the main shocks. The number of earthquakes per a unit time is often represented by the following relationship:

$$n(\tau) = n_0 \tau^{-p} \tag{3}$$

where τ is the time measured from the origin time of the main shock in reverse, and n_0 and p are constants [*Mogi*, 1962; *Comninakis*, 1968]. For the pre-swarms prior to VLP pulses, the time sequence of occurrences meets the same relation as equation (3). P values are 0.74, 1.51, and 1.20 for pre-swarm 2, 3, and 4, respectively. Pre-swarm 1 is removed because only nine earthquakes are involved.

[15] However, the pre-swarms also have a difference from AE. Elastic shocks in fracture experiments tend to have increasing amplitudes as they approaches the main shock, while, the amplitude of the pre-swarm earthquakes clearly decrease just before a VLP pulse. This strongly indicates that the pre-swarms are essentially different from AE.

[16] In order to interpret features (1) and (2) of the pre-swarms, we propose a model shown in Figure 5b, which resembles to the time predictable model of earthquake occurrence [*Shimazaki and Nakata*, 1980]. In our model, we assume that the maximum amplitudes represent the amount of stress drops. Figure 5b schematically shows stress change in the source region, compared with the critical stress value σ_{crit}. In the process leading to a VLP pulse, we assume that the stress tends to increase with time gradually, and a pre-swarm earthquake occurs when the stress reaches σ_{crit}. The stress is released to a certain level σ_{min} by the earthquake, and then the stress starts increasing again. For simplicity, we assume that σ_{min} is constant.

[17] In the initial process denoted by zone I, σ_{crit} should be constant because the observed maximum amplitudes of pre-swarms are nearly constant. In this zone, the time intervals of pre-swarms denoted by equation (1) decrease linearly with time (Figure 5c). Thus, we understand that the stress recovery rates R, which are proportional to the ratios between stress drops and the time intervals of earthquakes, increase with time (Figure 5d). In zone II, on the contrary, the observed maximum amplitudes decrease linearly with time and thus the stress drops also decrease linearly with time. The temporal changes of both the stress drops and the time intervals of earthquakes are approximated by lines, which cross zero at the same timing of the VLP pulse occurrence. This implies that R is constant (Figure 5d).

[18] Based on the model described above and on the framework of the falling piston in the conduit, the entire

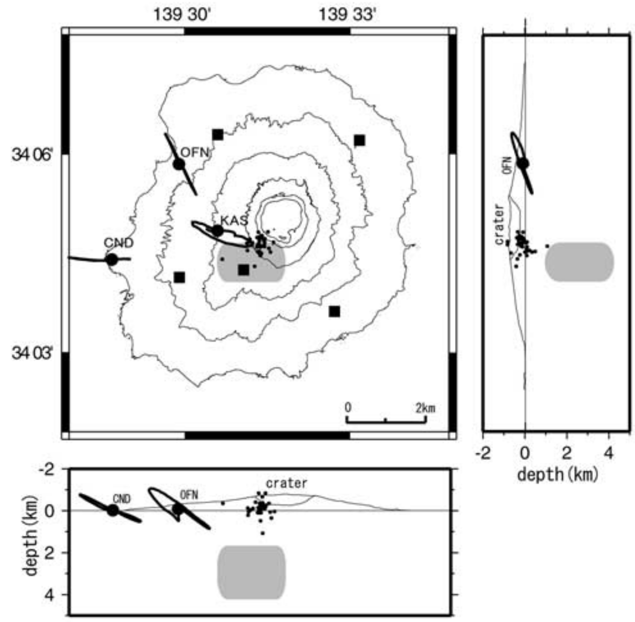

Figure 4. Hypocenters of earthquakes in pre-swarms. Shaded area shows the source region of VLP pulses estimated from the particle motions (Elliptical orbits).

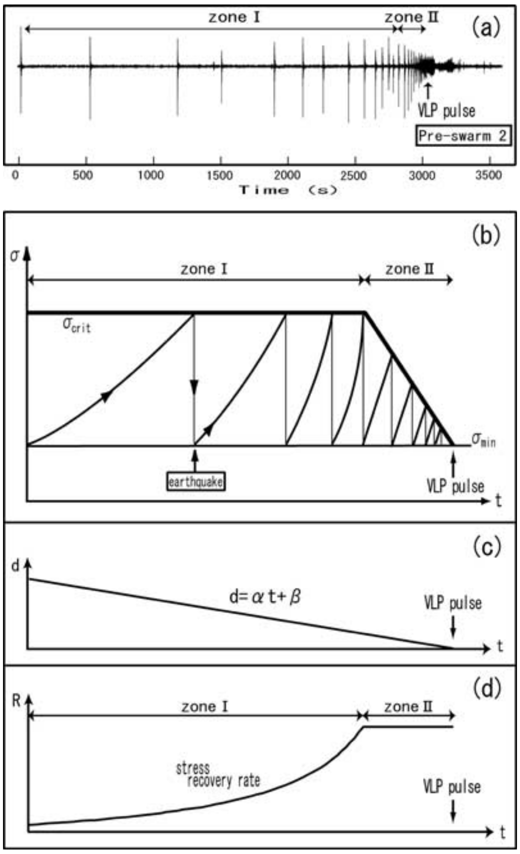

Figure 5. (a) Observed waveform (pre-swarm 2). (b) A model of pre-swarm. The stress gradually increases and then suddenly released from σ_{crit} to σ_{min} when a pre-swarm earthquake occurs. (c) The time interval decreases linearly with time. (d) The stress recovery rate in pre-swarms. Note that the stress recovery rate in zone I increases with time, while it is constant in zone II.

sequence from a pre-swarm to a VLP pulse can be interpreted as follows. Initially, the piston is coupled with the conduit wall, some parts strongly and others weakly. Hereafter, we call the strongly coupled parts as "asperities". In zone I, asperities have almost constant strength. Failures of the asperities, which correspond to the earthquakes in zone I, occur one by one. As the number of broken asperities increases, the stress recovery rates increase because the same amount of frictional force has to be shared with the smaller number of asperities.

[19] When the asperities cannot hold the piston against the downward force any longer, the piston starts moving down at a nearly constant velocity determined by the dynamic friction. This stage corresponds to zone II in the pre-swarms. In this stage, occurrences of pre-swarms are controlled by a constant stress recovery rate corresponding to the velocity of sliding piston. Ground water and magmatic fluid may have played a role in lubricating the conduit wall. Finally, a downward free slip of the piston is made possible by the smoothed wall of the conduit, and leads to a rapid increase of pressure in the magma reservoir and a VLP pulse.

[20] In both zones I and II, earthquakes are localized above the estimated source region of the VLP pulses as indicated in the feature (3). In addition, source region of the pre-swarms are restricted in a limited area as manifested by the waveform similarity (feature (4)). Thus, the asperities are mainly distributed in a certain restricted area at the shallow part of the piston.

[21] We have proposed a model in which the maximum amplitude of pre-swarms is regarded as the stress drop. Alternatively, a model in which the maximum amplitudes are proportional to the size of fractured faults with constant stress drop may be also possible. However, it is much more difficult to explain the systematic change of the fault size. Although the model is not constrained uniquely without further studies, we believe the pre-swarm is a quite interesting phenomenon usable to reveal the volcanic and seismic processes.

[22] **Acknowledgments.** We are grateful to Earthquake Observation Center, Earthquake Research Institute, Univ. of Tokyo for providing seismograms of short-period seismometers. Topographic map of Miyakejima shown in Figure 1 and 4 are created based on the GIS data for Miyakejima, Technical Report of Geographical Survey Institute.

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