

Long-period (12 sec) volcanic tremor observed at Usu 2000 eruption: Seismological detection of a deep magma plumbing system

Mare Yamamoto,¹ Hitoshi Kawakatsu,¹ Kiyoshi Yomogida,² and Junji Koyama²

Received 27 August 2001; revised 13 February 2002; accepted 28 February 2002; published 11 May 2002.

[1] From a temporal deployment of a broadband seismic network at Usu volcano, Japan, we observed long-period (12 sec) volcanic tremors during the first few weeks of the eruptive activity which started in the end of March, 2000. The source of these long period tremors are located relatively deep at a depth of 5 km, and their amplitude variation well correlates with the uplift rate of the eruption area. We thus attribute these long period tremors to the flow induced vibration of a magma chamber and its outlet located around the source region of the long period tremors. This may be the first seismological detection of long-period (>10 sec) vibrations of a deep magma plumbing system. *INDEX TERMS:* 7280 Seismology: Volcano seismology (8419); 8414 Volcanology: Eruption mechanisms; 8434 Volcanology: Magma migration

1. Introduction

[2] Mt. Usu is a dacitic stratovolcano located in southwestern Hokkaido, Japan (Figure 1), and has erupted repeatedly. During the 20th century, three eruptive activities occurred in 1910, 1943–45, and 1977–78 [e.g. *Yokoyama and Seino*, 2000]. In the end of March 2000, after twenty some years of quiescence, Usu volcano began its activity with an intensive earthquake swarm. After several days of the earthquake swarm, on March 31, 2000, the eruption began at the northwest foot of the volcano (Figure 1), and the eruptive activities accompanied by the uplifting of the crater area continued for several weeks [e.g. *Nakada*, 2001]. Here we report the results of our broadband seismic network deployment at Usu 2000 eruption. These include: (1) absence of pre-eruption inflations as observed at Aso volcano, Japan [*Kaneshima et al.*, 1996; *Kawakatsu et al.*, 2000], (2) presence of long period tremors with a period of about 12 second, and (3) their possible link to a deep magma plumbing system.

2. Broadband Seismic Network

[3] From March 31, 2000, we installed five broadband seismometers temporarily around Usu volcano (Figure 1). One of our stations SNZ was installed 10 minutes prior to the first eruption which occurred at 13:10 of March 31 (JST), and the other stations were set within the following few days. Several days after the first installation, two of the stations (HNW and SKR) were moved closer to the active craters (ABT and TKU), and we maintained the network until the end of June, 2000. Each station was equipped with a Guralp CMG-3T broadband seismometer with a free period of 100 sec and a Hakusan Data Mark LS8000WD portable recorder. Sensors were directly placed on the ground surface, and their outputs were recorded on hard disks continuously with a sampling rate of 100 Hz. Since there is no permanent broadband

seismic stations around the volcano, our data are the only available broadband records of the first stage of the activities.

3. Eruptions

[4] The main eruptions occurred at 13:10 March 31 and 02:50 April 1 (JST). They are magmatophreatic eruptions at the newly formed craters (Figure 1). *Kaneshima et al.* [1996] and *Kawakatsu et al.* [2000] observed pre-eruption inflations at Aso volcano with a time scale of more than one minute, and interpreted them as the gradual increase in fluid pressure beneath the crater. However, at Usu volcano, no distinguished precursory slow deformation with a time scale of a few minutes is resolvable with our data for these two eruptions. This appears to suggest the eruptions are caused by a rapid interaction of magma and water at a shallow part of the edifice, and the process of the eruption is not so gradual as in Aso volcano.

4. Long Period (12 sec) Tremor

[5] Although no eruption related long-period seismic signal was observed, we have instead detected long period tremors (hereafter called LPTs) which are continually emitted from the volcano. Figure 2 shows examples of the bandpass filtered (10–15 sec) seismograms. On these seismograms, LPTs are clearly seen as isolated wave packets of a few cycles. Although these LPTs are continually observed at an interval of a few minutes, there exist no corresponding surface activities such as eruptions. Figure 3 shows the spectrogram of the observed data at SNZ for the first one month of the eruption activity. In this figure, the continuous bright belt around 12 sec corresponds to the spectral peak of LPTs. The similar spectral peaks are observed at all other stations, and the common spectral peaks indicate that they are not due to a path effect but a source property. As shown in the figure, the period of LPTs varies gradually from 10 sec to 12 sec during the first two or three days after the first eruption, and becomes steady at 12 sec.

4.1. Location

[6] To locate the source of LPT, we use the waveform semblance method [*Kawakatsu et al.*, 2000]. In our application of the waveform semblance method, we use stacked signals with improved signal-to-noise ratio rather than using observed raw data. Since the shapes of LPTs are almost identical between events, we stacked observed data for each station according to the reference time determined using the data observed at SNZ. We use 96 LPTs observed during 5–7 April when the LPTs are most clearly seen.

[7] The resultant source location of LPTs is shown in Figure 4. The estimated source region is about 1.5 km southeast of the summit crater at a depth of 5–6 km, and the corresponding semblance coefficient takes values above 0.8. In Figure 4, particle motions observed at nearby stations are also shown. The particle motions both in the horizontal plane and radial/vertical plane point to the estimated source region.

4.2. Source Mechanism

[8] As the occurrence of LPTs is highly repetitive, the source mechanism is unlikely destructive. We therefore assume that the

¹Earthquake Research Institute, University of Tokyo, Japan.

²Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Japan.

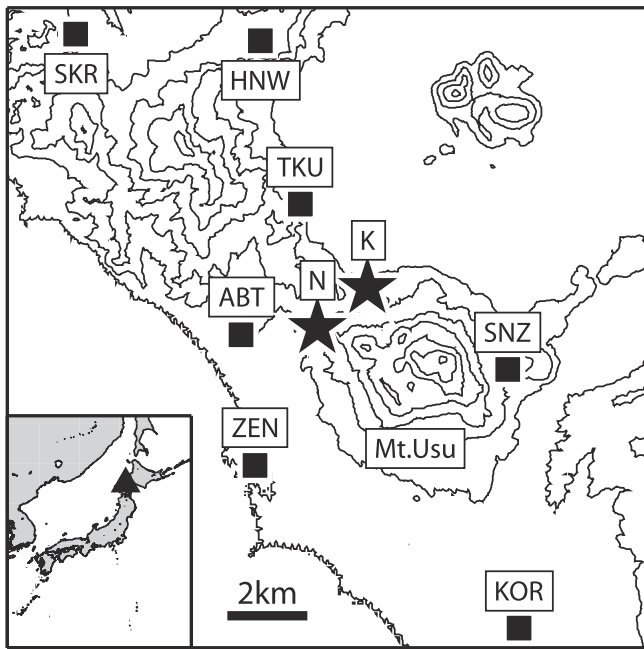


Figure 1. Usu volcano is located in southwestern Hokkaido, Japan. Solid squares represent our temporary broadband seismic stations. Stars indicate the locations of newly formed craters (N and K stand for Nishi-yama crater and Konpira-yama crater, respectively).

source moment tensor has only axisymmetric component, and is represented as a sum of isotropic and CLVD components. Using this decomposition, source mechanisms such as a tensile crack, a cylindrical source, and a force dipole which are usually observed in and around volcanos can be represented as well as a pure isotropic or a pure CLVD mechanism. The direction of the symmetry axis of the CLVD component is searched for every 5° in both strike and dip so as to minimize the variance between observed and theoretical velocity seismograms, and at the same time the ratio of the isotropic and CLVD components is inverted. In the inversion, we use the stacked bandpass filtered (10–15 sec) three component data describes above, and assume a homogeneous half space with a P velocity of 4 km/s. The epicenter is fixed at the point estimated

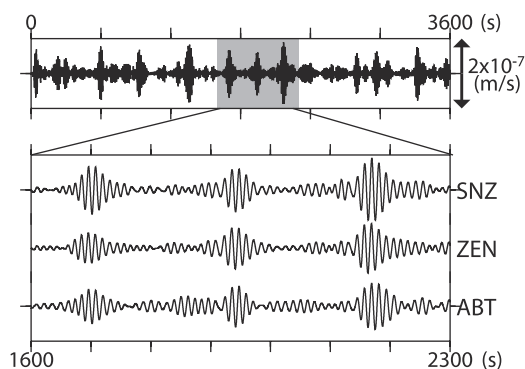


Figure 2. Vertical component bandpass filtered (10–15 sec) velocity seismograms. Top trace shows the one-hour seismogram from 01:00 on April 7 observed at SNZ. Lower traces are closeups of the seismograms observed at different stations. All traces are drawn in the same scale.

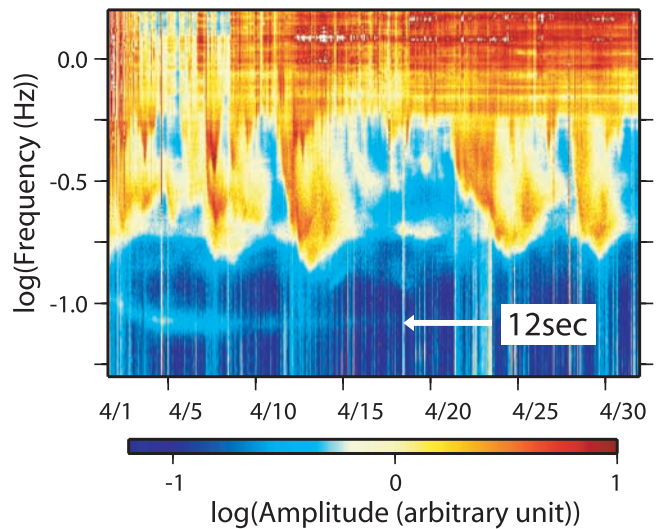


Figure 3. Spectrogram of the vertical component velocity data at SNZ. We first calculate amplitude spectra for every 5 minutes, and average them to make spectra for every one hour. A bright belt around 12 sec (about -1.1 in log-scale) is the spectral peak of LPTs.

by the waveform semblance analysis, and only the source depth is estimated. Since we observed long period signals in the near-source region, the observed signals share almost identical waveform, and the main constraint on the source mechanism is derived from the amplitude of the observed signals. Therefore we concentrate on fitting the waveform of the first two cycle of the signal observed at each station, and assume a single triangle function as the source time function of LPTs.

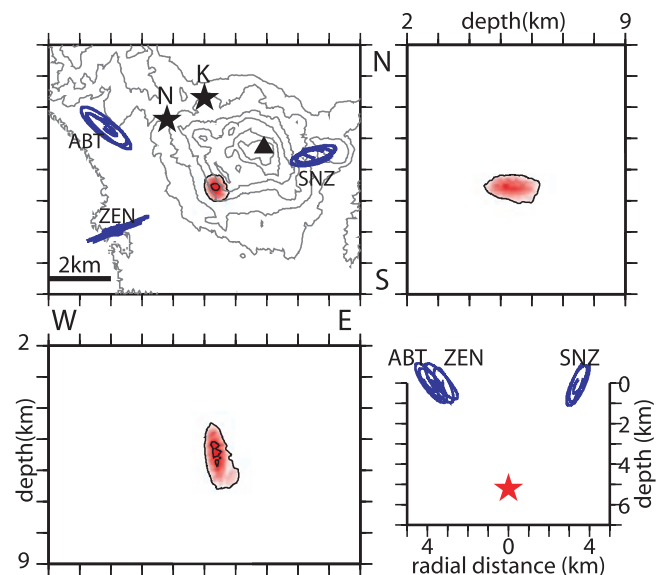


Figure 4. The source location of LPTs obtained by the waveform semblance method. Shaded region indicates the region which gives a high semblance coefficient. The best location is about 1.5 km southwest of the summit crater (triangle) at a depth of about 5 km. The particle motions of stacked LPTs observed at nearby stations are also shown on a map view (upper left) and on radial-vertical planes (lower right).

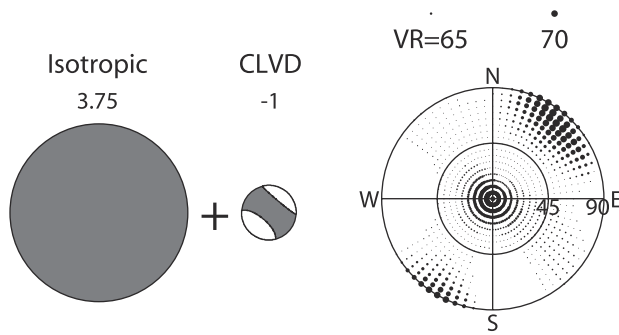


Figure 5. Source mechanism of LPT. The moment tensor consists of isotropic and CLVD components whose ratio is 3.75 : -1. In the right panel, for each symmetry axis direction, the maximum value of the variance reduction is represented as a circle whose radius is proportional to the value.

[9] Figure 5 shows the resultant source mechanism. The best seismic moment tensor consists of an isotropic component (three eigenvalues are 1:1:1) and a CLVD component (1:-0.5:-0.5) whose symmetry axis points northeast in an almost horizontal plane, and the ratio of these two components is 3.75 : -1. In the right panel, for each symmetry axis direction, the maximum value of the variance reduction is represented as a circle whose radius is proportional to the value. Due to insufficient station coverage and the narrow bandpass filtering, the ambiguity of the axis direction is rather large as apparent in the figure, and the ratio of the two components are not well constrained. However, with any other filters and velocity structures, the northeast-southwest trend of the axis direction is not changed drastically, therefore the trend is likely a real feature of the source mechanism of LPTs.

5. Discussion

[10] The estimated source depth of LPTs (5–6 km) is rather deep compared to those of the long period signals observed at other volcanos (typically 0–3 km; see *Kawakatsu et al.* [2000] for a review). This fact appears to suggest that LPTs are manifestation of some activity of magma itself in the deep part of the volcano.

[11] Based on petrologic arguments, *Tomiya* [1997] suggests the existence of two magma chambers at depths of about 4 km and 10 km. He also analyzes the ejecta of the Usu 2000 eruption, and suggests that they come from the dacitic magma chamber at a depth of 4 km [*Tomiya et al.*, 2000]. The existence of these magma chambers is also supported by other geophysical data. To explain GPS observations, *Murakami et al.* [2001] placed a deflating Mogi (spherical) source at a depth of 10 km beneath the summit, and a horizontal inflating crack (sill) at a depth of 3 km in west or northwest of the summit. The seismicity around the volcano shows a clear seismic gap in the area of our LPT source region in southwest of the summit crater at a depth of 4–6 km [*Oshima et al.*, 2000]. A tomographic structural study also shows a low-velocity area beneath the summit around a depth of 6 km [*Onizawa et al.*, 2001].

[12] The fact that the LPT source is located in a general area of the postulated magma chamber strongly suggests a relationship between magma activities and LPTs. Figure 6 shows the time variation of the RMS amplitude of LPTs at SNZ, and the rate of the volcanic uplift observed near the active crater reported by *Mori and Ui* [2000]. As the observed uplift is due to the intrusion of magma beneath the craters from a deeper source, the similarity of these two trends indicates not only that LPTs are related to the magma activities, but also that they are the direct

result of the upward magma migration. We, therefore, postulate that the volumetric flow out of the magma chamber, which is located in the LPT source region, generates long-period oscillations observed as LPTs.

[13] The volumetric flow rate may be estimated from the observed RMS amplitude of LPT. A RMS amplitude of 10×10^{-8} m/s may be equated to an event rate of 10^{-7} m/s-event per one minute (“ 10^{-7} m/s-event” is an event whose peak amplitude is 10^{-7} m/s, and one event is assumed to be a 12 sec period oscillation which decays after several cycles). A 10^{-7} m/s-event at SNZ roughly corresponds to a seismic moment (isotropic) of 10^{13} Nm located at the LPT source. If we assume pressure change in a spherical volume as the source for the isotropic moment tensor, the seismic moment can be directly compared to the volume change of the sphere as $M_o = (\lambda + 2\mu)\Delta V_M$, where the volume change $V_M = \frac{\pi a^3 P}{\mu}$ which can be estimated by geodetical means, and a , P , μ , λ are the sphere radius, pressure change, and Lamé’s constants of the country rock. It is then possible to translate the observed event rate into an equivalent volume flow rate (through a seismic moment rate). Assuming $\mu = \lambda = 1.5 \times 10^{10}$ Pa for the country rock, the volume change rate is estimated to be around 3×10^5 m³ per day. Geodetic observations report the deflation of a magma chamber at a depth of 10 km during the first few days of the eruption, and corresponding volume change is estimated as of the order of 10^7 m³ [e.g. *Murakami et al.*, 2001]. Although our estimation of the volume change rate may contain factorial errors since we assume a single triangle source time function regardless of the oscillatory feature of LPTs, it appears that the volume flow rate estimated from LPTs is about one order of magnitude smaller than that of the actual flow rate. This may be reasonable if we consider that through seismic waves we are observing a fluctuating part of the magma flow.

[14] The excitation mechanism for the LPT is not clear at the moment. A free resonance of the spherical magma chamber is unlikely to explain the observed period of 12 sec, as it requires a huge size for the magma chamber [e.g. *Kawakatsu et al.*, 2000]. We tentatively postulate the dynamic interplay between magmatic flow out of the magma chamber and the wall of a dike-like outlet as the cause of the LPT. The estimated moment tensor for LPTs shows a reversed polarity for the isotropic and CLVD components (Figure 5). This is consistent with a combination of a

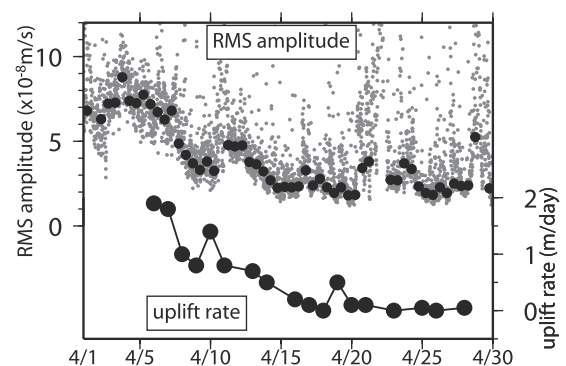


Figure 6. Time variation of the RMS amplitudes of the bandpass filtered (10–15 sec) seismograms observed at SNZ, and the time variation of the rate of the volcanic uplift observed at northwest of Nishi-yama [*Mori and Ui*, 2000]. We calculate RMS amplitudes for every 10 minutes. Scatters in data are mostly due to the presence of teleseismic signals. Superimposed circles show the mode of the RMS amplitudes calculated for every 12 hours. These two time series follow similar tracks (general trend, not necessarily small fluctuations which may be uncertain) and suggest a relationship between two activities.

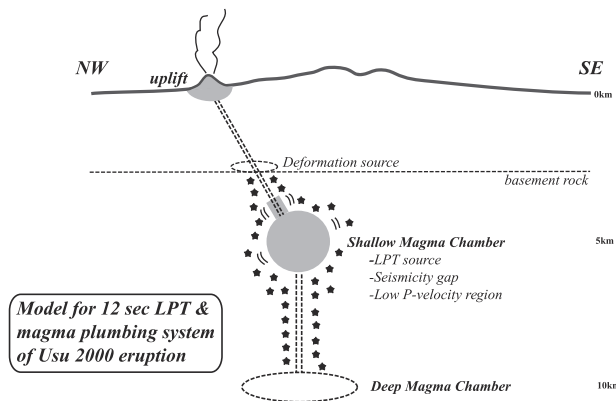


Figure 7. A conceptual model for the LPT source and the magma plumbing system of the Usu 2000 eruption.

deflating spherical source and an inflating crack which opens northwestern direction toward the eruption site. Such flow-induced non-linear coupling is shown to produce oscillatory behavior for a variety of frequencies: from less than a second [Julian, 1994] to days [Ida, 1996].

[15] Our conceptual model for the LPT source and the magma plumbing system of the Usu 2000 eruption (Figure 7) is as follows: The migration of magma starts from a 10 km-deep magma chamber to a shallow magma chamber at about 5 km depth southwest of the summit area where the LPT source is located. Magma further migrate upwards northwestern direction toward the eruption site. Tectonic earthquakes occur during this magma migration until the magma finishes breaking the basement rock layer to make its own pathway to the shallower and weaker sedimentary layer. When the magma reaches the sedimentary layer, the ground deformation likely accelerates partly due to the weakness of the surrounding country rock and partly due to the acceleration of vaporization of magmatic gases. This may explain why deformation sources are located shallower and northwestward [Murakami et al., 2001] relative to the location of the shallow magma chamber inferred seismologically (this study, Oshima et al. [2000]; Onizawa et al. [2001]). The upward migration of magma from the shallow magma chamber to the surface eruption site continues for the first several weeks of the eruptive activity, and causes the pressure change in the magma plumbing system to result in generation of LPTs.

[16] As presented in this study, the 12 sec long period volcanic tremors associated with Usu 2000 eruption are likely the direct results of the upward flow of magma from the magma chamber located around a depth of 5 km. Although a large number of studies on the seismic signals associated with

volcanic activities has been made, there were a few works in which the magma plumbing system beneath the active volcano and the magma movement in that system were detected. If we could provide high quality and high density data as was done in Aso volcano [Yamamoto et al., 1999], it might have been even possible to constrain the geometry of the magma plumbing system beneath volcanos. The importance of broadband seismometry at volcano has been further confirmed from this deployment.

[17] **Acknowledgments.** We thank Y. Morita for allowing us to use his observation systems, and T. Moriya for sharing the adventure.

References

- Ida, Y., Cyclic fluid effusion accompanied by pressure change: implication for volcanic eruptions and tremor, *Geophys. Res. Lett.*, 23, 1457– 1460, 1996.
- Julian, B. R., Volcanic tremor: nonlinear excitation by fluid flow, *J. Geophys. Res.*, 99, 11,859– 11,877, 1994.
- Kaneshima, et al., Mechanism of phreatic eruptions at Aso volcano inferred from near-field broadband seismic observations, *Science*, 273, 642– 645, 1996.
- Kawakatsu, et al., Aso94: Aso seismic observation with broadband instruments, *J. Volcanol. Geotherm. Res.*, 101, 129– 154, 2000.
- Mori, H., and T. Ui, Crustal deformation and eruptive activities of Mt. Usu in 2000 (in Japanese), *J. Natural Disaster Science*, 19, 383– 390, 2000.
- Murakami, et al., A model of magma movements associated with the 2000 eruption of Usu volcano inferred by crustal deformation detected by continuous GPS and geodetic measurements (in Japanese), *"Kokudo-Chiriin Jihou"*, 95, 99– 105, 2001.
- Nakada, S., Sequence of the 2000 eruption at Usu volcano, Japan (in Japanese), *Bull. Earthquake Res. Inst.*, 76, 203– 214, 2001.
- Oshima, et al., Seismic activity associated with the 2000 eruption of Mt. Usu (in Japanese), *Proc. Seis. Soc. Japan*, 2000, 33, 2000.
- Onizawa, et al., Three-dimensional seismic velocity structure around Usu volcano, Japan, *Kazan*, submitted, 2001.
- Tomiya, Depth of a magma chamber inferred by experimental petrological methods (in Japanese), *Chikyu Monthly*, 19, 720– 724, 1997.
- Tomiya, et al., Essential material of the 2000 eruption of Usu volcano (in Japanese), *Proc. Volcano, Soc. Japan*, 2000 (No.2), 30, 2000.
- Yamamoto, et al., Detection of a crack-like conduit beneath the active crater at Aso volcano, Japan, *Geophys. Res. Lett.*, 26, 3677– 3680, 1999.
- Yokoyama, I., and M. Seino, Geophysical comparison of the three eruptions in the 20th century of Usu volcano, Japan, *Earth Planets Space*, 52, 73– 89, 2000.

M. Yamamoto and H. Kawakatsu, Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan. (mare@eri.u-tokyo.ac.jp; hitosi@eri.u-tokyo.ac.jp)

K. Yomogida and J. Koyama, Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan. (yomo@ep.sci.hokudai.ac.jp; koyama@mande001.sci.hokudai.ac.jp)