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# 10s-Period volcanic tremors observed over a wide area in southwestern Japan

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**Abstract.** Unusual seismic oscillations with a period of 10 seconds were observed over a wide area of southwestern Japan. Several lines of evidence indicate that the origin of these 10s waves must be around the Aso volcano, located in the central part of Kyushu Island, Japan. Although a 10s period is unusually long for a volcanic tremor and no corresponding surface activity at the crater was reported by the local observatory, the volcanic origin of the tremor is indisputable. A further astonishing aspects of the observation is that there exists a strong correlation between the onset of 10s waves observed remotely and cessation of high-frequency (>1Hz) volcanic tremors at the Aso volcano. The Aso volcano appears to be trembling with a 10s period without this having been noticed. Since seismic monitoring of volcanic activity is limited to high frequencies (above 1 Hz) at the most of the volcanoes in the world, long-period tremors of the type observed here might be a widespread phenomenon that has been overlooked.

## Introduction

It is well known that there is a gap in the frequency range of geophysical monitoring of volcanic activities. Seismic observations are usually limited to frequencies above 1 Hz, and geodetic observations only cover periods longer than about one minute. Except for few cases [*Sassa,* 1935; *Seidl et al.,* 1981; *Churei, 1985*], however, no serious attempts to cover the missing frequency range have been made. Considering the success in predicting eruptions at several volcanoes [*Ishihara,* 1989; *Pinatubo Volcano Observatory Team,* 1991], observations of frequencies greater than 1 Hz may be sufficient for issuing warnings before hazardous volcanic activity. If we wish to understand how volcanoes work, however, observations which cover the missing frequency range are highly desirable. Recent advances in seismometry make such observations much easier than before; portable equipment which can cover a wide frequency band (50Hz-0.01Hz) can be easily installed at volcanoes [*Kawakatsu et al.,* 1992; *Neuberg et al.,* 1994].

In a series of experiments, we have conducted broadband seismic observation at the Sakurajima volcano, Japan [*Kawakatsu et al.,* 1992; *Ohminato et al.,* 1993]. In the records of multi-station broadband observations at the Sakurajima volcano conducted in the winter of 1992 [*Ohminato et al.,* 1993], we often noticed unusual oscillations with a 10s period (Figure 1). The signal is very weak below the level of the ambient seismic noise, but can be seen after lowpass-filtering below 0.1 Hz. The fact that these waves are recorded at all of the stations in Sakurajima island (separated from each other by less than 10 km) indicates that they are real signals rather than local noise. There exist, however, no corresponding seismic signals at higher frequencies. Furthermore, we could not identify any corresponding activity of the Sakurajima volcano itself and no corresponding earthquakes were reported by regional or teleseismic agencies. The 10s oscillations typically last about one minute with 5-6 cycles of 10s waves, although some events last for almost one hour.

From the phase delay at the three stations on Sakurajima, we found that these puzzling 10s waves are arriving from an azimuth of around N20°E. Searching other long-period seismic recordings in the region, we found that similar 10s waves are observed in a wide area in southwestern Japan, as far as 350 km away from the Sakurajima volcano (Figure 2a). Using the arrival times at all stations, we infer the source location to be around the Aso volcano (Figure 2b), which is located at an azimuth of about N16°E from Sakurajima. The particle motions at two sites (Sakurajima and Shiraki) where high quality three-component data were available also indicate that these 10s waves are Rayleigh waves arriving from the direction of Aso. All these lines of circumstantial evidence indicate that the 10s waves are generated somewhere around the Aso volcano.

At the Aso volcano, it has been known that long-period (3.5-8 seconds) micro-tremors exist [*Sassa,* 1935]. There has been also a report that these micro-tremors were recorded all over Kyushu when the activity of the volcano was very high [*Hashida,* 1990]. So it is very likely that the 10s wave we observed is a similar kind of volcanic micro-tremor, although the peak period is longer than previously recognized (Figure 3). We could, however, find no report from the local observatory of the



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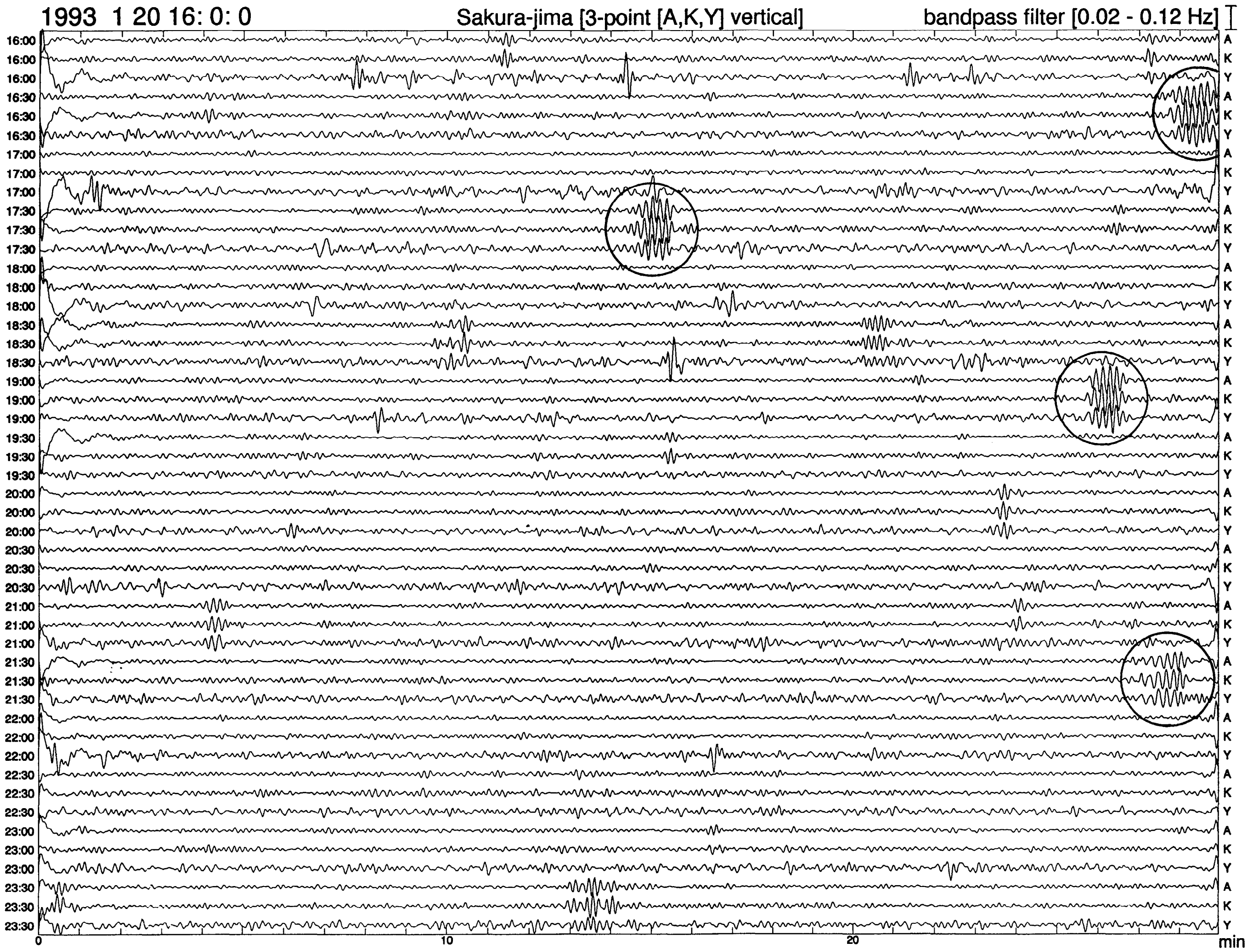


**Figure 1.** Broadband seismograms recorded at three stations (KMN, YNH, ARM) on Sakurajima island on January 20, 1992. Vertical components are bandpass-filtered between 0.02 and 0.12 Hz to remove ambient seismic noise. The length of each trace is about 30 minutes, and the beginning time is indicated on the left. Each group of three seismograms starting at the same time was recorded at three different stations on Sakurajima Island. Large amplitude 10s waves are circled; the fact that they are recorded at all three stations at the same time indicates that these are real signals, rather than local noise. The vertical scale at the upper-right corner corresponds $1\mu/s$

Kyoto University and the Japan Meteorological Agency (JMA) to indicate specific corresponding activity of the Aso volcano, except that the volcano was in general relatively active during this period.

A careful examination of smoked-paper records of the above-mentioned local observatories, however, revealed a totally unexpected result. We could not find any indication of activity in the records of long-period instruments (Wiechert and Galitzin seismometers) which were extensively used by Sassa 60 years ago to study the nature of the long-period tremor [*Sassa,* 1935]. Instead, the records of short-period instruments show continuous activity which must be related to some shallow activity around the crater. It turned out that the almost continuous activity of short-period (above 1 Hz) volcanic tremors ceases at the time of occurrence of the 10s oscillations (Figure 4). For example, the 10s wave on Figure 1 arrives at about 17:44. Since the travel time between Sakurajima and Aso is about 45 sec, the origin time would be at 17:43:15 at Aso. Figure 4 indeed shows that the quiescence starts at about 17:43. This correspondence (occurrence of the 10s wave and the onset of "tremor quiescence") is very good; when the 10s waves were continuously observed for about 7 minutes, the short-period tremors also ceased for about the same length of time. The physical mechanism for the origin of the short-period tremors itself is not yet well understood, so we do not have a good idea of what this correspondence really means. The simultaneous occurrence of the 10s wave and the onset of "tremor quiescence", however, strongly supports an origin beneath the Aso volcano for the 10s waves.

The peak particle velocity amplitude of the 10s waves at Sakurajima, which is 150 km distant from Aso, is

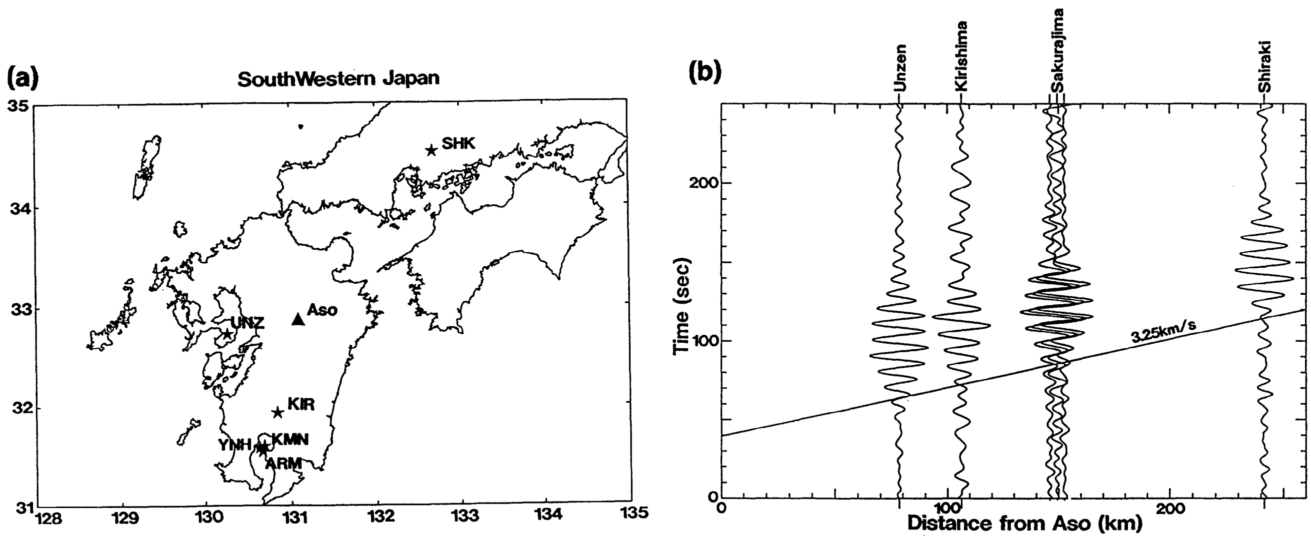


**Figure 2.** (a) Map of southwestern Japan. The triangle shows the location of the Aso volcano, and stars indicate the six stations where 10s waves are observed. They are UNZ (Unzen) of Japan Meteorological Agency, SHK (Shiraki) and KIR (Kirishima) of the Earthquake Research Institute, and three temporary stations in Sakurajima (KMN, YNH, ARM). (b) Records of 10s waves are lined up in a distance section. The distance is measured assuming that the Aso volcano is the origin. The travel time line is for a group velocity of 3.25 km/s.

about $0.6\mu/sec$. Using a reasonable seismic velocity structure for the area, this corresponds to a source moment of $M_o = 0.5 \times 10^{21} dyne \cdot cm$ for an isotropic source at a depth of 1 km. If the 10s wave is generated by the free vibration of a sphere as suggested by Sassa [*Sassa*, 1935], the estimated moment gives a pressure change of about $0.05\,bar$ for a sphere with a diameter of 1 km (the pressure change scales inversely proportional to the cube of the diameter). However, there seems to exist no strong evidence that the 10s oscillations are due to the free vibration of a magma chamber. Slow movement of magma itself may well be the origin of the 10s waves [*Ukawa and Ohtake*, 1987], but this can be only determined when we have good near-field waveform data. Such observations are currently planned, and we hope to resolve the physical origin of the 10s waves in the near future.

Besides the observation of the 10s wave itself, several other important conclusions may be drawn from our observations. Firstly, some volcanoes definitely generate long-period waves below 1 Hz [*Kawakatsu et al.*, 1992; *Neuberg et al.*, 1994], and such oscillations are likely to have been overlooked in view of the current practice for routine geophysical monitoring of volcanoes. Secondly, because longer-period waves can propagate farther, we may be able to monitor the activity of remote volcanoes, such as those at the mid-oceanic ridges, using long-period waves. Also, it is in general easier

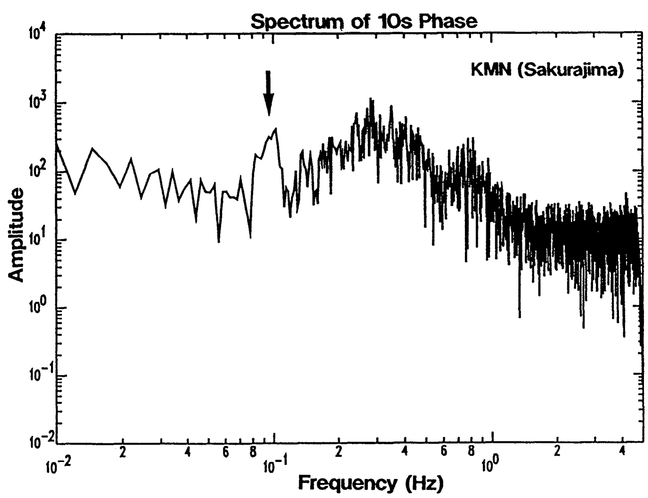


**Figure 3.** Typical spectrum of the broadband records of the 10s waves at Sakurajima. Note that the signal level of the 10s phase is below that of the ambient noise.

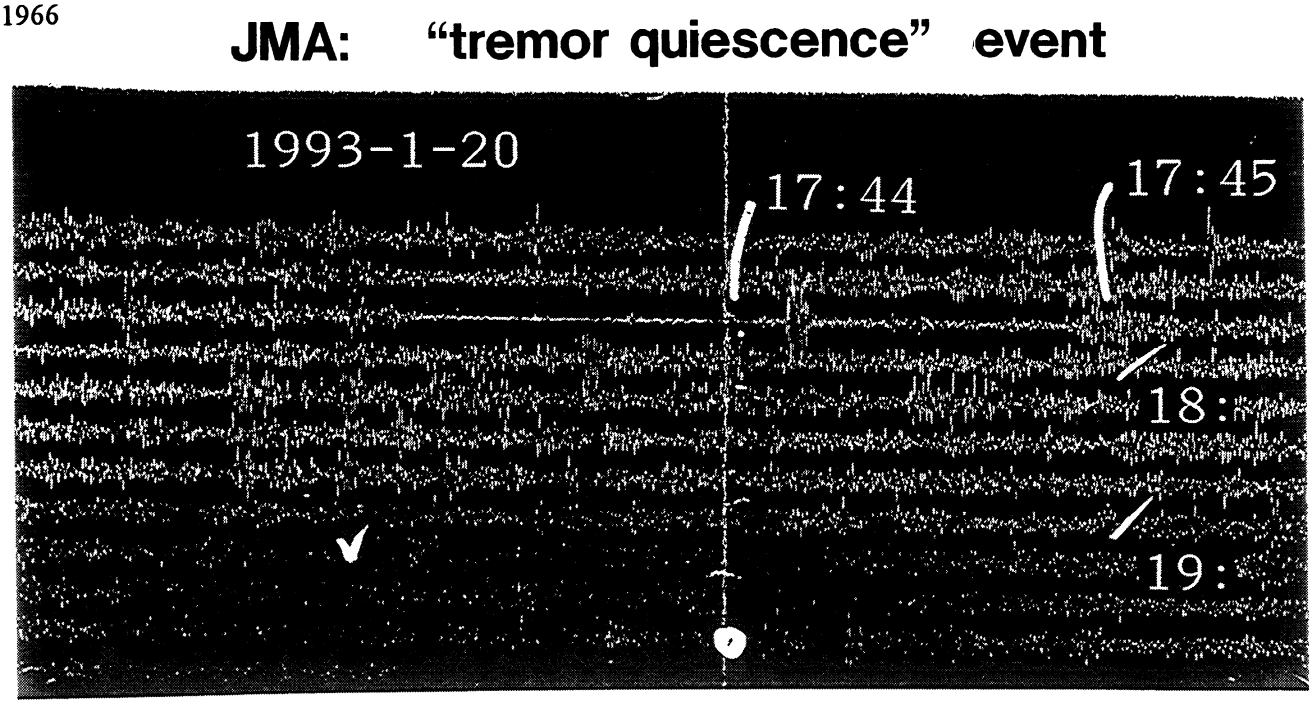


**Figure 4.** Smoked-paper record of a short-period instrument at the Aso volcano recorded by JMA. High frequency tremor is observed almost continuously except between 17:43 and 17:45. This time corresponds exactly to the expected time of the 10s waves seen in Figure 1.

to study the physical mechanisms that generate long-period waves, since waveform modeling is much easier than for high-frequency sources [*Takeo et al.,* 1990; *Uhira,* 1993; *Uhira and Takeo,* 1994]. Finally, considering the simultaneous occurrence of the long-period 10s waves and the onset of the short-period "tremor quiescence", broadband monitoring of volcanoes may be essential to understand how volcanoes work.

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