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# Detection of a crack-like conduit beneath the active crater at Aso volcano, Japan

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**Abstract.** To constrain the source of long period tremors (LPTs), we deployed a very dense broadband seismic network consisting of totally twenty-four stations around the active crater of Aso volcano in Kyushu, Japan. The spatial variation of the observed signal amplitudes reveals that the source of LPTs consists of an isotropic expansion (contraction) and an inflation (deflation) of an inclined tensile crack with a strike almost parallel to the chain of craters. The detected crack has a dimension of 1 km and its center is located a few hundred meters southwest of the active crater, at a depth of about 1.8 km. The extension of the crack plane meets the crater chain including the active fumarole at the surface, suggesting that the crack has played an important role in transporting gasses and/or lava to the craters from below. This work also demonstrates a powerful usage of broadband seismometers as geodetic instruments to constrain subsurface structures at active volcanoes.

## Introduction

At Aso Volcano in Kyushu, Japan, volcanic signals with unusually long periods (about 7 sec) have been observed since their discovery by *Sassa* [1935], and recent advances in broadband seismometry have revealed the existence of signals of even longer period [*Kaneshima et al.*, 1996]. A typical LPT has a short duration of several tens of seconds, and its spectrum shows peaks at about 15, 7.5, 5, and 3 sec. LPTs are emitted from the volcano continually, regardless of surface activity, at least during the last several years.

Analyzing the data of ASO94 campaign, we have previously attempted to locate the source of LPTs and to understand their mechanism by using methods such as waveform semblance [*Kawakatsu et al.*, 1999] and point source moment tensor waveform inversion [*Legrand et al.*, 1999]. We have shown that the source of LPTs is located at a few hundred meters southwest of the first crater and at a depth of 1-1.5 km; The resolved seismic moment tensor corresponds to a combination of isotropic expansion (contraction) and inflation (deflation) of a vertical crack, but the significance of the crack component was questionable because of the limited station coverage. From our deployment of a dense broadband seismic network in 1997, we show here the presence of a crack-like structure beneath the crater based on the spatial pattern of the observed LPTs amplitudes.

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## ASOBOI 97

From August 24 to 30, 1997, we deployed a broadband seismic network named ASOBOI 97 (Kawakatsu et al., submitted to Bull. Earth. Res. Inst., 1999) around Naka-dake of Aso volcano (Fig. 1(a)). The temporary part of the network comprised of three mobile instruments (Guralp CMG-40T) that were moved after each one-night session to form a total of eleven observation sites during August 26-29 (hereafter noted as mobile array), and ten stationary instruments (Guralp CMG-3T). Their velocity outputs were recorded continuously at a sampling rate of 100 Hz. Besides these temporary stations, our network included three permanent stations HND (with CMG-3T), SUN (with Streckkeisen STS-2), and NAR (with STS-2) to form in total twenty-four stations. Most of these stations were located within 1.5 km from the first crater of Naka-dake, and provided good azimuthal coverage. Among these twenty-four stations, eighteen stations within 1.5 km whose records are with good signal-to-noise ratio (S/N) are used in the following analysis.

Fig. 2 shows examples of the displacement signals after integrating and applying a 0.03-0.1 Hz band-pass filter to the observed velocity data. On filtered records LPTs are seen as isolated wave packets. Visual comparison of these filtered signals shows strong similarity of LPTs among stations and between events. Although the signal amplitudes vary substantially from station to station and from event to event, the relative amplitudes of each event at different stations are fairly constant.

The amplitude of LPT varies with time [*Kawakatsu et al.*, 1999], and was relatively small during the observation period. Thus, the amplitude of each LPT measured directly from the records is likely to be polluted by noises. So we use stacked signals with improved S/N to measure the spatial variation of the signal amplitudes. We choose totally 340 LPTs from seismograms observed at HND (our reference station, located in a 30 m-deep

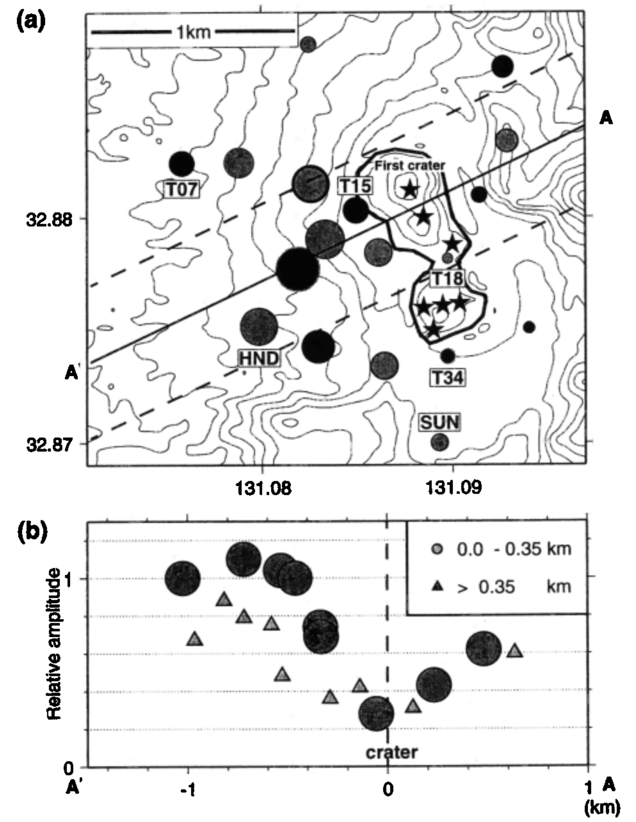


**Figure 1.** Spatial variation of LPT amplitudes (a): The solid circles indicate the stations used in our analysis and their radii are proportional to relative LPT amplitudes (black and gray circles represent the observed and the model predicted amplitude, respectively. See the text for the further information). The chain of craters of the Naka-dake consists of seven craters represented by stars (only the first crater is active at present). The contour lines represent 25 m contour intervals. (b): Two dimensional projection of the signal amplitudes along the line **A-A'**. Stations are classified into two classes according to the distance from the line.

tunnel) during the period when the mobile array was in operation, and determine the reference times for stacking for the period. For each station, signals are stacked using same reference times which are randomly selected from the 340 reference times; For each stacked trace, peak-to-peak amplitude is measured after applying a 0.03-0.1 Hz band-pass filter, and then relative amplitude to that of HND is estimated. Since the ratios of signal amplitudes between stations are almost constant for all the selected LPTs, no normalization is applied prior to stacking. Standard errors of the relative amplitudes estimated by re-sampling techniques [*Efron and Tibshirani*, 1993] are less than 0.02 for most of the stations. Station calibration in terms of amplitude is performed by comparing amplitudes of filtered (0.03-0.1 Hz) teleseismic surface waves. Considering the long wavelength of the LPTs, the observed seismic amplitudes are unlikely to be biased by the complex structure of the volcano. The calibration factor for each station falls within a range of 0.85-1.05 if we take the factor for HND as a unity. Thus the total error of the estimated relative amplitude of each station may be about 0.1 or less (i.e., about the size of the circles in Fig. 1(b)).

## Detection of a crack-like conduit

The spatial pattern of the estimated relative amplitudes of the vertical component is illustrated in Fig. 1(a). The pattern shows a clear feature that amplitudes are large around the southwest of the edifice, small along the chain of the craters , and again large around the northeast of the edifice. Fig. 1(b) shows a two-dimensional projection of this spatial pattern onto a vertical plane perpendicular to the chain of the craters. On this projection, the amplitudes at stations within 0.35 km from the line **A-A'** (between two broken lines) show a simple pattern. This pattern invokes an idea of a crack-like source of LPTs with a node along the chain of the craters. In addition, from the fact that amplitudes at all stations have the same sign, we expect that the source of LPTs consists of not only a crack component but also a component which gives uniform sign of displacement (e.g., an isotropic component).

With these points in mind, we model the observed LPT amplitudes using a simple source which consists of an isotropic point source and an inclined tensile crack. This simple source model is used to find the best fitting model by grid-search in the model parameter space described later. The amplitudes of the vertical component of eighteen stations are used in the analysis.

We assume that an isotropic point source is situated on the crack surface, and the crack is laterally symmetric about the isotropic point source. Uniform opening of the crack over the entire crack is also assumed. With these parameterizations, unknown parameters for the grid-search are as follows: location and seismic moment of the isotropic point source, width, lengths, strike, dip, and seismic moment of the tensile crack (Fig. 3(a)). In the grid-search, using our earlier results [*Kaneshima et al.*, 1996; *Kawakatsu et al.*, 1999; *Legrand et al.*, 1999],

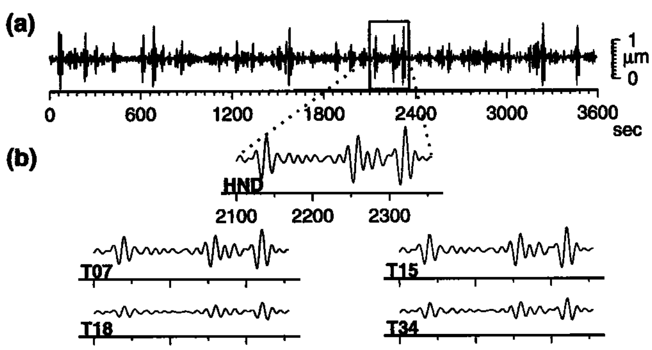


**Figure 2.** (a): Vertical component band-pass filtered (0.03-0.1Hz) displacement seismogram for one hour starting at 01:00 on Aug. 26, 1997 (JST).
(b): Examples of seismograms observed at different stations. All traces are drawn in the same scale for the same time window.

the location of the isotropic point source is restricted to southwest of the first crater. The other parameters are allowed to take a wide range of values (Table 1). The parameters are searched for every 0.1 km in spatial dimension and 1° in angle.

In our model search, we use the fact that the amplitude of the long-period signal observed in the near-field is proportional to that of the static displacement [*Legrand et al.*, 1999]. This assumption allows us to use the code developed by *Okada* [1992] which calculates static displacements due to a source in a half space, and makes the model search far more efficient compared to waveform inversions. To correctly calculate static displacement for the station altitude, we assume that each station is located at the free surface of the half space, and equate the relative altitude of the station from the source to the depth of the source in the half space. The slope of the flank of Naka-dake is not too steep, hence the effect of the topography is unlikely to be significant (e.g., *Cayol et al.*, 1998).

The final model we obtained is summarized in Table 1 and the image view of the model is illustrated in Fig. 3(b). The RMS error $= \sqrt{\frac{1}{N}\sum(D_i - M_i)^2}$ of the best model is 0.058, where $N, D_i$, and $M_i$ represent the number of stations, the observed, and the calculated amplitudes of the $i$th station, respectively. Since these parameters are non-linearly dependent on each other, ordinary error analysis can not be applied easily. We estimate the reasonable range of values for each parameter as a range out of which the RMS error exceeds 0.063 for any set of the other parameters within the entire parameter space (Fig. 4). The value 0.063 is chosen such that the pattern of the surface displacement changes significantly. This value roughly corresponds to a change of the location of the isotopic point source by 0.1 km in the North-South direction (NS in Fig. 4). Resultant ranges are summarized in Table 1. This value of the RMS error indicates that the model prediction error for each station is about 6% of the amplitude at HND (i.e., about half the size of the circles in Fig. 1(b)). In Fig. 1(a), the observed and the model predicted amplitudes are respectively represented as black and gray

**Table 1.** Model parameters

| | | search range | best model | reasonable range |
|---|---|---|---|---|
| isotropic | north | 0.0 ~ -0.5 | -0.2 km | -0.3 ~ -0.1 |
| point source | east | 0.0 ~ -0.5 | -0.1 km | -0.2 ~ -0.1 |
| | depth | 0.6 ~ 2.1 | 1.8 km | 1.6 ~ 1.8 |
| tensile crack | dip | 45 ~ 90 | 85° | 83 ~ 86 |
| | strike | 0 ~ -45 | -28° | -26 ~ -31 |
| | width | 0.0 ~ 2.0 | 1.0 km | 0.8 ~ 1.2 |
| | length1 | 0.0 ~ 2.0 | 1.5 km | > 1.4 |
| | length2 | 0.0 ~ 3.0 | 1.0 km | 0.4 ~ 1.4 |

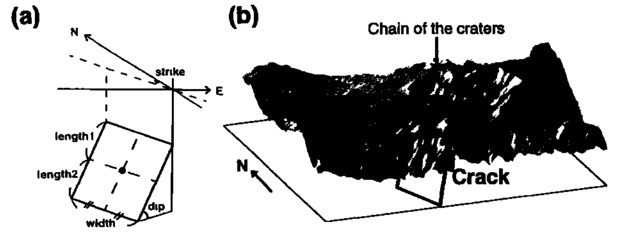


**Figure 3.** (a): Model parameters used in our model search. The length of the upper part of the crack from the isotropic point source (length1) and the that of the lower part (length2) are treated separately.
(b): Bird's-eye view of the obtained model. The crack is almost parallel to the chain of craters and the extension of the crack meets the active fumarole at the surface.

circles whose radii are proportional to the values of the amplitudes. In this figure, a smaller circle is put onto a larger one, thus the width of the ring represents the misfit which is very small.

## Discussion

So far, we use only the vertical component. As mentioned earlier, the LPTs amplitude is relatively small during our observation, and the S/N of the horizontal components is lower than that of the vertical component. We have attempted to determine the relative amplitudes of noisy horizontal components by various stacking techniques, but we could not obtain reliable estimates for the mobile array, hence we use the horizontal component of the other stations for the three-component analysis. The resulting model turns out to be almost identical to that for the vertical component alone, thus we retain it as the best model.

Our best model for the LPT source indicates that the strike of the inclined crack is almost parallel to the chain

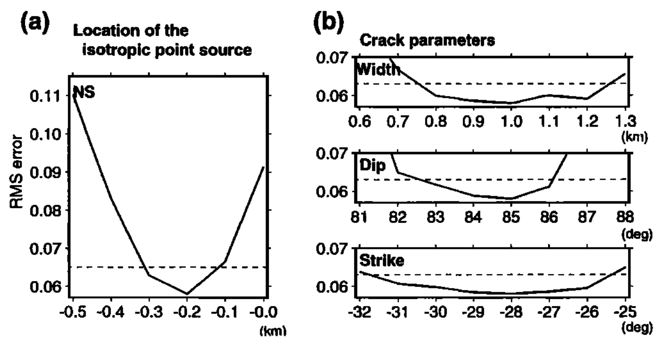


**Figure 4.** Variation of the minimum RMS error as a function of each parameter. Examples for (a) the location of the isotropic point source and (b) crack parameters [width, dip, strike] are shown. A minimum RMS error for a given value of a specified parameter is obtained by seeking a set of the other parameters within entire parameter space which gives the minimum value of the RMS error.

of old craters of the Naka-dake, and that the extension of the crack plane meets the crater chain including the active fumarole at the surface. The horizontal length of the crack (1.0 km) is also almost equal to that of the chain of craters. The obtained result appears to suggest that the chain of the craters is the surface expression of the detected buried crack, and that the crack has played an important role in transporting gasses and/or lava to the craters from below.

Using the parameters obtained above, we can write the seismic moment tensor of the source of the LPTs as $M = 3.25\ \mathcal{I} + 1.62\ \mathcal{C}\ (\times 10^{11}\mathrm{N}\cdot\mathrm{m})$, where $\mathcal{I}$ is a unit isotropic moment tensor with eigenvalues of (1:1:1) and $\mathcal{C}$ is a unit tensile crack moment tensor with eigenvalues of (1:1:3) for a Poisson material (we use 5 $\mu$m as the mean displacement of filtered LPT signals at HND). Our result ($M \propto 2\ \mathcal{I} + 1\ \mathcal{C}$) is a little different from the decomposition of the centroid moment tensor of LPTs by *Legrand et al.* [1999] ($M \propto 3.6\ \mathcal{I} + 1\ \mathcal{C}$). This difference is likely due to the fact that they used data observed at more distant stations than our analysis, and thus have lower resolution. Overall similarity of the source decomposition indicates that the spatial pattern of amplitudes has been almost constant during the period between these two observations, and suggests the repetitive source process of LPTs.

The presence of the large isotropic component requires some consideration, since a single thin crack alone cannot produce it. One way to account for it is to have the crack with an appreciable thickness. *Davis* [1986] derived approximate expressions for surface displacements due to an ellipsoidal pressure source in an elastic half-space. Following his result, if we take the lengths of the two longer axes of ellipsoid to be 2.5 km and 1.0 km (our estimate of the length and width of the crack), the seismic moment tensor of the LPT source whose eigenvalues are (3:3:5) can be interpreted as a result of the pressure change in an ellipsoid whose thickness is about 0.5 km. This estimate of the crack thickness is fairly large, and we will have a difficulty in applying the crack-wave theory [*Chouet*, 1986] to explain the long resonance period of LPTs (*cf. Kawakatsu et al.*, 1999; *Yamamoto*, 1999).

The detected crack-like conduit gives more detailed image of the LPT source region given in our previous work [*Kaneshima et al.*, 1996; *Kawakatsu et al.*, 1999] in which the source is considered to be more-or-less isotropic. Although there are still many problems to be resolved, with a dense broadband seismic network, we now have clear lines of evidence for the presence of a crack-like conduit beneath the active crater at Aso volcano. We have also demonstrated a powerful usage of broadband seismometers as geodetic instruments to infer structures under active volcanoes.

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