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Source amplitudes of volcano-seismic signals determined by the amplitude source location method as a quantitative measure of event size

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ABSTRACT

The amplitude source location (ASL) method, which uses high-frequency amplitudes under the assumption of isotropic *S*-wave radiation, has been shown to be useful for locating the sources of various types of volcano-seismic signals. We tested the ASL method by using synthetic seismograms and examined the source amplitudes determined by this method for various types of volcano-seismic signals observed at different volcanoes. Our synthetic tests indicated that, although ASL results are not strongly influenced by velocity structure and noise, they do depend on site amplification factors at individual stations. We first applied the ASL method to volcano-tectonic (VT) earthquakes at Taal volcano, Philippines. Our ASL results for the largest VT earthquake showed that a frequency range of 7–12 Hz and a Q value of 50 were appropriate for the source location determination. Using these values, we systematically estimated source locations and amplitudes of VT earthquakes at Taal. We next applied the ASL method to long-period events at Cotopaxi volcano and to explosions at Tungurahua volcano in Ecuador. We proposed a practical approach to minimize the effects of site amplifications among different volcano seismic networks, and compared the source amplitudes of these various volcano-seismic events with their seismic magnitudes. We found a proportional relation between seismic magnitude and the logarithm of the source amplitude. The ASL method can be used to determine source locations of small events for which onset measurements are difficult, and thus can estimate the sizes of events over a wider range of sizes compared with conventional hypocenter determination approaches. Previously, there has been no parameter widely used to quantify the sources of volcano-seismic signals. This study showed that the source amplitude determined by the ASL method may be a useful quantitative measure of volcano-seismic event size.

1. Introduction

Seismic signals at volcanoes, including long-period (LP) and very-long-period (VLP) events, tremor, and volcano-tectonic (VT) earthquakes, are generated by magmatic and hydrothermal activity, and thus contain information about internal dynamics and stress states of volcanoes (e.g., Chouet, 1996; Neuberg, 2000; McNutt, 2005; Kawakatsu and Yamamoto, 2007; Zobin, 2012; Chouet and Matoza, 2013). Source location and event size are fundamental parameters used to characterize volcano-seismic signals, and their rapid and correct determination is critically important in volcano monitoring. However, it is often difficult or impossible to locate these signals by conducting traditional hypocenter determinations, because onsets of typical LP events and tremor are emergent and those of VT earthquakes are masked by the relatively large ambient noise at volcanoes. Because of the difficulty of source location determination, the magnitudes of the events usually cannot be reliably determined. Although the reduced displacement (Aki and Koyanagi, 1981) has been used to estimate tremor source amplitudes, there is no widely used parameter to quantify the size of volcano-seismic events at different volcanoes.

Battaglia and Aki (2003) proposed the amplitude source location (ASL) method, which is based on a method originally proposed by Yamasato (1997). The ASL method assumes isotropic *S*-wave radiation and uses seismic amplitudes corrected for site amplifications. Kumagai et al. (2010) showed that the ASL method is useful to locate various volcano-seismic signals in a high frequency band around 5–12 Hz, including an LP event, an explosion event, and tremor associated with lahars and pyroclastic flows. They interpreted that the assumption of isotropic *S*-wave radiation is valid in this frequency band; the

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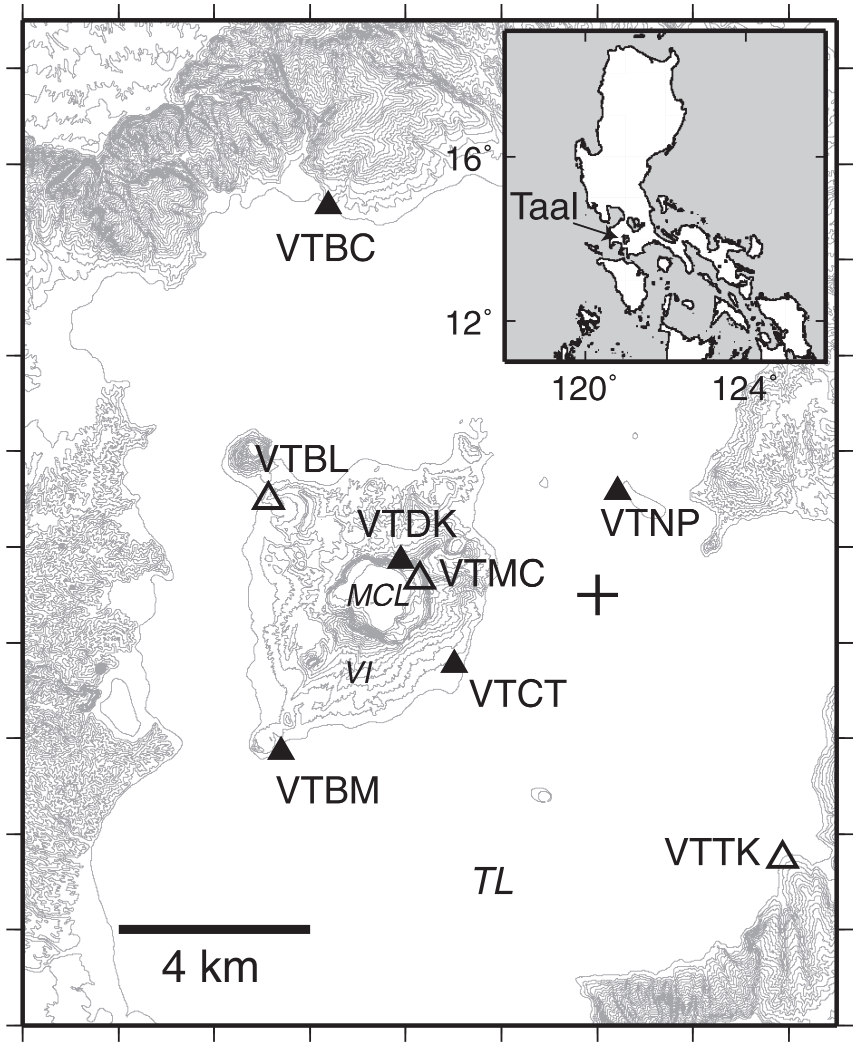

Fig. 1. Locations of broadband (solid triangles) and short-period (open triangles) seismic stations at Taal volcano, Philippines. The inset shows the location of Taal volcano. VI, Volcano Island; MCL, Main Crater Lake; TL, Taal Lake. The source location (plus sign) used to calculate the synthetic seismograms is at 3 km below sea level.

path effect caused by the scattering of seismic waves due to small-scale heterogeneities distorts the *S*-wave radiation pattern and results in isotropic *S*-wave radiation in a high frequency band. The frequency dependence of the *S*-wave radiation patterns of tectonic earthquakes was shown by Takemura et al. (2009). The validity of the assumption of isotropic *S*-wave radiation is supported by Kumagai et al. (2011b), who numerically simulated high-frequency seismic waveforms in heterogeneous media with volcano topography. Battaglia et al. (2003) used the ASL method to locate LP events beneath Kilauea volcano, Hawaii, and it has also been applied to the analysis of tremor signals at the Piton de la Fournaise volcano, Réunion Island (Battaglia et al., 2005a, 2005b) and at Meakandake, Japan (Ogiso and Yomogida, 2012). Kumagai et al. (2011a) also used the ASL method to analyze an explosion event at Tungurahua volcano, Ecuador.

One of the advantages of the ASL method over traditional hypocenter determination methods is that it can simultaneously determine the source location and the initial or source amplitude. It might be possible to use the source amplitude, defined as the amplitude at the source location calculated under the assumption of isotropic radiation of far-field *S* waves, as a quantitative measure of the size of an event producing volcano-seismic signals. Although Battaglia et al. (2005b) and Kumagai et al. (2011a) used the source amplitude to quantify tremor signals at the Piton de la Fournaise and an explosion event at Tungurahua, respectively, the source amplitudes of various volcano-seismic signals observed at different volcanoes have yet to be systematically examined. Because the accuracy of the source amplitude estimate depends on the correct determination of the source location by the ASL method, the accuracy and resolution of source locations determined by this method must be examined. Furthermore, site amplification factors depending on a reference site should be carefully considered when comparing the source amplitudes at different volcanoes.

In this study, we first tested the ASL method at Taal volcano, Philippines by using synthetic seismograms for a network of eight seismic stations. As demonstrated by Kumagai et al. (2011b), extensive full waveform simulations using a highly heterogeneous structural model are required to reproduce high-frequency seismograms with isotropic radiation. Such extensive simulations, however, are beyond the scope of the present study. We therefore used Ricker wavelets assuming isotropic *S*-wave radiation for synthetic seismograms. Using

Table 1
One-dimensional *P*-wave velocity structure used in this study.

Depth (km)	*P*-wave velocity (m/s)
−1.0	3100
2.0	4300
4.0	4800
6.0	5200
8.0	6000
15.0	6000