Spatio-temporal variations in seismic scattering characteristics at Taal volcano and their relation to magma activity

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Taal volcano in the Philippines is one of the most active volcanoes in the world, which produced 33 eruptions since 1572. Seismic, geodetic, electromagnetic, and geochemical studies have been conducted to investigate the volcano’ s magma system [e.g. Zlotnicki et al., Bull. Volcanol., 2009]. A high-resistivity region beneath Main Crater Lake (MCL) revealed by magnetotelluric surveys was interpreted as a hydrothermal reservoir containing gases or two-phase hydrothermal water exsolved from magma [Yamaya et al., Bull. Volcanol., 2013]. A high-attenuation region beneath the eastern part of the volcano estimated from high-frequency seismic waveform analysis was interpreted as an active degassing magma [Kumagai et al., Geophys. Res. Lett., 2014], although Yamaya et al. [2013] interpreted that sediments containing altered clay exist in this region. Both studies suggest the existence of fluids near the surface, but their interpretations are not consistent.
changes associated with hydrothermal and magmatic activities may appear in high-frequency scattering waves. Therefore, we analyzed high-frequency seismic waveforms of volcano-tectonic (VT) earthquakes at Taal volcano to investigate the scattering characteristics represented by the mean free path (l_0) and the quality factor of *S* waves (Q_s). The earthquakes analyzed in this study occurred at similar locations NW of the volcano in May 2012-January 2013. We first estimated l_0 and Q_s assuming their homogeneous distributions using the analytical solution of the radiative transfer theory [Paasschens, Phys. Rev. E, 1997], and found that our estimates of l_0 and Q_s values ranged from 1000 to 1500 m and from 100 to 125, respectively, in the 7-12 Hz frequency band. The estimated l_0 values are smaller than those in the ordinary crust (10^4-10^5 m), indicating that Taal has a strong structural heterogeneity.
However, the VT waveform on 15 May 2012 at VTCT located in the southeastern part of the volcano showed a clear direct *S* wave with small coda amplitudes, while those at other stations have large coda amplitudes characterized by multiple scattering. We found that the coda amplitudes at VTCT in the event on 25 June 2012 were clearly larger than those at VTCT in the event on 15 May 2012. Since these two events occurred at similar locations with similar mechanisms, these features suggest that l_0 was not spatially homogeneous and changed temporally within one month.
To synthesize seismogram envelopes in 3D media with nonuniform distributions of l_0 and Q_s, we used the Monte Carlo method of Yoshimoto [J. Geophys. Res., 2000]. When we assumed an anomaly region with l_0 = 10000 m beneath the eastern part of the volcano with a layered structure consisting of a highly heterogeneous (l_0 = 500 m) surface layer underlain by a less heterogeneous (l_0 = 10000 m) layer, the synthesized waveform at VTCT was similar to the observed waveform on 15 May 2012 at VTCT. Furthermore, we found that the relatively strong scattering of the observed waveform on 25 June 2012 at VTCT is explained by changing the l_0 value in the anomaly region to smaller one (l_0 = 500 m).
These spatio-temporal variations in l_0 may be explained by the existence of magma containing volatiles near the surface, in which the amount of degassed bubbles temporally changed. Geochemical surveys performed at MCL in 2010-2011 indicated that CO_2 emissions fluctuated in a short period within months and increased significantly during a volcano-seismic unrest period [Arpa et al., Bull. Volcanol., 2013]. The temporal change in the amount of bubbles in the magma suggested by this study may correspond to such CO_2 fluctuations at MCL, if bubbles in the magma are released through cracks in the unconsolidated sediment layer to MCL.

Keywords: Volcano-tectonic earthquake, Envelope waveform, Monte Carlo method, Mean free path, Q factor, Degassing

