Abstract. We analyzed observations of a swarm of long-period (LP) seismic events with a peak frequency around 0.8 Hz and Q = 6 at Taal volcano, Philippines. Our travel time analysis and waveform inversion of the events pointed to a tensile crack source dipping 30-60° at a shallow (100-200 m) depth beneath the northeastern flank of the active volcano island. A simulation using a fluid-filled crack model indicated that the complex frequencies of the waveforms are explained by the fundamental longitudinal mode resonance of a vapor-filled crack. A satellite thermal infrared image acquired during the swarm period suggests that the LP events were not accompanied by surface gas releases. We considered a vapor transportation model in which vapor exolved from magma and rose in a fissure extending to the LP source. This model yielded estimates that 10^6 m^3 of magma was involved in the LP swarm and that the temperature of vapor in the LP source crack was around 600 K. We modeled a triggering mechanism of the crack resonance based on sudden condensation of vapor at the crack tip in a cold aquifer. This model explains observations of the dilatational first motion and the total volumetric change.

1. LP events at Taal
Taal volcano, Philippines (Fig. 1), is a basaltic stratovolcano on a subduction zone of the South China Sea crust. Historical activities of the volcano suggest a high risk of near future eruption. Two volcanic crises occurred in 2010 and 2011, between which a swarm of LP events with a peak frequency of 0.8 Hz and Q = 6 was observed (Fig. 2). The event waveforms are quite similar to each other (Fig. 3), suggesting a fixed source location and mechanism. We therefore used the stacked waveforms to improve the signal-to-noise ratios in the following analyses.

2. Source location and mechanism
(1) We estimated the source location using P arrivals at six stations (Fig. 4a).
(2) We performed waveform inversion assuming this source location and four source geometries (vertical crack, horizontal crack, vertical pipe, and sphere) using data at VTDK and VTMC. We obtained the minimum AIC value for a vertical crack.
(3) Next, we performed a grid search for the location, strike, and dip of a crack source. We obtained small residuals for cracks ranging in dip from 30° and 60° at a shallow (100-200 m) depth beneath the northeastern flank of the volcano island (Fig. 4b).
(4) Waveforms except for the NS component at VTDK were well reconstructed (Fig. 5).

3. Complex frequency analyses
We used the fluid-filled crack model of Chouet (1986, JGR). The observed Q was explained by the fundamental longitudinal mode resonance of a vapor-filled crack. Assuming that this mode represents oscillations of 0.8 Hz, the crack size L was estimated at the order of 10^4 m. A fitting of the observed and calculated waveform amplitudes yielded an estimation that the volumetric decrease was on the order of 10^3 m^3 (Fig. 6).

4. Satellite imaging of the region above the LP source
A Landsat thermal infrared image showed a low temperature in the region above the LP source, suggesting that the events were not directly linked to high-temperature surface gas releases (Fig. 7).

5. Source model
We considered a vapor transportation model from magma to the LP source through a fissure without a significant mass loss. This model yielded an estimation that 10^5 m^3 of magma was involved in the LP swarm (*1). We further assumed an adiabatic process and that the pressure of vapor is in equilibrium with the lithostatic pressure at each depth. When the temperature of vapor at the LP source depth was estimated at around 600 K (Fig. 8), an easy way to explain the total volumetric change without surface gas releases may be a phase transition between liquid and gas. Because the first motion of the stacked waveform at VTMC was downward (Fig. 3), we considered condensation as a possible triggering mechanism of the LP events at Taal. The net volumetric change induced by condensation is \( \Delta V = \frac{\Delta m R (\rho C_p \Delta T)}{\rho V} \), where we took into account a temperature increase caused by the latent heat. Under the lithostatic pressure of 200 m depth (5 MPa), \( \rho C_p \Delta T \) is so that \( \Delta V \) is estimated to have a negative sign. Thus condensation is expected to induce a dilatational motion.

To produce condensation rapidly enough to emit an observable amount of seismic energy, we considered a cold aquifer layer (Fig. 10a). When vapor in the fissure enters the aquifer, it is sufficiently cooled (Fig. 10b). Vapor near the crack tip then condenses, inducing a volumetric decrease that triggers the crack resonance (Fig. 10c).

\[ (1) \] We used \( R = \frac{M}{T} \) g/cm, where \( M \) is the mass fraction of exsolved vapor; \( \rho = 10^3 \) kg/m^3 is the density of magma; \( \rho' = 10^3 \) kg/m^3 is the density of vapor at the LP source depth; \( \rho' = 10^3 \) kg/m^3 is the average volume of vapor that flowed into the LP source per event (assumed to be comparable to the crack volume); and \( V \) (10^6) is the total number of events throughout the swarm.

\[ (2) \] We consider a slight release of magma that was heated by the mantle. Then \( P_{\text{in}} = \rho V \), \( P_{\text{in}} = \rho V \), and Phugoid, which yield a depth--temperature relationship of vapor (Fig. 8). We assumed that vapor exsolved from magma at a depth of 5 km with density of 10^3 K.

Oscillation of a Shallow Hydrothermal Fissure Inferred from Long-Period Seismic Events at Taal Volcano, Philippines

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