Ascending seismic source during an explosive eruption at Tungurahua volcano, Ecuador

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[1] Application of seismic techniques to an explosion event at Tungurahua volcano, Ecuador, provided clear images to elucidate its source process. A source location method using high-frequency seismic amplitudes with an *S*-wave velocity of 2000 m/s indicates that the event was triggered at a depth of 6 km below the summit, and the source ascended toward the summit at a speed of about 1600 m/s. Waveform inversion of low-frequency signals at the event onset points to an isotropic mechanism with initial deflation at a similar depth of 6 km. The ascending source suggests that a pressure wave propagated along the magma conduit, triggering fragmentation of magma at shallow depths. Rapid decompression of magma in a shock tube has been considered to be an important mechanism for explosive eruptions triggered by ruptures at the magma surface. However, our study suggests that explosive eruptions are triggered by pressure disturbances in magma at depth. **Citation:** Kumagai, H., P. Placios, M. Ruiz, H. Yepes, and T. Kozono (2011), Ascending seismic source during an explosive eruption at Tungurahua volcano, Ecuador, *Geophys. Res. Lett.*, *38*, L01306, doi:10.1029/2010GL045944.

1. Introduction

[2] The processes leading to explosive eruptions are of fundamental importance in volcanology [e.g., *Alidibirov and Dingwell*, 1996]. The mechanism of explosive eruptions has been explained by rapid decompression of magma in a shock tube (the shock-tube model). According to this model, bubbly magma at high pressure is initially separated from air at atmospheric pressure by a surface capping layer of solidified magma. When the surface of magma is ruptured, shock and rarefaction waves propagate into the air and bubbly magma, respectively, resulting in an explosive eruption. These processes have been extensively investigated in theoretical and experimental studies [e.g., *Turcotte et al.*, 1990; *Mader et al.*, 1994; *Alidibirov and Dingwell*, 1996; *Koyaguchi and Mitani*, 2005; *Ichihara et al.*, 2002].

[3] *Kanamori et al.* [1984] proposed a seismic source model for an explosive eruption that is similar to the shock-tube model. They suggested that the sudden removal of the cap above a pressurized magma cavity at shallow depth created a force system represented by a vertical single force and an implosive source. This model has been used to interpret seismic source mechanisms of explosions [e.g., *Uhira and Takeo*, 1994; *Nishimura*, 1998; *Ohminato et al.*, 2006]. On the other hand, *Tameguri et al*. [2002] showed that the seismic source of an explosive eruption at Sakurajima volcano, Japan, originated at a depth of 2 km beneath the summit, and was followed by surface waves generated at shallow depths. These results suggest that the eruption was triggered by a pressure wave generated by the initial deep source, whereas the model of *Kanamori et al.* [1984] or shock-tube model places the eruption trigger at the magma surface. *Nishimura and Chouet* [2003] performed numerical simulations of a magma conduit-reservoir system to model eruptions based on these two possible trigger mechanisms.

[4] An explosive eruption was recorded at five broadband seismic and infrasonic stations at Tungurahua volcano, Ecuador, on 11 February 2010. We used waveform inversion and a source location method using high-frequency seismic amplitudes to analyze the explosion event. The source location method has been proved useful to locate long-period (LP) events and tremor [*Battaglia and Aki*, 2003; *Battaglia et al.*, 2003; *Kumagai et al.*, 2009, 2010] for which traditional hypocenter determinations using onset arrival times are usually difficult or impossible. Our results indicate that the initial source of the explosive eruption was at a depth of 5–6 km beneath the summit, and that the source ascended toward the summit. The ascending source suggests that a pressure wave propagated along the magma conduit, triggering fragmentation of magma at shallow depths.

2. Data and Methods

[5] Tungurahua volcano (elevation 5023 m) is an andesitic stratovolcano in the central Ecuadorian Andes. It has been active since 1999, and is characterized by vulcanian and strombolian eruptions. In July and August 2006, Tungurahua's activity reached a peak with frequent explosive eruptions accompanied by pyroclastic flows [*Kumagai et al.*, 2007; *Fee et al.*, 2010]. Five observation stations featuring broadband seismometers and low-frequency infrasonic sensors are maintained at the volcano (Figure 1a) [*Kumagai et al.*, 2010]. On 11 February 2010, an explosion event was recorded at the five stations (Figure 2). Impulsive acoustic waves recorded by infrasonic sensors clearly indicated that the event was associated with an explosive eruption. This event was followed by long seismic coda waves characterized by oscillations at frequencies of around 1–2 Hz (Figure 2a). Unlike the usual explosion events at this volcano, this event was accompanied by very-long-period (VLP) signals at its onset (Figure 2b). Since both waveform inversion and the source location method are applicable to this event, we analyzed the event to investigate its source processes.

[6] We first applied waveform inversion to the VLP signals at the event onset (Figure 2b) by following the procedure of *Kumagai et al.* [2010], in which isotropic, vertical pipe, and crack mechanisms were assumed as possible mechanisms

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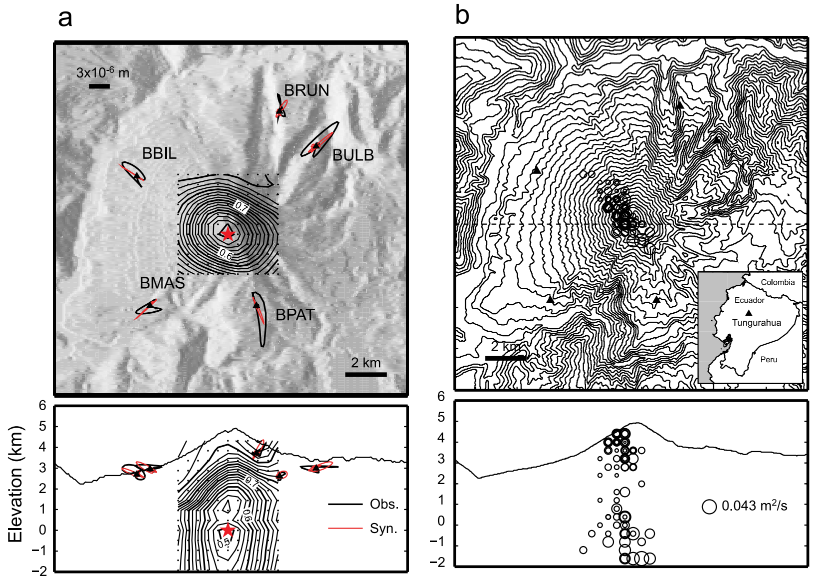

Figure 1. (a) Locations of broadband seismic and infrasonic stations (triangles) at Tungurahua volcano, Ecuador, and contour plots of horizontal and vertical distributions of the normalized residuals obtained by waveform inversion of an explosion event on 11 February 2010. Observed (black lines) and synthetic (red lines) particle motions obtained from displacement seismograms are also shown. Dots indicate the nodes used in the grid search to estimate the source location. The elevations at BRUN, BPAT, BMAS, BBIL and BULB are 2640 m, 3720 m, 2680 m, 2600 m, and 2860 m, respectively. (b) Source locations of the explosion event estimated by using vertical seismic amplitudes in a frequency band of 5–10 Hz. The circles showing source locations are scaled by the initial amplitudes. The horizontal dashed line in Figure 1b (top) is the horizontal location of the vertical profiles shown in Figures 1a (bottom) and 1b (bottom).

for a point source. We calculated Green's functions with the topography of Tungurahua and a *P*-wave velocity of 3500 m/s, an *S*-wave velocity of 2000 m/s, and a density of 2500 kg/m^3. The observed three-component waveforms from the five stations were band-passed between 2.5 and 10 s. We conducted a grid search in space to find the best-fit location for isotropic, vertical pipe, and crack mechanisms in our inversion.

[7] Using the high-frequency seismic amplitudes of the explosion event, we then applied the source location method of *Kumagai et al.* [2010], which uses a far-field approximation and assumes isotropic radiation of *S* waves. This model was used to fit the envelopes of observed vertical velocity amplitudes at the individual stations to estimate the initial amplitude and resultant normalized residual at each node. A spatial grid search was conducted to find a minimum residual node, which was regarded as the source location. *Kumagai et al.* [2010] interpreted that the assumption of isotropic radiation becomes valid in the 5–10 Hz frequency band because of the path effect caused by the scattering of seismic waves.

3. Results

[8] The inversion results pointed to an isotropic source mechanism at a depth of around 5 km beneath the summit (Figure 1a). The normalized residual at the best-fit isotropic source location shown in Figure 1a was 0.485, whereas those for the best-fit vertical pipe and crack sources were 0.59 and 0.57, respectively. Thus, the isotropic mechanism best explains the observed seismograms. Small residuals in the waveform inversion result are elongated in the vertical direction (Figure 1a), which may indicate a limited resolution in this direction. The source-time function at the best-fit isotropic source location showed deflation followed by inflation (Figure S1).[1] A single-force source is also a possible mechanism. However, because we used the limited number of stations (5) and the relatively short period band (2.5–10 s), we could not constrain a single-force source in our waveform inversion. Because the estimated source is deep (5 km), a possible single-force source may have been generated by mass advection [*Takei and Kumazawa*, 1994]. This single-force mechanism is different from that proposed by *Kanamori et al.* [1984] in the seismic source model for an explosive eruption.

[9] In the source location method, we used a frequency band of 5–10 Hz and sliding time windows of 2 s overlapping by 1 s, and determined the source location in each window assuming an *S*-wave velocity of 2000 m/s. As the estimated source locations using high-frequency amplitudes were affected by noise, we selected reliable source locations as those with the normalized residuals of less than 0.1. We also excluded the source locations that were affected by infrasonic waves and those determined at the domain boundaries. The selected source locations aligned vertically beneath the summit (Figure 1b). Figure 3 shows the source locations with the residual distributions for three time windows (17–22 s) at the event onset, which indicate that the source ascended toward the summit from a depth of around 6 km beneath the summit. These high-frequency source locations in 17–21 s are similar to the source location of the VLP signals of this time period (Figure 1a). We plotted the depths of the high-frequency source locations as a function of time with the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL045944.

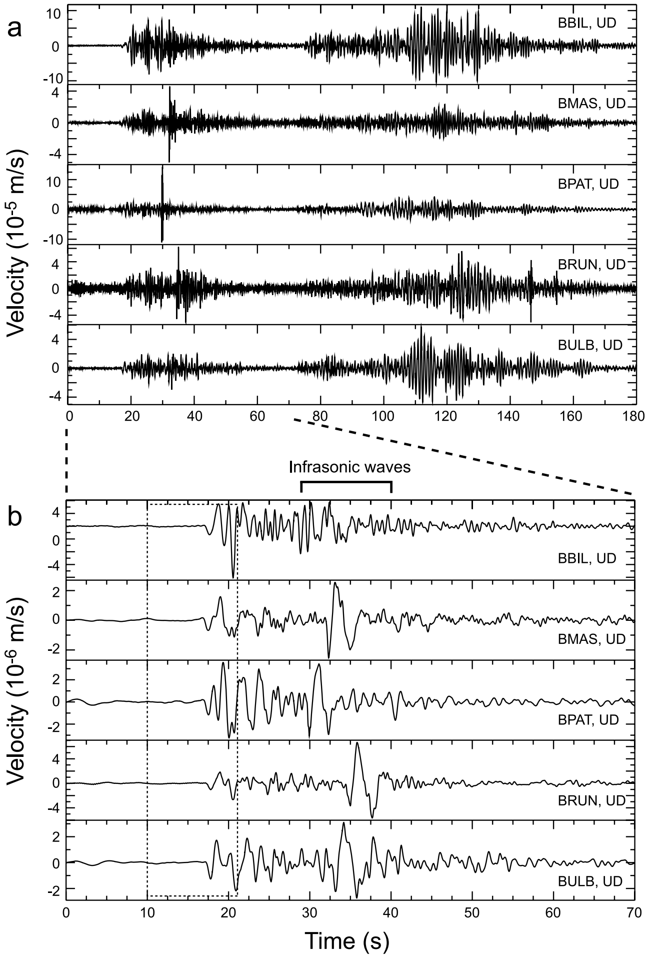

Figure 2. (a) Broadband vertical velocity seismograms of the explosion event at Tungurahua. The time axis in seconds is measured from 00:55 on 11 February 2010 (UTC). (b) Waveforms of Figure 2a band-passed between 2.5 and 10 s in a time period between 0 and 70 s. Signals enclosed by the dotted rectangle were used in the waveform inversion. The horizontal bar indicates seismic waves that were affected by infrasonic waves.

seismic and infrasonic records from station BMAS in Figure 4. The ascending source is seen in the 17–22 s period as well as during 71–75 s (Figure 4c), both instances followed by infrasonic signals (Figure 4b). Speeds of the ascending sources in 17–22 s and 71–75 s were estimated as 1600 and 1300 m/s, respectively.

[10] We used an *S*-wave velocity of 1443 m/s estimated from a *P*-wave velocity of 2500 m/s near the surface of Tungurahua [*Molina et al.*, 2005] to evaluate the dependence of the assumed velocity model on the locations estimated by the source location method. We also used a *P*-wave velocity of 3500 m/s to check the validity of the assumption of *S*-wave amplitudes. The estimated sources using these velocity models were selected in the same way as mentioned above. The source locations obtained using a *S*-wave velocity of 1443 m/s (Figure S2a) are similar to those obtained using a *S*-wave velocity of 2000 m/s (Figure 1b). The ascending sources and their speeds were also similar between the two results. On the other hand, the source locations obtained using a *P*-wave velocity of 3500 m/s were widely scattered (Figure S2b). As discussed by *Kumagai et al.* [2010], there are strong scattering effects in volcanic environments, and *P*-*S* conversion scattering occurs more readily than *S*-*P* conversion scattering, suggesting that *S* waves dominate over *P* waves in scattered waves. If we use a time window close to and including the direct *S*-wave arrival, the scattered *S* waves may be dominantly those around the ray path between the source and a recording station. Such scattered *S* waves may be approximately explained by the isotropic radiation equation of direct *S* waves used in this study. We note that using a homogeneous velocity model may compromise the accuracy of results. Numerical simulations using depth-dependent random models may be required to validate the use of a homogeneous velocity model and the assumption of *S*-wave amplitudes in the source location method.

[11] The results of our waveform inversion and source location method consistently point to a source initiated at a depth of 5–6 km beneath the summit (Figures 1a and 3). The estimated speeds of the ascending sources (1300–1600 m/s) are smaller than the sound speed of andesitic magma (2500 m/s). The admixture of bubbles in magma decreases the sound speed [e.g., *Kieffer*, 1977], and a fluid-solid coupling generates a slow wave [e.g., *Chouet*, 1986]. Therefore, the ascending sources can be interpreted as pressure waves travelling in magma.

[12] The source-time function obtained from the waveform inversion showed deflation and subsequent inflation (Figure S1). This feature may be explained by a sudden pressure drop and subsequent bubble growth in magma [*Nishimura*, 2004]. The water content of Tungurahua's magma is estimated to be less than 3–4 wt % in view of the absence of amphiboles in volcanic products from Tungurahua [*Kumagai et al.*, 2010]. Using Henry's law and Henry's constant of 0.9 to 1.6 × 10^{-11} Pa^{-1} [*Nishimura*, 2004] and assuming a closed conduit, we obtained a saturation pressure of 100–178 MPa (depths of 4–7 km below the summit) for magma containing an initial water content of 4 wt %. This depth range is consistent with our estimated source depths (5–6 km) at the event onset, suggesting that the explosion event was triggered by growth of H_2O bubbles at these depths.

4. Discussion

[13] Based on the results described above, we interpret the source process of the explosion as follows. The conduit was filled with magma that was supersaturated to a depth of 6 km below the summit. A sudden pressure drop at the base of the supersaturated magma triggered the growth of bubbles and generated a pressure wave in the magma conduit. The pressure wave traveled up the magma conduit, which progressively triggered further bubble growth and generated seismic waves. Gas-volume fractions due to the exsolution of steam from the magma increased as the depth decreased, which resulted in fragmentation of the magma at shallow depths. Fragmented magma with gases exploded and generated infrasonic waves. These pressure disturbances in the magma excited resonances of the magma conduit with frequencies around 1–2 Hz. The same process repeated about a minute later, but the second instance generated smaller infrasonic waves and excited stronger resonances of the magma conduit (Figure 4).

[14] Our results indicate that the explosive eruption had a deep origin. Explosion sources have been estimated at shal-

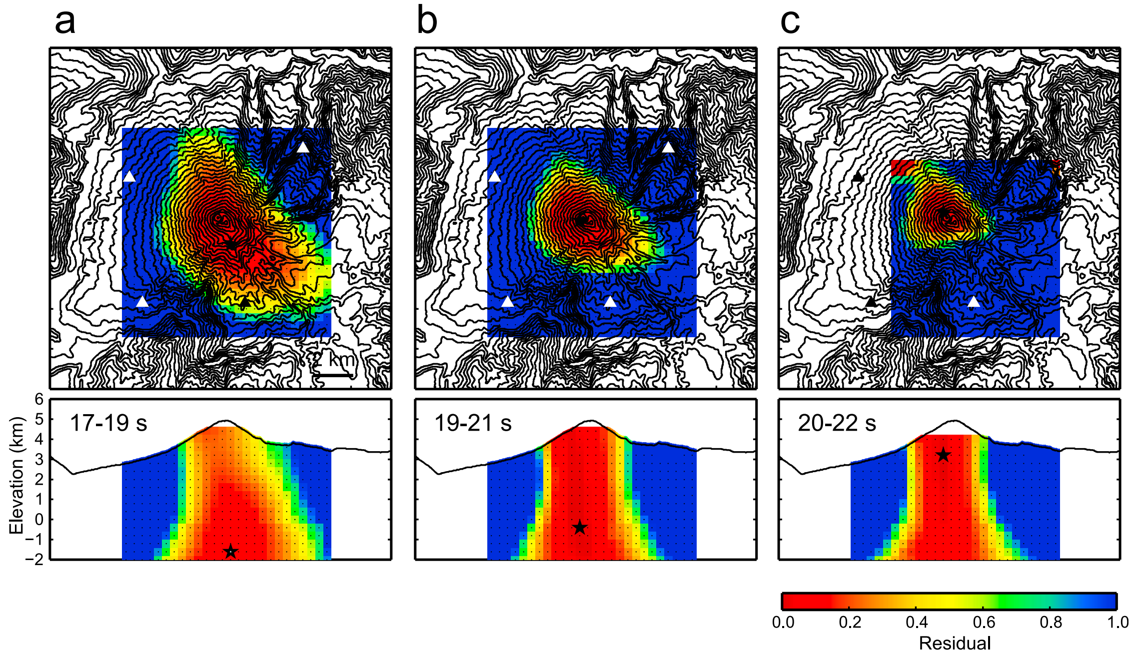

Figure 3. Horizontal and vertical distributions of the normalized residuals estimated for the explosion event in three time periods (17–19, 19–21, and 20–22 s) at the event onset. Stars indicate the minimum residual points. Dots indicate the nodes used in the grid search to estimate the source location.

low depths down to several hundred meters at Stromboli [*Ripepe et al.*, 2001] and Etna [*Gresta et al.*, 2004] in Italy, and at depths of around 2 km at Popocatépetl [*Chouet et al.*, 2005] in Mexico. The source depth of 5–6 km that we estimated at Tungurahua is clearly deeper than those of the other volcanoes. The initial deflation in the source-time function at Tungurahua suggests that a sudden pressure drop was the trigger for the explosion. A sudden pressure drop has been interpreted in terms of escape of gases from magma [e.g., *Chouet et al.*, 2005]. However, this interpretation may not be applicable for explosion events triggered deep in the magma conduit. Networks of bubbles that allow the escape of gases may not form easily in the deep portion of magma, where fewer bubbles are nucleated owing to the gradient of supersaturation caused by the ambient pressure gradient. We may need another mechanism to explain the initial deflation in a deep magma conduit.

[15] The existence of an ascending seismic source before eruption is similar to the source mechanism proposed by *Tameguri et al.* [2002] for an explosion at Sakurajima volcano, although the source depth at Sakurajima (around 2 km beneath the summit) was much shallower than at Tungurahua. *Nishimura and Chouet* [2003] examined the magma motion triggered by the removal of a plug from the magma reservoir. Their simulation results indicated that shock waves ascended within the conduit. However, because such a plug pressurizes magma reservoir, waves generated in the conduit by removal of the plug show compressional motion, which is not consistent with the initial deflation observed in the source-time function of the explosion event at Tungurahua.

[16] In this study, we used the waveform inversion and source location method to image the source process of an explosive eruption at Tungurahua. Our results show that a pressure disturbance in the magma at depth and its upward

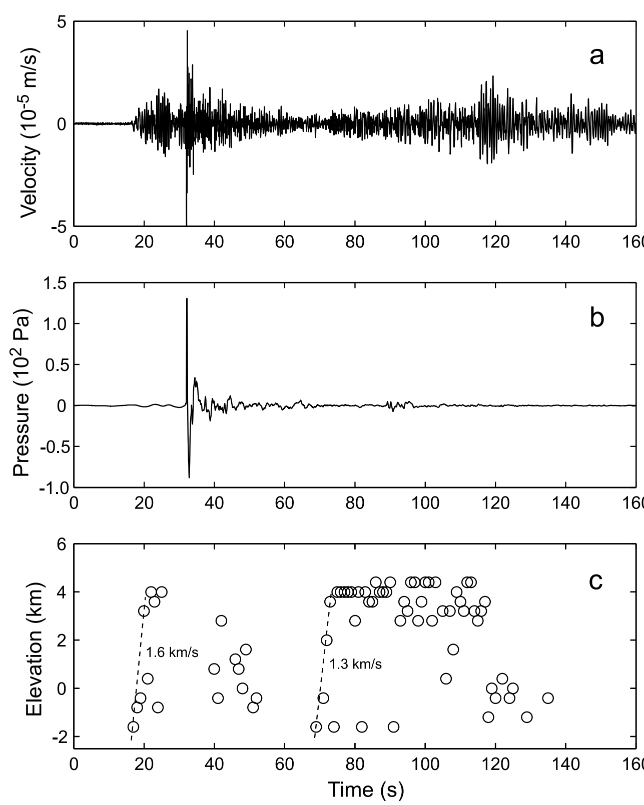

Figure 4. (a) Broadband vertical seismogram, (b) infrasonic waveform observed at station BMAS, and (c) source depths estimated from high-frequency seismograms plotted as a function of time.

propagation are the fundamental processes that triggered an explosive eruption. The initial deflation of the source-time function in a deep magma conduit is the key to understanding the mechanism that triggers an explosive eruption. The source location method has great potential to successfully image dynamic processes in magma conduits that are not resolvable by waveform inversion of VLP signals. The source location method as well as waveform inversion would be promising tools to improve our better understanding of source processes of eruptions at active volcanoes.

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