

Enhancing Volcano-Monitoring Capabilities in Ecuador

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Ecuador has 55 active volcanoes in the northern half of the Ecuadorian Andes. There, consequences of active volcanism include ashfalls, pyroclastic flows (fast moving fluidized material of hot gas, ash, and rock), and lahars (mudflows), which result in serious damage locally and regionally and thus are of major concern to Ecuadorians.

In particular, Tungurahua (elevation, 5023 meters) and Cotopaxi (elevation, 5876 meters) are high-risk volcanoes. Since 1999, eruption activity at Tungurahua has continued and has produced ashfalls and lahars that damage towns and villages on the flanks of the volcano. More than 20,000 people live on these flanks.

Cotopaxi is one of the world's highest glacier-clad active volcanoes. Pyroclastic flows during the last major eruption, in 1877, melted the glaciers at the summit of the volcano, causing lahars that traveled more than 300 kilometers into the Pacific Ocean and devastated surrounding areas. The average recurrence interval of eruptive episodes of Cotopaxi—estimated as 117 years—and the fact that the seismic activity remains high since 2001 are indicative of the magmatic system beneath Cotopaxi being in a mature state.

The hazards and risks posed by Tungurahua and Cotopaxi prompted disaster management officials to seek new ways to enhance the capability of monitoring these two volcanoes. An international collaboration between Ecuador and Japan is contributing to this effort through the deployment of permanent broadband seismic and infrasonic networks on these volcanoes. These networks, which became operational in the

late summer of 2006, provided useful observations to monitor the most recent of Tungurahua's volcanic crises, in July and August 2006 (Figure 1). This article describes some of these monitoring efforts and highlights examples of how the new networks were successfully used to warn people living on the flanks of Tungurahua and Cotopaxi.

Deployment of Observation Networks

In March 2004, in response to a request from the Ecuadorian government, the Japan International Cooperation Agency (JICA), an agency fostering sustainable development in developing countries, in partnership with Ecuador's Instituto Geofísico, Escuela Politécnica Nacional (IG-EPN), began a technical

cooperation project to enhance Ecuador's volcano-monitoring capability.

Prior to this collaboration, IG-EPN had monitored Tungurahua and Cotopaxi since the early 1990s. At Tungurahua, a network of seven short-period seismometers as well as one broadband seismometer and tiltmeter continuously monitored activity. A network of six short-period seismometers and one tiltmeter was used to monitor Cotopaxi's activity. Slope distance measurements on the flanks of both volcanoes were repeatedly performed by using an electronic distance measurement (EDM) instrument.

To enhance the capability of monitoring these two volcanoes, the JICA project facilitated the installation of five observation stations featuring broadband seismometers (Guralp CMG-40T: 0.02–60 seconds) and low-frequency infrasonic sensors (ACO TYPE7144/4144: 0.01–10 seconds on each volcano (Figures 2a and 2b). Seismic and infrasonic waveform data at each station are digitized by a **Geotech Smart24D** data logger

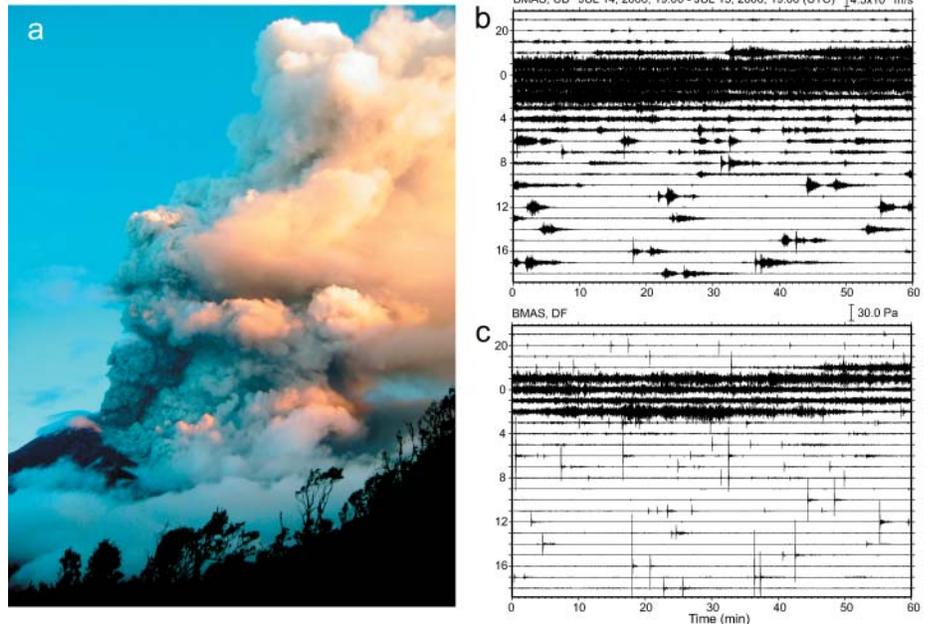


Fig. 1. (a) A photo of Tungurahua's Vulcanian eruption, which accompanied pyroclastic flows, that occurred on 14 July 2006, 2320 UTC. One-day-long records of (b) the vertical component of a broadband seismometer (UD) and (c) an infrasonic sensor (DF) from 14 July, 1900 UTC observed at Tungurahua's BMAS station (for station locations, see Figure 2b). Amplitude scales in meters per second (m/s) and pascals (Pa) are indicated at the upper right of Figures 1b and 1c, respectively. Note that the heightened activity began 2233 UTC on 14 July and continued for more than 4 hours, during which time six pyroclastic flows including the one shown in Figure 1a descended the western flank of the volcano.

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and transmitted by a digital telemetry system using 2.4-gigahertz wireless local area network to the central data collection office in Quito via repeaters that relay the waveform data (Figure 2c).

The installation began in November 2005 with the construction of repeaters. After the completion of the telemetry network, the installation of five observation stations on Cotopaxi began at the end of June 2006 and was completed on 7 July. Next, network installation moved to Tungurahua. However, during the installation of the third station, on 14 July, Tungurahua's eruption activity suddenly increased, and a Vulcanian eruption (a type of explosive eruption accompanying a high eruption column) reached a height of 15 kilometers from the summit and accompanying collapse-type pyroclastic flows occurred (Figure 1a).

Tungurahua's Eruptions Observed by the Network

Three new stations installed on Tungurahua (BCUS, BMAS, and BRUN) clearly detected seismic and infrasonic signals associated with the heightened eruption activity. One-day-long broadband seismic and infrasonic records from 14 July, 1900 coordinated universal time (UTC), observed at BMAS (Figure 2b) are displayed in Figures 1b and 1c, respectively.

Mild Strombolian eruptions (intermittent fountaining of lava fragments with less explosivity than a Vulcanian eruption) at the summit crater continued until 2233 UTC on 14 July 2006, when an explosive event occurred that marked the start of heightened Vulcanian eruption activity (Figures 1b and 1c). Strong tremor signals continued for more than 4 hours, during which six pyroclastic flows descended the western flank of the volcano.

Very long period (VLP) seismic signals were observed in synchronization with some of the eruptions and accompanying pyroclastic flows. The VLP signals observed at BCUS are characterized by impulsive waveforms, accompanying relatively larger tremor signals (Figures 3a and 3b). The eruption activity gradually decreased after 4 hours of the heightened activity. At 0600 UTC on 15 July, isolated strong explosions began. These explosions were observed as impulsive seismic signals with high-frequency codas and infrasonic pulses (Figures 1b and 1c). The explosions were frequently accompanied by pyroclastic flows and continued for more than 10 days.

On 16–17 August, Tungurahua reached the highest eruption activity. Strong tremor signals, whose amplitudes were much larger than those observed during the activity on 14–15 July, continued for more than 11 hours from 1900 UTC on 16 August, during which time a series of VLP signals were identified. The individual VLP signals are also characterized by impulsive signatures. About 20

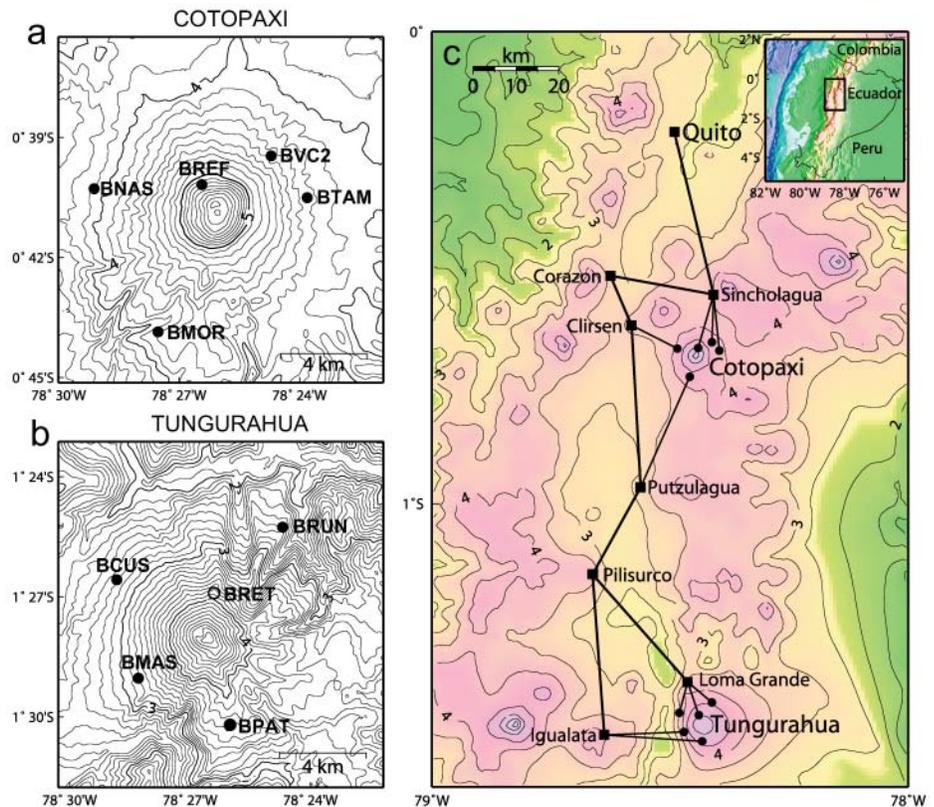


Fig. 2. Locations of broadband seismic and infrasonic stations at (a) Cotopaxi and (b) Tungurahua volcanoes. The open circle in the Tungurahua map shows the location of the station yet to be installed. (c) Digital radio telemetry routes from the observation stations at Cotopaxi and Tungurahua (circles) to the central office in Quito via repeaters (squares). The rectangle in the inset shows the area featured in Figure 2c.

pyroclastic flows swept the western flank of the volcano during this activity.

Monitoring information from the new Tungurahua network was successively transferred to disaster prevention authorities through telephone, fax, Internet, and mass media. Three to four thousand people were evacuated from the risk areas before the generation of pyroclastic flows in response to the warning information issued by IG-EPN. This helped to save many lives; however, six people unfortunately did not follow the evacuation order and were killed by the suffocating flows.

Long-Period Seismicity at Cotopaxi

On 25 July 2006, just after the installation of the broadband seismic and infrasonic network on Cotopaxi, peculiar seismic signals were detected by the Cotopaxi network (Figure 3c). These signals have a broad spectral peak around 2 seconds, and accompany oscillatory signals in the band 1–5 hertz (Figure 3d).

These waveform features are very similar to those observed by a temporary broadband seismic station deployed on Cotopaxi during a period of renewed seismic activity, which occurred in June 2002. Waveform analyses of the signals observed in 2002 point to volumetric changes of a subvertical

crack at the source, which is located at a depth of 2–3 kilometers beneath the northeastern flank (I. Molina et al., Source process of very-long-period events accompanying long-period signals at Cotopaxi volcano, Ecuador, submitted to *Journal of Volcanology and Geothermal Research*, 2007, hereinafter referred to as Molina et al., submitted manuscript, 2007). Molina et al. (submitted manuscript, 2007) interpreted that these signals were generated by the volumetric changes associated with gas-release processes in an intruded magmatic dike beneath Cotopaxi. The intrusion of a dike is also supported by a swarm of volcano-tectonic (VT) earthquakes that occurred in November–December 2001 and by deformation data.

The current observation of the same type of event suggests that the intruded dike is still active, although the event activity is very low compared with the activity in June 2002. Careful monitoring of these events as well as other volcano-seismic signals is maintained to detect any future changes in Cotopaxi's activity.

Future Works

Telemeter equipment (antennas and modems), infrasonic sensors, solar panels, and GPS antennas at BCUS and BMAS were completely destroyed by Tungurahua's erup-

tions and pyroclastic flows on 17 August, although the seismic sensors, data loggers, and other equipment kept in the ground were not damaged. The replacement of the destroyed equipment at BCUS and BMAS is the highest priority in the project. Although we installed one new station (BPAT) after the volcanic crisis, no other work can be performed now due to potential dangers of eruptions and lahars.

Recent advances in volcano seismology provide quantitative approaches to the analyses of volcano-seismic signals. These include seismic tomography accommodating topography of a volcano to determine three-dimensional velocity structure and precise source locations, waveform inversion to estimate source mechanisms of volcano-seismic signals, and forward modeling based on the fluid-filled crack model to diagnose the state of fluids at the source of these signals. These techniques already have been used for volcano-seismological studies of Tungurahua and Cotopaxi (Molina et al., 2004, 2005; submitted manuscript, 2007). Systematic uses of these techniques to analyze the data from the new networks as well as the short-period seismometer networks will lead to better understanding of magmatic systems and eruption mechanisms. This would further contribute to improved monitoring of Tungurahua and Cotopaxi.

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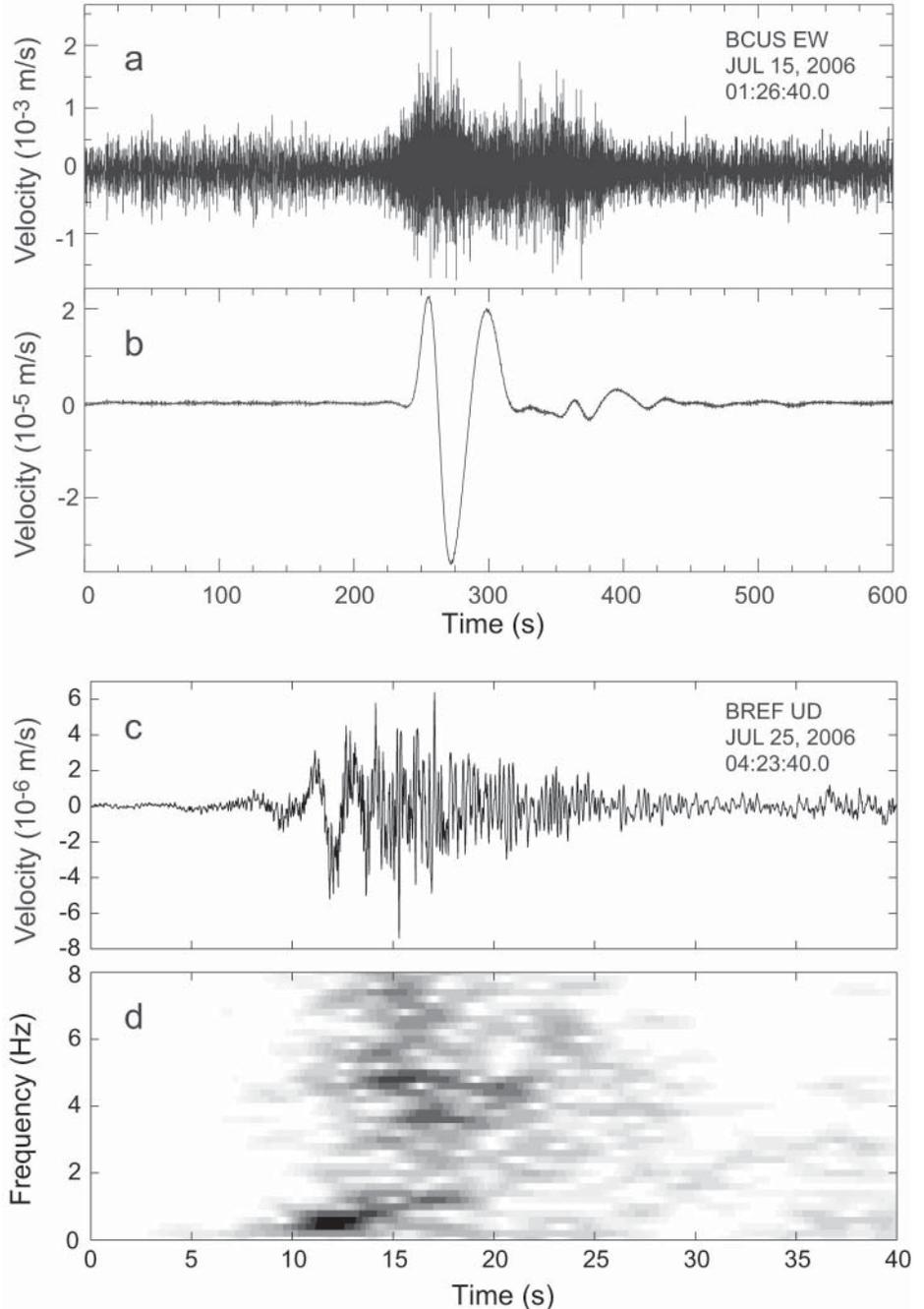


Fig. 3. (a) Broadband horizontal (EW) velocity waveform of Tungurahua's tremor that occurred during heightened eruption activity observed at BCUS between 0126:40.0 and 0136:40.0 UTC on 15 July 2006. (b) Waveform of Figure 3a band-passed between 20 and 50 seconds, where a very long period impulsive signal is clearly visible. (c) Vertical (UD) velocity seismogram of Cotopaxi's seismic event recorded at BREF (for location, see Figure 2a). (d) A time-frequency diagram (spectrogram) of the waveform shown in Figure 3c with the spectral amplitude represented by a gray scale. Figures 3c and 3d display that the waveform has a broad spectral peak around 0.5 hertz (period of 2 seconds) at the event onset and accompanies oscillatory signals in the band 1–5 hertz.

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