LOCATING LONG PERIOD EVENTS AND TREMOR BENEATH GALERAS VOLCANO USING SEISMIC AMPLITUDES – STOCHASTIC APPROACH

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ABSTRACT

A source location method using seismic amplitudes is applied to locate long period (LP) events and tremor at Galeras volcano. Galeras in the Colombian Andes is an active andesitic stratovolcano. This method is appropriate to estimate source locations of seismic signals that show emergent onsets such as LP events, or stationary signals for a long time that do not exhibit onset times such as tremor. The method assumes isotropic radiation of S-waves and uses seismic amplitudes corrected for station site effects. Site amplification was estimated at stations of the Galeras network in five different frequency bands (1-6, 3-8, 5-10, 7-12, and 9-14 Hz) using the coda normalization method. The estimated site amplification factors may be consistent with geological features observed at Galeras. For source location determinations, grid searches with respect to the frequency range, quality factor for medium attenuation (Q), and space for each origin time were performed in each event to estimate the minimum normalized residual, which is regard as the source location. The five frequency bands used in the estimations of site amplification factors were used in source location determinations. For LP events, the best-fit locations were found using a frequency band of 9-14 Hz and Q values of around 70. Also, using these parameters, a reasonable source location was estimated for tremor. It has been interpreted that the isotropic S-wave radiation assumption becomes valid in high frequency bands because of the path effect caused by the scattering of seismic waves propagating in structural heterogeneities beneath volcanoes. This study supports this interpretation and demonstrates the applicability of the source location method to LP events and tremor at Galeras volcano.

Keywords: Long-period events, tremor, isotropic radiation, site amplification.

1. INTRODUCTION

1.1 Background

Galeras is an active andesitic stratovolcano (elevation 4276 m) located in the southwest of Colombia near the Ecuatorian border at 1°13.73' N, 77°21.55' W. Its active cone is located at 9 kilometers to the west of Pasto, a city with 450,000 inhabitants and the capital of Nariño province (Figure 1).

Galeras volcano is considered to be one of the most active volcanoes in the country. In the last 4500 years, most of the eruptive events have been interpreted as vulcanian-type eruptions, with small eruptive columns (less than 10 km in height) that produced small pyroclastic flow deposits, containing a high proportion of non-juvenile materials, lava flow fragments and scoria clasts (Calvache and Williams 1992). During the last 21 years, 20 explosive eruptions have taken place after the emplacements of lava domes, producing small pyroclastic fall deposits.

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1.2 Seismic Monitoring Network

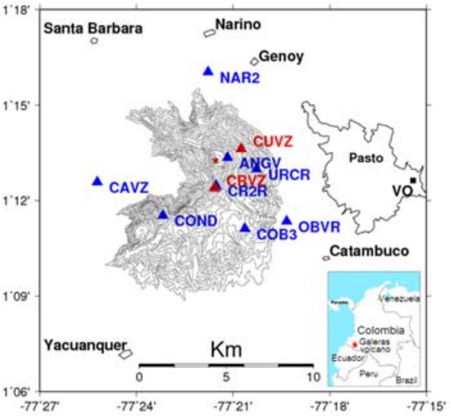

Figure 1. Location of Galeras volcano and the seismic monitoring network

The Galeras seismic monitoring network was established in February 1989 by the Colombian Institute of Geology and Mining, INGEOMINAS. At present the seismic network consists of ten permanent radio-telemetered stations with velocity sensors. The seismic stations are located at the range between 1 km and 7 km from the active crater. Figure 1 shows the location of the short period seismometers (blue triangles) and the broad band seismometers (red triangles) with flat velocity response between 0.02 and 60 s. Digital data are recorded in real time at a rate of 100 samples per second in the Volcanological Observatory (VO) located in the Pasto city.

1.3 Types of seismic events at Galeras volcano

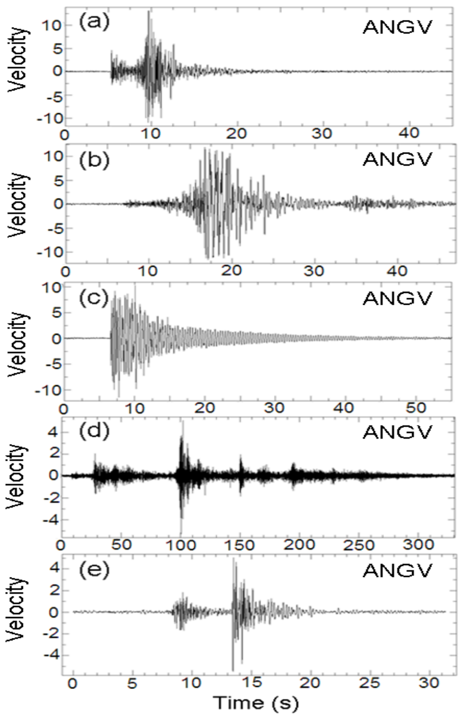

Figure 2. Examples of types of seismic events at Galeras volcano recorded at ANVG short period station. The velocity values are not corrected by instrument response. (a) VT earthquake, (b) LP event, (c) Tornillo type of LP event, (d) tremor, and (e) hybrid event.

According to the classification proposed by Chouet (1996), the following families of seismic events are distinguished at Galeras volcano: volcano- tectonic (VT) earthquakes, long period (LP) events, a particular type of LP events called “Tornillos” (Spanish word for “screws”), tremor and hybrid events (Figure 2).

VT events are associated to tensile or shear fractures in the solid rock due to the pressures induced by magma, while LP events and tremor are related to magmatic and/or hydrothermal activity and they are interpreted as the resonances of fluid-filled cavities or cracks due to the pressures transient originated by the movement of fluids. Hybrid events are associated with the fractures in the solid material but in addition involving pressures transient originated by the movement of fluids (Chouet 1996).

Often VT seismograms show clear onsets of P- and S-wave arrivals. Sometimes LP seismograms show clear onset of P-wave arrival but they usually exhibit emergent onsets, and the signatures of tremor show continuous oscillations for a relative long time that do not exhibit onset times.

1.4 Purpose of Study

Source positions of LP events and tremor are useful in evaluating the volcanic activity and for improving the knowledge about the structure of volcano. Hypocenter determinations of LP events and tremor based on phase arrival times are usually difficult or impossible. The main problem is the identifications of phases because their onsets are usually emergent (LP events) or their waveforms are stationary for a long duration (tremor). As an alternative, relatively a new method has been introduced to locate these kinds of events. Battaglia and Aki (2003) proposed an approach to locate these events using their amplitudes assuming isotropic radiation of S-wave, and located LP events and volcanic tremor at the Piton de la Fournaise volcano located in Réunion island (French territory in the Indian Ocean). Kumagai et al. (2010) used the method to locate LP events, explosions, tremor associated with lahars and pyroclastic flows at Tungurahua and Cotopaxi volcanoes in Ecuador, and their results provided reasonable source locations in a frequency band around 5-12 Hz and Q factor around 60. Kumagai et al. (2010) interpreted that the assumption of isotropic radiation may become valid because of the path effect caused by the scattering of seismic waves in this frequency band, and based on that, the source location method may be categorized as a stochastic approach based on the nature of scattering waves.

The purpose of this study is to locate LP events and tremor at Galeras volcano using the method proposed by Kumagai et al. (2010) to test the validity and applicability of the method. Furthermore, the implementation of this method running in an automatic way and provision of permanent hypocenter solutions will contribute to improved monitoring.

2. METHODOLOGY

The source location method of LP events and tremor uses the spatial distribution of their amplitudes recorded by a seismic network (Battaglia and Aki 2003; Kumagai et al. 2010). The method uses the far-field approximation for a body wave and assumes isotropic radiation of S-waves. The seismic amplitude at the *i*-th station, A_i, excited by a point seismic source can be expressed as (Kumagai et al. 2010):

$$A_i\left(t+\frac{r_i}{\beta}\right)=A_0 \;\; s_0\delta(t-t_s)\;\frac{1}{r_i}\;e^{-\frac{\pi f}{Q\beta}r_i}, \tag{1}$$

where A_0 is the coefficient for radiation pattern of S-wave (constant value for isotropic wave radiation), $s_0\ \delta(t\text{-}t_s)$ is the rate source time function represented by the delta function, r_i is the distance between the *i*-th station and the seismic source, f is the frequency, Q is the quality factor for medium attenuation, β is the S-wave velocity, and t_s is the source origin time.

Observed amplitudes are fitted by minimizing the normalized residuals E

$$E=\frac{\sum_{i=1}^{N}\left\{A_i^o\left(t_s+\frac{r_i}{\beta}\right)-A_i\left(t+\frac{r_i}{\beta}\right)\right\}^2}{\sum_{i=1}^{N}\left\{A_i^o\left(t_s+\frac{r_i}{\beta}\right)\right\}^2}, \tag{2}$$

where N is the number of stations and A_i^o is the observed amplitude at the *i*-th station corrected by local site conditions. Minimizing E leads to the following solution at $t=t_s$:

$$A_0^{'}=\frac{1}{N}\sum_{i=1}^{N}A_i^o\left(t_s+\frac{r_i}{\beta}\right)r_i e^{Br_i}\ . \tag{3}$$

Since observed amplitudes at individual stations are affected by local site conditions, we correct those by using coda normalization method (Aki and Chouet 1975; Phillips and Aki 1986). According to Aki and Chouet (1975) the time- and frequency-dependent amplitudes of coda waves for a lapse time t greater than about twice the S-wave travel time can be described as:

$$A_i(f,t) = S(f)C(f,t)G_i(f), \tag{4}$$

where $A_i(f,t)$ is the Fourier amplitude of a coda wave at the i-th station, $S(f)$ is the source term, $C(f,t)$ is the path term, and $G_i(f)$ is the site term of the i-th station. Relative site amplification between two stations i and j can be determined by using spectral ratio of $A_i(f,t)$ to $A_j(f,t)$ at the same t from the same event (e.g., Kato et al. 1995):

$$\frac{A_i(f,t)}{A_j(f,t)} = \frac{G_i(f)}{G_j(f)}. \tag{5}$$

3. RESULTS AND DISCUSSION

3.1 Site amplification factors

The relative site amplification factors were estimated at individual stations of the Galeras network by using CUVZ (Figure 1) as the reference station due to its continuous recording and high signal to noise ratio. First, a set of 14 well recorded regional tectonic earthquakes between September 2008 and May 2009 were selected (Figure 3a). The magnitudes of these earthquakes were in a range between 3.2 and 4.8. These earthquakes with the epicentral distances between 50 and 234 km from the active crater are diversely distributed around the volcano except in the east direction, where a zone of low seismicity exists. Sometimes, the seismograms were not available at all stations of the Galeras network because of equipment troubles or low signal to noise ratio. So a second set of 17 local tectonic and volcano-tectonic earthquakes between October 2008 and May 2009 were also selected (Figure 3b). The magnitudes of this set of earthquakes were ranging between 0.8 and 2.1 and the distances were between 4 and 16 km from the active crater.

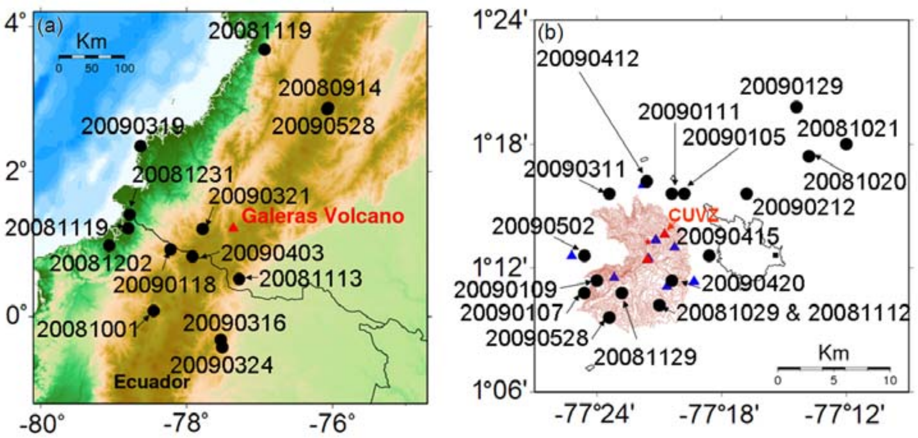

Figure 3. Location of regional tectonic earthquakes (a) and local tectonic and volcano-tectonic earthquakes (b) used to estimate the site amplification factors. Black circles and numbers indicate the locations and occurrence dates.

Site amplification factors for the stations at the Galeras network in five individual frequency bands (1-6, 3-8, 5-10, 7-12 and 9-14 Hz) were estimated by using coda waves of regional earthquakes, and local tectonic and volcano-tectonic earthquakes. In general, smaller errors in the coda amplitude ratios were obtained by using codas from regional earthquakes. This may be due to the availability of high signal-to-noise ratio seismograms in most of the stations, as opposed to the volcano-tectonic earthquakes with smaller magnitudes, of which codas were contaminated by the background noise of the volcano activity. Consistent results for ANGV, URCR, COB3 and OBVR were obtained by using codas of regional and local earthquakes, and some discrepancies were found for the remaining stations (Figures 4a and 4b).

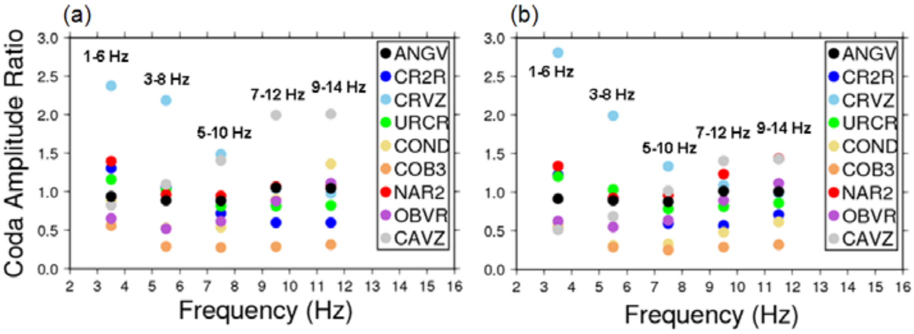

Figure 4. Site amplification factors for all stations in individual frequency bands by using regional earthquakes (a), and local and volcano- tectonic earthquakes (b).

3.2 Source location of LP events and tremor

LP events and tremor at Galeras volcano were located by using the method proposed by Kumagai et al. (2010). Grid searches with respect to the frequency range, quality factor, and space for each origin time t_s were performed in each event to estimate the spatial distributions of normalized residuals. Five different frequency ranges were considered (1-6, 3-8, 5-10, 7-12, and 9-14Hz), fifteen Q values from 5 to 180 were used (5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 150 and 180), and point sources were positioned at individual grid nodes spaced 400 m apart covering an area of 10x10 km centered at the active crater and a vertical extent of 6 km covering the summit. Topography grid data with a 20-m resolution were used in the spatial grid search. For LP events, a set of 6 events recorded on November 20 and 21, 2008, were selected. The criteria for this selection were: (1) good quality of seismograms, (2) a good coverage involving most of the stations of the Galeras network, and (3) a broad spectrum with significant frequency contents above 5 Hz. The global minimum normalized residual, which is regards as the source location, was found by using a frequency band of 9-14 Hz, Q values between 60 and 80, and the amplitudes corrected by the amplification factors obtained from regional earthquakes (Figure 5). Using these parameters, the spatial distributions of the normalized residuals and best-fit location were conducted for each LP-event (Figure 6).

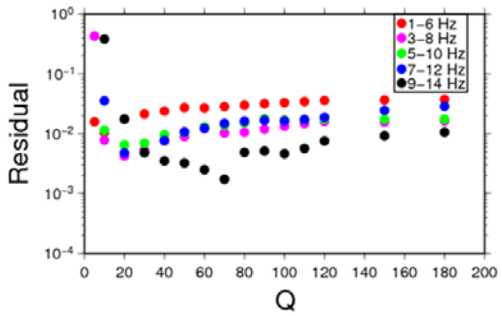

Figure 5. Plots of the minimum normalized residuals for the LP-event recorded on November 21, 2008 as a function of Q values in the five frequency bands, in which the amplitudes were corrected by the coda amplification factors of regional tectonic earthquakes.

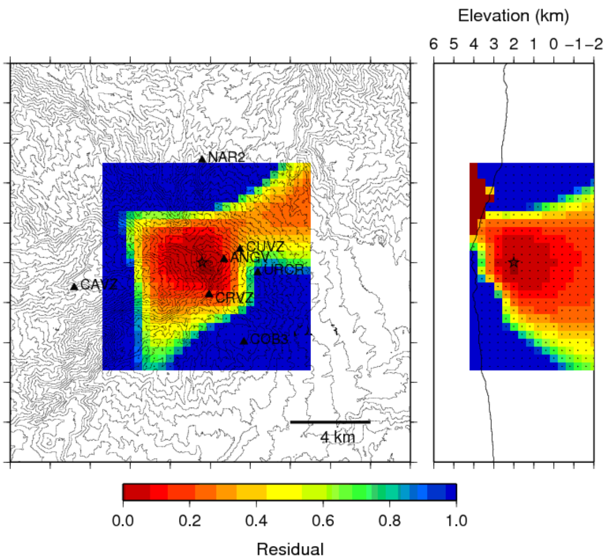

Figure 6. Spatial distributions of the normalized residuals estimated for the LP-event recorded on November 21, 2008 using amplitudes band-passed between 9 and 14 Hz, Q of 70, and amplitudes corrected by the site amplification factors obtained from regional earthquakes. Star indicates the minimum residual and the best fit source location.

The estimated source locations of these six LP events are beneath the active crater region at shallow depths. Using these parameters, a reasonable source location was estimated for tremor recorded on November 20 and 21, 2008 at Galeras.

The estimated source locations of LP-events at Galeras are in agreement with hypocenters estimated for other LP events that occurred in 2008 by using first arrivals with Hypo71. However, we note that the hypocenter determination with Hypo71 using first arrivals is not always reliable due to the difficulties arising from the identification of phases when the onsets are usually emergent as well as due to the oversimplification of the structure (flat layers) used in Hypo71.

A frequency band of 9–14 Hz and Q value around 70 for the best fit locations of LP events at Galeras are in agreement with the results found by Kumagai et al. (2010) at Ecuadorian volcanoes: a frequency band of 7–12 Hz and Q value of 60 for the best-fit location of a VLP/LP event at Cotopaxi, and a frequency band of 5–10 Hz and Q value of 60 for the best-fit source location of an explosion event at Tungurahua. Kumagai et al. (2010) interpreted that the isotropic radiation assumption becomes valid in high frequency bands because of the path effect caused by the scattering of seismic waves propagating in structural heterogeneities through the volcanoes. This study supports the interpretation of Kumagai et al. (2010).

4. CONCLUSIONS

A source location method using seismic amplitudes was used to locate LP events and tremor at Galeras. The method assumes isotropic radiation of S-waves and uses seismic amplitudes corrected for local site effects. Site amplification factors were estimated at stations of the Galeras network in five different frequency bands (1-6, 3-8, 5-10, 7-12, and 9-14 Hz) by using the coda normalization method, which geographically diverse sets of well-recorded regional and local earthquakes were used. For the source location determinations, grid searches with respect to the frequency range, quality factor, and space for each origin time were performed in each event to estimate the minimum normalized residual, which is regard as the source location. The five frequency bands used in the estimations of site amplification factors were used in the source location determinations.

For LP events, best-fit locations were found when using a frequency band of 9-14 Hz, Q values of around 70, and the amplitudes corrected by site amplification factors obtained from regional earthquakes. Also, a reasonable source location was estimated for tremor using these parameters. These results demonstrate the applicability of the method proposed by Kumagai et al. (2010) to LP and tremor at Galeras. This source location method, without requiring an expert intervention for picking arrival times, offers a possibility of automatic estimations of source locations of LP events and tremor. A permanent provision of source location determinations will contribute to improve volcanic monitoring.

The introduction of this method at Galeras is worth in evaluating volcanic activity and in improving the knowledge about the structure of the volcano.

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