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Possible causes for the seismic activity observed in Cotopaxi volcano, Ecuador

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Abstract. Continuous monitoring of Cotopaxi volcano from January 1989 to September 1997 shows that it is subject to a steady shallow Long Period (LP) activity. LP events are concentrated in a column with a diameter of about 3 km and a height of about 12 km, between an elevation of 4 km and 8 km depth. They do not occur in swarms, nor have there been periods of complete calm. High frequency volcano-tectonic (VT) events are mostly located on the northeastern side of the LP column, with the maximum activity of both types of events coinciding in depth. LP activity cannot be related to unrest of the volcano. The most likely explanation for the continuous occurrence of LP events beneath Cotopaxi is that they are produced by the interaction of glacier thaw water and hot material at shallow depths. The relative spatial distribution of both type of events in two adjacent zones suggest that VT and LP activities are interconnected.

Introduction

Cotopaxi volcano is one of the active volcanoes of the Ecuadorian Andes. It is located in the Cordillera Real, about 50 km South of Quito City (pop. 1,200,000) and 30 km North of Latacunga City (pop. 120,000) (Figure 1). It has an elevation of 5897 m and a 16 km x 19 km base located at an altitude of about 3.500 m. It is constituted by a composite cone made up of lava and tephra erupted from the summit crater. The summit crater, 800 m across and 334 m deep, is largely free of snow and contains a small pyroclastic cone at the bottom [Barberi et al., 1995]. Glaciers with an estimated 0.5 km^3 volume cover its flanks from the summit downward to an altitude of about 4800 m.

Wolf [1904] and Barberi et al. [1995] made a critical review of the most significant historical sources of information in order to examine Cotopaxi activity of the last four centuries. Since its first reported eruption in 1534, Cotopaxi volcano has erupted at least 35 times, including major explosive events or eruption phases in 1534, 1742-1744, 1766-1768 and 1877, with pyroclastic flows and ash falls, and usually linked to lahars that severely affected the surrounding areas [e.g. Mothes et al., 1998]. Apart from a possible minor eruption in 1942 and lahars and lava flows in 1903-1904, Cotopaxi has remained inactive since the 1878-1885 period. Barberi et al. [1995] using repose length estimations of the past 2000 years find that with repose periods ranging from 15 to 210 years, the average time interval between two eruptions is 117±70 years. They also assess that as the last eruption occurred in 1877, the length of the present repose is about average, and that the probability of having an explosive eruption similar or greater than that of 1877 in 50, 100 and 200 years is respectively of 0.35, 0.57 and 0.82.

Given this very active eruptive history and associated volcanic hazards (pyroclastic flows, lahars, tephra falls, lava flows) that could affect populated areas, the Instituto Geofisico (IG) of Quito started continuous monitoring of the seismic activity of Cotopaxi in 1989. The goal of this paper is to describe the characteristics of the Cotopaxi seismic activity, using the recordings of the IG array from January 1989 up to September 1997.

LP and VT Events Characteristics.

Typical seismograms of LP events recorded across the Cotopaxi array show that they have monochromatic coda lasting over 30 seconds, with a very different signature than that of a typical VT event (Figure 2). The enrichment of higher frequencies at the beginning of the tracks is also apparent, although not as clear as on examples shown by other authors [e.g. Pitt and Hill, 1994; Chouet, 1996]. Given their very emergent onset, it is difficult to verify that the events always display the same polarity at all stations as mentioned by Lahr et al. [1994], in order to discriminate them from hybrid events. LP events usually show a clear and energetic wave less than 10 seconds after their onset.

The main energy content of Cotopaxi LP events is in the 0.5 - 3.5 Hz range, always with a very sharply peaked velocity spectra. We compared the velocity spectrum for a LP and a VT event, generated by stacking the spectra from the records at the four Cotopaxi stations. The resulting stacked spectrum for the LP event is dominated by a single peak centered near 1 Hz with little energy above 2 Hz (Figure 3). In contrast, the VT event

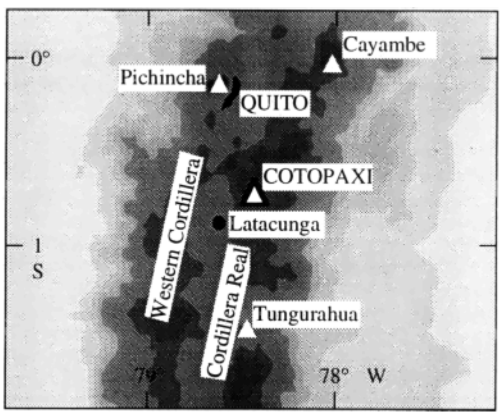

Figure 1. Map of the central Ecuadorian Andes. Cotopaxi volcano is represented by an open triangle with thick bordering lines. Other volcanoes mentioned in the text are represented by white triangles. The shape of Quito appears in black, and the location of Latacunga is shown by a black circle.

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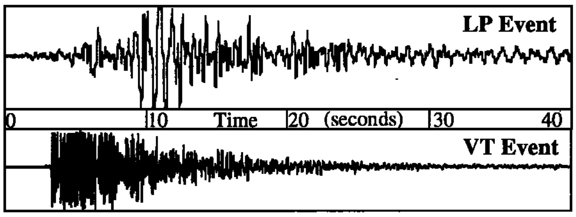

Figure 2. Signal of a typical LP Cotopaxi event (top trace) and of a typical VT event (bottom trace) both recorded at station VC1.

shows little energy below 1.5 Hz and a number of high amplitude peaks above that frequency (Figure 3).

Data Acquisition and Earthquake Location

The Cotopaxi volcano has been continuously monitored since January 1989 with a 1 Hz vertical seismic station (VC1) located at 5.8 km from the crater (Figure 4). Three additional 1 Hz vertical seismic stations were installed in August-September 1990 at distances of 7.0 km (NAS1), 9.2 km (MARY) and 10.4 km (TAMB) from the crater (Figure 4). The signals detected by these stations are telemetered to Quito, where they are recorded on smoke-drum seismographs as well as digitally.

The locations were performed using the Hypoinverse program [Klein, 1978]. The top of the model used for the location has been set at 6000 meters, i. e. about the elevation of the Cotopaxi. Time delays were used to take account of the station elevations. We used a (S - S) vs (P - P) diagram [Chatelain, 1978] to determine the ratio Vp/Vs for the Long Period (LP) and high frequency volcano-tectonic (VT) events separately. For the LPs "P" is the time of the beginning of the event and "S" the arrival time of the second wave described in the previous section. Average values of 1.166 and 1.536 were found for LP and VT events respectively. We used a trial and error approach to locate the earthquakes using a flat one-layered velocity model, with P-wave velocities varying from 0.69 km/s to 3.29 km/s, with a 0.3 km/s step. This approach was taken because the velocity structure of the Cotopaxi is not known, and as it is difficult to use travel-time curves due to the emergent nature of the onset of LP P-waves.

The best locations were obtained when a minimum was reached in each of the plots of average of RMS, ERH, ERZ, and condition number versus P-wave velocities. In the zone where the curves reached a minimum, the velocity step was then downed to 0.1 km/s. The locations obtained with the velocity for which the location error parameters reached a minimum were also the less dispersed.

The best error parameters were obtained for a P-wave velocity of 0.79 km/s for the LP events and 2.39 km/s for the VT events. The very low P-wave velocity found for the LP events is in agreement with observations that the highest amplitudes of LP waves are Rayleigh waves [Chouet, 1981; McNutt, 1986], and is in the range found for tremors, i.e. sustained occurrence of LP events [Aki, 1984], by Gordeev et al. [1990] in the 1-2 Hz band in the Kluychesvskoy volcano.

Due to various reasons, only the events that occurred since November 1994 could be localized. From that date up to September 1997 1211 LP events and 252 VT events, recorded by all 4 stations of the array, were localized. LPs were then selected using the following criteria: (1) number of P+S arrival times ≥ 5, (2) RMS < 0.4 sec, (3) ERH < 0.6 km, (4) ERZ < 1 km, and (5) condition number < 40. VTs were selected using the following criteria: (1) number of P+S arrival times ≥ 5, (2) RMS < 0.3 sec, (4) ERH < 0.8 km, (5) ERZ < 1 km, and (5) condition number < 25. However, the picture obtained using these criteria was somewhat biased as no earthquake between 6 km and 1 km of elevation made it through the selection criteria. In order to get a picture more conform to reality, the condition number limit has therefore been raised to 100 for both types of events in this depth range. The final set of selected events used to study the spatial distribution of the seismicity is made up of 812 LPs and 209 VTs.

Seismicity of Cotopaxi

Spatial distribution. In map view, LPs are concentrated in a 3x3 km zone centered on the volcano, while VTs are more widely distributed around the zone defined by the LPs, northeast of the NW-SE line passing through the center of the volcano (Figure 4). The two zones abut with little overlap. In depth, LPs occur in an elongated zone ranging from an elevation of 4 km down to a depth of about 8 km, while VTs occur in the 0 - 8 km depth range (Figure 5). We can therefore see that LPs occur in a narrow column about 3 km in diameter and 12 km in height, surrounded from the southeast to the northwest by a more diffuse VT activity. The maximum of activity of both type of events coincide in the 0 - 6 km depth range (Figure 5), where 78 % of the LPs and 94 % of the VTs are located. However, preliminary locations using data from a station newly installed at the summit of the volcano show that more LP events occur between the summit of the volcano and 1 km of elevation than found in this study (IG unpublished data).

Time distribution. The time distribution study of both LPs and VTs is based on event counting at the first station installed in December 1988 (VC1), which signal is continuously recorded on a smoked drum seismograph. Only events with peak to peak amplitude higher than 5 mm were

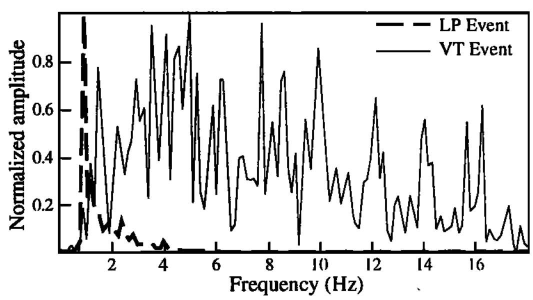

Figure 3. Stacked velocity spectra of LP (dashed) and VT (solid) events. The four stations shown on figure 4 are used for both events.

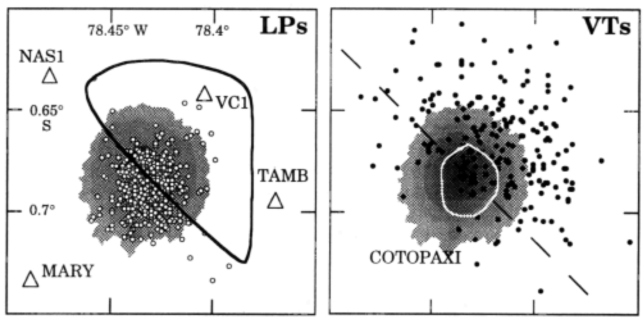

Figure 4. Map showing the distribution of selected LP (left; open circles) and VT events (right; closed circles). The stations of the Cotopaxi array are shown by triangles. The black curve on the left map shows the zone where most VTs occur, and the white curve on the right map the zone where most LPs occur. Note that most VTs occur to the northeast of the dashed line.

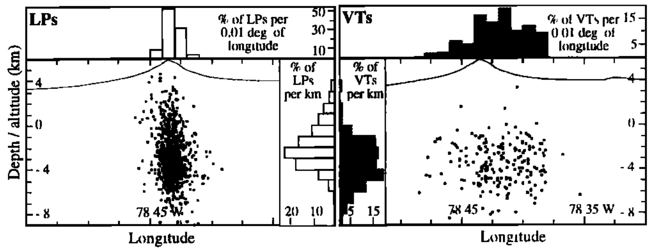

Figure 5. West-East vertical cross-section across the maps of figure 4 showing the distribution in depth of LP events (left; open circles) and VT events (right; closed circles). Also shown are the histograms of the percentage of events per 0.01° of longitude (top) and per km of depth (side).

considered. From January 1989 up to September 1997 a total of 8827 events have been identified (7335 LPs and 1492 VTs). LPs did not occur in swarms and there are no periods of complete calmness (Figure 6). Since 1989 three stages of activity can be recognized in their time distribution : (1) a lesser active stage from January 1989 to March 1992, with average of 48 events/month, followed by two more active stages (2) from April 1992 to May 1996 and (3) from June 1996 to September 1997 (Figure 6) with averages of 71 and 125 events/month respectively. This variation is not linked to changes in the station amplification. There is no such difference of regime for VT activity (Figure 6), as during the same time periods the average numbers of events/month are 12, 16, and 16 respectively. Although the rate of occurrence of 7-9 events per month found in previous studies [e.g. Hall and Yepes, 1981] was heavily underestimated, they show that the Cotopaxi activity did not start in 1989.

Energy Release. Magnitudes were determined from the coda length read at VC1 using local empirical formulas determined by Aguilar [1994], and transformed into energy using Richter's relationship [Richter, 1958]. The cumulative LP energy release from 1989 to 1997 can be divided in three segments following linear trends corresponding to the periods defined above with slope values gradually rising (4, 6.5 and 12), without steep burst of energy release, but showing a slow increase over time (Figure 7). To the contrary, VT energy release occurs very irregularly (Figure 7). At least eight major bursts of activity can be seen in the figure from January 1989 to September 1997 accounting for about half of the total energy released during this period. Although there are about five times less VTs than LPs, they released about two times more energy than the LPs.

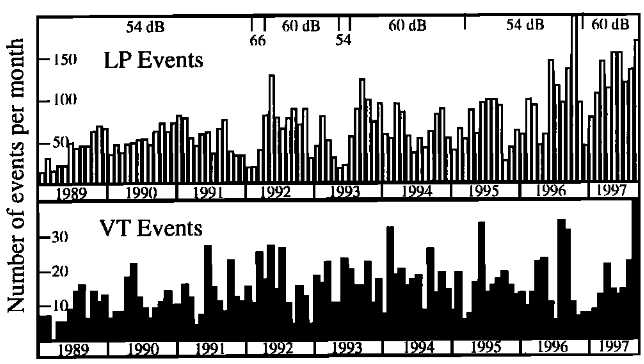

Figure 6. Histograms of the monthly number of LP events (top) and VT events (bottom) recorded at station VC1 from January 1989 to September 1997. Station amplification is shown by the numbers at the top of the figure.

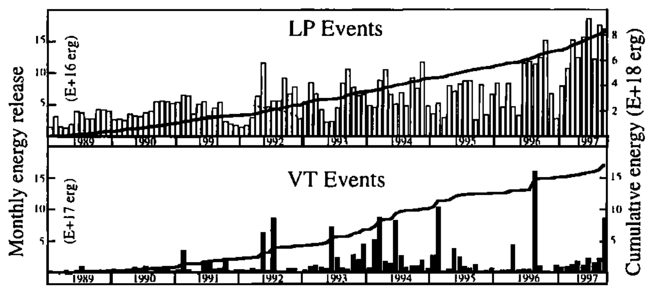

Figure 7. Monthly energy released by LP (top) and VT (bottom) events. The curves on both figures represent the cumulative energy release.

Discussion

A direct link between shallow LP activity and eruptions has been observed in many occasions and are strongly in favor of using shallow LP activity as an important indicator of impending eruptions [Chouet, 1996].

The steady shallow LP activity observed beneath Cotopaxi volcano does not follow the patterns reported prior to eruptions. For example, we do not observe swarms of 3-5 events per minute as observed before the eruption of Redoubt volcano in December 1989 [Chouet et al., 1994] or over a thousand of events per day as observed before the paroxysmal eruption of Mt. Pinatubo on 15 June 1991 [Pinatubo Volcano Observatory team, 1991]. Neither do we observe the pattern of activity that preceded the Galeras eruption, i.e. a small activity of 1-2 LPs per day starting 2 weeks before the eruption and following a long period of quiescence [Fisher et al., 1994]. Also, Cotopaxi LP events never merge into tremor activity as observed prior to the 1989 Redoubt eruption [Chouet et al., 1994].

Although a small and constant fumarolic activity is observed in the summit crater and on the upper flanks of the volcano, there is not any evidence of a relationship between it and the LP events, and there is no signal of important unrest of the volcano which could be linked to the LP activity. It seems therefore that the LP activity observed at Cotopaxi is not a precursory activity indicating a impending eruption, unless we admit that precursory activity can last over a decade. Rather, LP activity is a normal feature in Cotopaxi volcano and only a significant increase in the number of events or of released energy might be used as eruption forecasting tool in the future.

A low background of deeper LP activity (30 km or more) as observed, for example, beneath Kilauea [Shaw and Chouet, 1989], not directly related to surface activity is not uncommon and may be the rule rather than the exception [Chouet, 1996]. We do observe steady background activity in the Cotopaxi case, but at shallower depths and in the cone of the volcano. Also, given the location in depth of the Cotopaxi LP events and their steady occurrence, we can discard as possible sources glacier movements as found by Weaver and Malone [1976] or collapses or landslides as found by Hamaguchi et al. [1992].

Our observations fit with the interpretation of Gil-Cruz et al. [1987] and Martinelli [1990] that shallow LP events can originate in thermal interaction between magmatic heat and a ground water system. Moreover, Almendros et al. [1997] suggest as source of the volcanic tremor observed at Deception Island, Antarctica, the interaction between thaw water and hot materials in a shallow aquifer. Thus, we propose that the most likely source of Cotopaxi LP is the interaction between thaw water from the summit glaciers and hot materials. The fact that to the contrary of what is observed at Deception Island, only LPs and no tremors are recorded at Cotopaxi volcano could be explained by the lesser amount of thaw water produced, which would not be sufficient for the phenomenon of water-steam phase change to reach a critical stage that would produce tremors.

Our hypothesis is further supported by local observations. The Instituto Geofisico of Quito is continuously monitoring two other active Ecuadorian volcanoes : the Tungurahua and the Pichincha (see figure 1 for location). At Tungurahua a clear correlation has been shown between periods of dense rain and LP tremor activity [Ruiz et al., 1997], thus strengthening the hypothesis of LPs being produced by the interaction between surface water and hot materials. It should be noted though that in the Cotopaxi case rain water does not seem to play the key role that it plays in the Tungurahua, as we do not observe seasonal changes in LP activity. As a counter-example, at the Pichincha, an active volcano that is not covered by glaciers, no LP activity nor tremors have been detected, except during short periods of 1 to 2 weeks (unpublished IG data). Also, in order to check our hypothesis, we conducted a short recording experiment with four stations on the Cayambe volcano, which, as Cotopaxi, is covered by a glacier and is active. An average of 60 LPs per day has been detected over a period of 4 months, located in-between the summit of the volcano and 8 km depth (unpublished IG data).

Finally, while there is no obvious temporal relationship between LP and VT activity both in number of events and energy release, the spatial distribution of most VT events outside the zone where the LPs occur, as well as the coincidence of the maximum of activity of both types of events in the same depth interval, strongly suggest that VT and LP are interconnected. The phenomena of water-steam phase change that produces the LPs could be confined in cracks or conduits beneath the volcano, while in the surrounding zone brittle fracture associated with VT events would open the system sufficiently to reduce the pressure, as proposed by Pitt and Hill [1994] for their observations beneath Mammoth Mountain.

Conclusion

We suggest that LP events beneath Cotopaxi volcano are due to the interaction between the magma conduits and underground water system that provokes disturbance in the magma flow and provides the pressure perturbations that cause LP events as proposed by Chouet [1996], the main feeding source of the underground water system being the thaw water from the glacier covering the top of the volcano. The occurrence of LPs increases stress on the surrounding zone thus provoking bursts of VT activity. As to why VTs occur mostly on the northeastern side of the zone where LPs occur, there is no strong basis on which to state why this side is weaker than the southwestern side. Further experiment involving more seismic stations distributed on and around the volcano would be necessary in order to precise the LP distribution in the first kilometer of the top of the cone and to better understand the VTs distribution.

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