

## **INDUCED SEISMIC ACTIVITY BY A GLACIER IN VOLCANIC AREAS: APPLICATION TO NORTH FLANK OF COTOPAXI VOLCANO, ECUADOR.**

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### **INTRODUCTION**

Cotopaxi (5897m) is an active volcano covered by large glaciers and located on the eastern cordillera of the Ecuadorian Andes and which has a base diameter of 25 Km (Hall and Mothes; 1997). Due to its frequent eruptive activity during the last few centuries, future eruptions pose serious hazards for an important sector of Ecuadorian territory especially for East valleys of Quito and Latacunga.

The monitoring of seismic activity of Cotopaxi is carried out by four permanent telemetered one-component seismic stations of the Instituto Geofísico of the Escuela Politécnica Nacional (EPN) since 1989. Additional information about seismic activity related is based on an experiment made by ORSTOM-IG EPN in 1996-1997 using 12 additional seismic stations (Métaxian et al; this volume).

Worldwide, there are few monitored active glacier-clad volcanoes, thus only a few studies have produced in volcanic areas. Nevertheless investigations made on Mount St. Helens and Mount Rainier volcanoes (Washington State, USA) by Weaver and Malone (1976, 1979), serve to these authors to relate the discrete glacier movement with of icequakes. Experiments made on Mount St. Helens were carried out placing sensors over rock and in the icecap. They found that icequakes have similar characteristics to low frequency earthquakes when they are registered on rock and that most of the seismicity on Mount St. Helens was of glacier origin. The authors pointed out the risk of confusion between icequakes and low frequency events which have volcanic-related sources.

In this work, we analyzed the seismic activity produced by Cotopaxi glaciers and we present their principal characteristics, which allows differentiating the icequakes from the volcanic events.

## EXPERIMENT DESCRIPTION AND DATA

The field experiment was made in July 1998 for three weeks. We installed two seismic stations equipped with Mark Products 3-component seismometers (L4-3D). The first one (CORE) was located on a rock base near the Refuge "José Ribas" at 4800 meters. The second one (COHI), was placed on the glacier on the North side of the volcanic cone, 1100m distant from CORE. The seismometer of COHI station was buried inside the ice with an initial depth of 0.5 m below the surface. The seismometer was leveled once a week in accordance to glacier movement.

These stations registered a daily average of 350 events in CORE and 850 events in COHI. In order to process the data, we selected a packet of events respecting two conditions: to have been registered by both seismic stations and to have a signal to noise ratio greater than 7 at CORE station and greater than 10 at COHI. Considering these parameters we obtained a total of 171 events for signal processing.

Using the data of the permanent network of the Instituto Geofísico (EPN), we verified that the seismic activity of Cotopaxi was stable during the time frame of experiment

## METODOLOGY AND RESULTS

In order to do this work, we look at the signal shape, the spectral content, the spectrogram and we measured the difference of amplitude between events registered at both stations. The signal shape and spectral analysis allowed us to identify tectonic earthquakes (local, regional and volcano-tectonic events) which represent 21% of the total activity. For the remaining events we analyzed the S-P arrival times for each station and also the arrival differences of the P waves in both sites. We also calculated the correlation function between each of the select events. Finally, the signal was filtered and graphics of particle motion were performed.

These analyses allow us to define two distinct types of events: 20% of total activity registered in both sites has a symmetric shape, similar amplitudes, emergent front and frequencies below 10 Hz. These events are similar to long-period- type events (LP) described by Chouet (1996). The 59% remaining events (Figure 1) show the following characteristics at COHI: asymmetric shape, impulsive front, short coda duration (~2s) and frequencies over 10Hz. In addition to this, the spectrogram shows concentrated energy in a short period of time (Figure 2 sup). Chouet (1996) associates this kind of spectrogram with shallow brittle failures. On the other hand, the same events registered at CORE have similar characteristics with LP events: symmetric envelopments, slight impulsive fronts, longer coda duration (~10 s), frequencies below 10 Hz and a broad spectrogram distribution of the event (Figure 2 inf).

Moreover, these events always arrive first at COHI which suggest that the source is closer to this station. This is confirmed by the value of  $t_s - t_p$  which is always smaller for the events registered at COHI

than those registered at CORE. Also the average amplitude of events registered at COHI station is ten times bigger than those registered at the CORE station. Finally, graphics of particle motion give a linear polarization in East-Vertical plane. The complete results strongly suggest that these events have shallow sources and are originated in the ice structure.

## DISCUSSION AND CONCLUSIONS

We observed two kinds of local events in Cotopaxi: 1) LP events which are related with volcanic process and 2) events normally associate with glacier movements. The characteristics of this second category of events coincides with the icequakes characterized in the Cascade Volcanoes by Weaver-Malone (1976, 1979). In both cases we have: occurrence of almost one event per minute, initial detection and higher amplitude at the station placed on ice, shorter coda for an ice station's signals than those stations on bedrock and impulsive initial waves at the glacier station becomes emergent at the bed-rock station. We also observe, like for Mount St. Helens icequakes, a strong dispersion effect, which could be the result of a large velocity contrast across the ice-rock interface (Weaver-Malone; 1979). This observation is an additional argument to relate Cotopaxi events to a glacier origin.

The icequakes differ from LP events in all the analyzed parameters: signal shape, spectral content, spectrogram, wave front, duration, amplitude, S-P phases and particle motion. These differences are observable at the ice station but not at the bedrock station. No dispersion effects are observed for LP events. Icequakes and LP events are practically identical in the data registered on the bedrock, such was observed by Weaver and Malone (1976) at Mount St. Helens. This suggest that it is essential to install a seismometer on the glacier to differentiate both kinds of events.

Weaver and Malone (1979) suggest that icequakes are the result of a stick-slip type of motion taking place at the bed of the glacier. Other authors like Neave and Savage (1970) suggest that icequakes appear to originate from extensional faulting near the surface of the glacier. Based on a particle motion diagram, we believe that icequakes are generated by cracks in crevasses produced by gravity force that moves the glacier downhill. Therefore, the registered seismic signal originates by elastic behavior of ice when it is submitted to the rupture process (Paterson; 1994, Feynman; 1972, Middleton-Wilcock; 1994)

We compared our set of LP events with the classification made by the IG EPN's data registered by the Cotopaxi permanent network (Convenio Incecl-EPN; 1999). We found that 27% of the events classified as LP events are in reality icequakes (Fig 4). This confirms the similarity of LP events and icequakes when registered on bedrock. This could explain in part the great number of LP events registered in Cotopaxi by Ruiz et al. (1998).

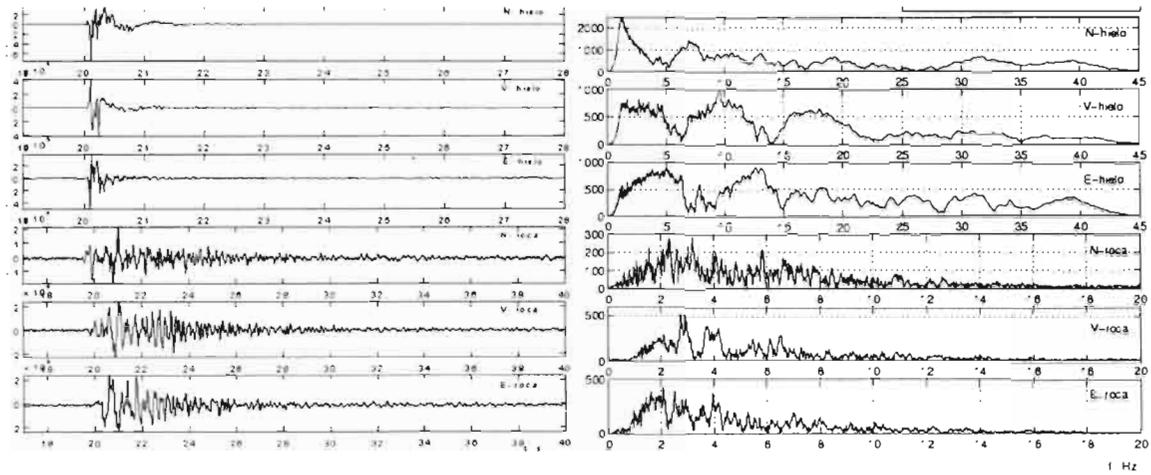


Fig.1: event 98.196.01.06.12. Example of an icequake registered by COHI (up) and CORE (down) stations with the corresponding spectra.

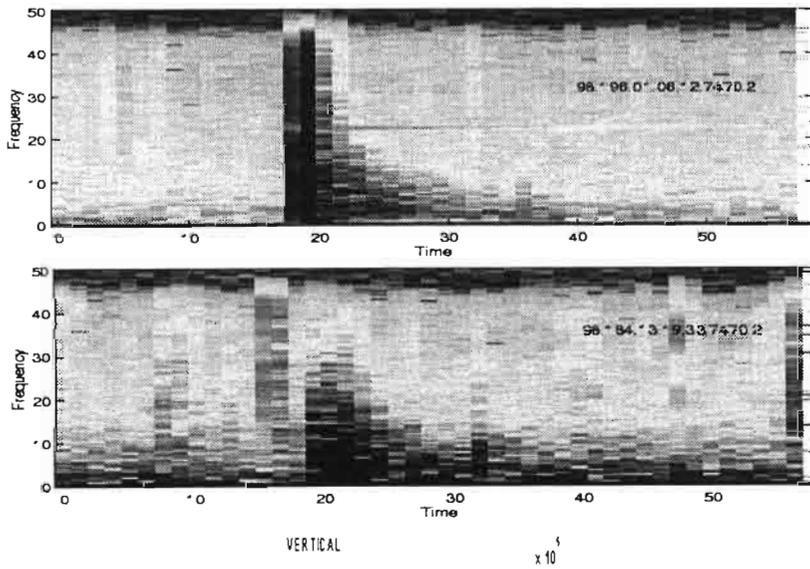
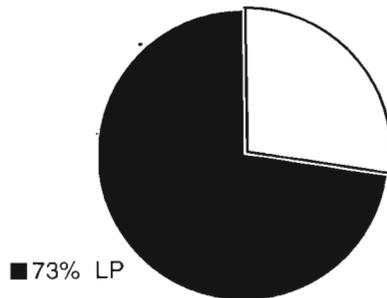


Fig.2 sup: Spectrogram calculated for the vertical component of an icequake registered in ice. The spectral density distribution is restrained to short period of time.

Fig 2 inf: Spectrogram calculated for the vertical component of a LP event registered in ice.



□ 27% icequake

■ 73% LP

Fig 4: Comparison between the LP events detected by the network of Instituto Geofísico Escuela Politécnica Nacional and the classification established in our study. We found that 27% of events classified as LP events are in reality icequakes.

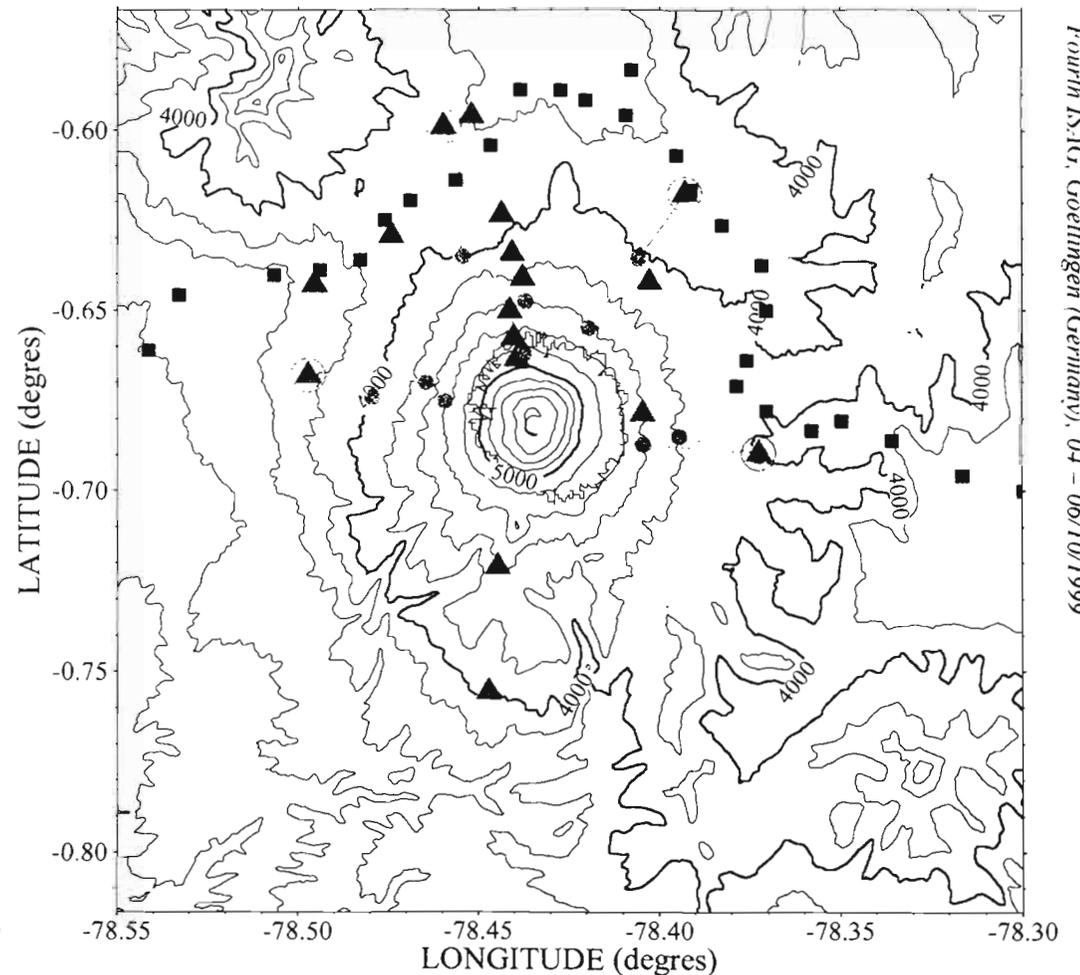
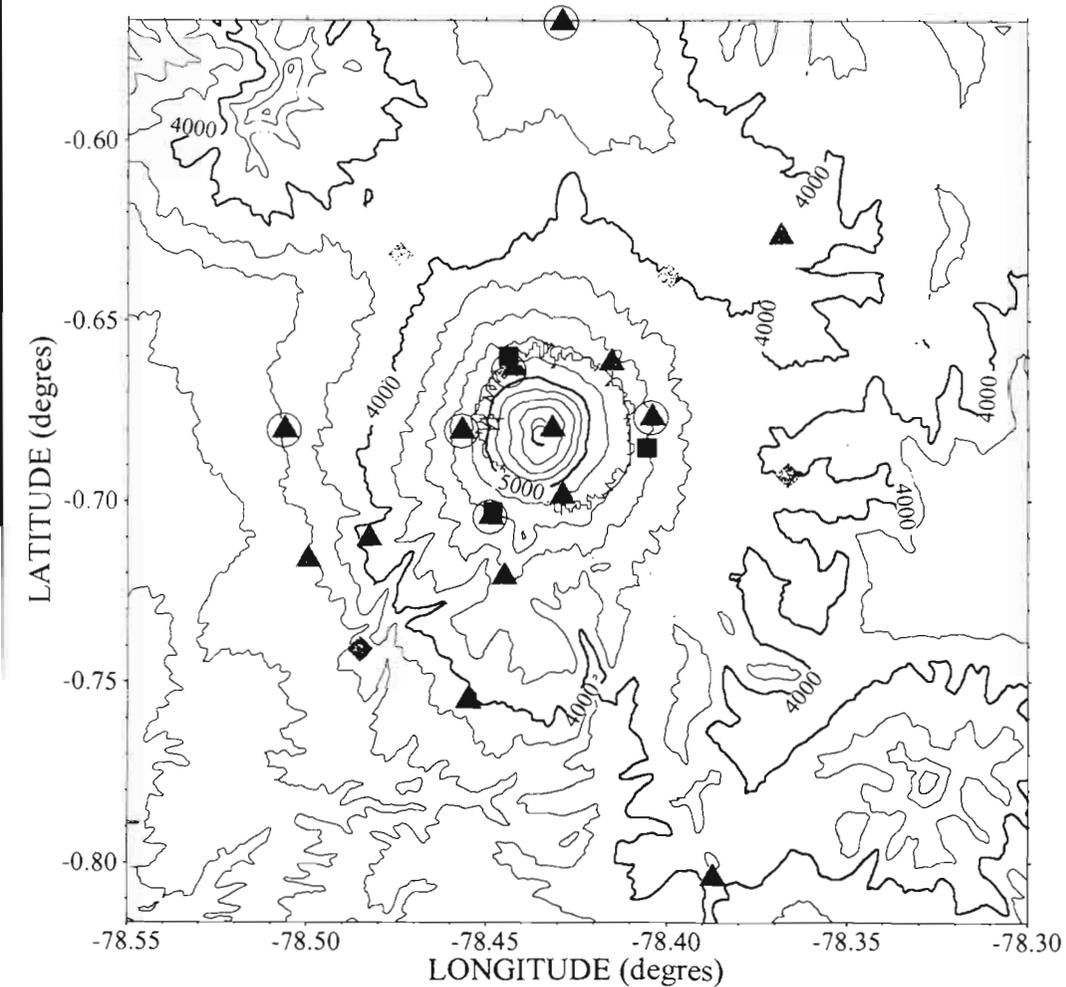
# Geophysical Networks at Cotopaxi volcano (IRD/EPN)

## (1) Sismological array

- EPN permanent seismic array
- ▲ IRD telemetered seismic array
- ▲ IRD seismic stations
- Temporary seismic stations
- 3 components station

## (2) Ground deformation & Gravity repetition network

- ▲ GPS
- ▲ GPS/microgravity
- Levelling/microgravity
- EDM Base
- EDM reflector





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