

## **GEOPHYSICAL STUDIES OF COTOPAXI VOLCANO, ECUADOR : SEISMICITY, STRUCTURE AND GROUND DEFORMATION.**

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### **INTRODUCTION**

Cotopaxi volcano (5897 m) lies in the Cordillera Real, 60 km south of Quito. This andesitic stratovolcano, with a base diameter of 25 km and almost 3000 m of relief, is covered by an icecap on the uppermost 1000 m of the cone. It is one of the most active volcanoes of Ecuador; the most recent eruptions occurred in 1742-44, 1768 and 1877. In a stratigraphic study covering the last 5000 years, Barberi et al. (1995) calculated an average eruption recurrence interval of 117 years. In the last eruption, huge debris flows were generated as a result of ash flows melting the icecap. Mothes (1992), and Hall and Mothes (1997) reported that in the eruption of 1877, the debris flow arrived at the ocean in 18 hours, covering a distance of 326 km. An event of similar magnitude, if it were to occur today, would directly affect more than 80 000 people (Hall and Mothes, 1997, Mothes et al., 1998).

Cotopaxi volcano has been monitored by the Instituto Geofísico of the Escuela Politécnica Nacional (IGEPN) with one seismograph since 1977 and with four permanent telemetered one-component seismic stations since 1989. Deformation studies using a laser EDM on radial lines started in 1987 (WOVO, 1994). Between August 1996 and June 1997, we operated an array of 12 additional seismic stations (Figure 1). This work was accomplished in the framework of collaboration between ORSTOM and the IGEPN. The goal was to characterise and analyse the nature of the volcano's seismic activity and to perform a preliminary study of the internal structure of the volcano. Geodetic, gravity and microgravity studies were also carried out at Cotopaxi in the frame of this research program with the aim to study ground deformation and internal changes related to the volcanic activity. In this summary, we present a synthesis of the preliminary results of the seismological experiment made in 1996-97 and of the geodetic and gravity data gathered in October 1996.

### **Description of the SEISMOLOGICAL experiment and data ACQUISITION**

The experiment was carried out in two phases. First we installed some stations on the volcanic cone varying at azimuths and distances from the crater and other stations in a wide area around the volcano, up to 20 km distance from the crater, to do the structural study (Figure 1). In a second phase, we moved part of the equipment closer to the crater in order to register in greater detail the volcanic activity concentrated below the summit area. One station was installed along the edge of the crater on a rock base at an elevation of 5820 m.

The array was composed of 3 RefTek stations employing Mark Products L4-3D seismometers, one Leas station equipped with a Mark Products L4C seismometer and 8 telemetered stations divided in two groups of four stations comprising sub-arrays which had separate reception and acquisition units. Three other Leas stations worked occasionally between March and June 1997. One of these stations was equipped with a Guralp 40T seismometer, and the others with Mark Products L4C vertical seismometers. The data were registered on 500 Mb hard disks with the RefTek stations and on 170 Mb PCMCIA disks with the Leas stations, both at 100 samples/sec. The acquisition, digitalization and storage of the telemetered data was performed at the same sample rate with the program ACQ (Fréchet and Glot, 1994).

### **Characteristics of the seismic activity**

The local activity associated with Cotopaxi volcano represents roughly 2000 events per month. We categorize for the 10 month period three main classes of local seismicity :

- 1) About 100 well located volcano-tectonic events. The volcano-tectonic hypocenters are located 2-10 km under the summit and are distributed under the volcano's flanks and the crater.

2) Clear long-period-type event (LP) with emergent first arrival waves detected by all of the array and with a low frequency spectral content (3 Hz). About 500 LP events occurred each month, although only 70 have identifiable phases, as the emergent first phase makes these events difficult to locate. The LP activity is superficial (< 2 km under the summit), concentrated under the crater and may be associated with transport of fluids and vaporisation of water in conduits beneath the crater. The source of water is probably the glacier, which could explain the permanent and constant LP activity.

3) Earthquakes with a typical LP signature (emergent onset and low frequency spectra) for the events registered at the stations located below the glacier and with a volcano-tectonic signature (impulsive onset and dominant frequency at 6 Hz) for data registered at the summit station. This grouping comprises 75% of the seismic activity at the volcano. Comparatively, the wave amplitude is ten times greater at the summit than 2 km lower and proximal to the glacier. The P wave arrival time difference between the summit and a second station at 3 km distance is between 2 - 3 seconds. Most of these events are not registered by the IGEPN's permanent seismic array which is located nearer to the base of the volcano and that has a distance to the summit ( 7 km. This clearly implies that the source of this type of event is superficial, close to the summit and the propagation occurs in a superficial, very slow medium. These events could be associated with glacier motions. They are similar to events observed in Cascades volcanoes partially covered by an icecap (Mount St Helens, Mount Baker and Mount Rainier) and are interpreted by Weaver and Malone (1976, 1979) as icequakes. The Cotopaxi events have similar characteristics as those observed on these volcanoes, i. e., initial detection and higher amplitude at the higher station, impulsive initial waves at the summit station becomes emergent at the bedrock stations located at the base of the glacier, strong dispersion effect. Araujo and Métaxian (1999, this volume) show, by comparison between events registered on ice and on bedrock, that part of this seismic activity has a glacier origin. The model proposed by Weaver and Malone to explain the mechanism of glacier earthquakes is sliding of ice over bedrock. Neave and Savage (1970) suggest that icequakes appear to originate from extensional faulting near the surface of the glacier. The model proposed by Araujo and Métaxian (1999, this volume) is ice cracks. The observation of multiple icequakes, registering tens to hundreds of similar events each month, seem to support this hypothesis.

We also registered 1000 regional tectonic events of which half originated from the Pisayambo seismic concentration and from the region of Pujili, situated respectively 35 km south and 45 km southwest of Cotopaxi. Most of the activity is situated at less than 20 km depth. There are few events originating from the west or north except superficial activity from the Quito area (< 10 km) and Guagua Pichincha volcano.

### **Preliminary results of the structural study**

A preliminary processing was performed using the volcano-tectonic events located inside the array at a maximum depth of 10 km. A joint inversion of the P wave arrival times and velocities fixed from an average linear velocity model adapted from other andesitic volcanoes show for the superficial layer (-6 to 0 km depth) a low velocity anomaly centered on the volcanic cone and a positive anomaly situated in the southern part of the volcano, corresponding to an old volcanic structure or proto Cotopaxi, named Morurco. Between 0 and 4 km depth, we observe a positive anomaly centered under the volcanic cone. Our goal is to process regional seismic events located in a radius of 100 km around the volcano, using the arrival times at 12 seismic stations of the IGEPN's array situated in this area. This extended array will allow for greater precision in locating the regional tectonic events in order to perform ray tracing between the tectonic sources and the Cotopaxi array stations.

### **PRELIMINARY RESULTS OF THE Geodetic and gravity sTUDIES**

In november 1996, we set up a repetition network of 18 GPS stations distributed from the base of the volcano up to 4850 meters (Figure 2). The GPS and microgravity observations were performed in a differential mode using dual frequencies Ashtech Z12 surveyor receivers and Scintrex CG-3M micro-gravity meters. For this network, we also reoccupied 4 GPS stations determined in 1993 by the USGS as well as some of the IGEPN's EDM bases. In addition, SAR interferometry using ERS satellite images is also used to evaluate the ability of the interferometric method to produce coherent interferograms for ground deformation measurements on Cotopaxi volcano. The results of the GPS and microgravity surveys as well as SAR interferometric studies are discussed here in relation with other geophysical data in terms of baseline measurements for monitoring of the volcanic activity.

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