Volcano Monitoring in Ecuador: Three decades of continuous progress of the Instituto Geofisico

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• Nor-andean Block – South America Plate:
  \(10 \pm 2\) mm/yr.

• Carnegie ridge

• Nazca – Sud American Plate convergence:
  \(56\) mm/yr. N83°E
Geodynamic context: volcanism

The Continental Arc

- **84 volcanic complexes** have been identified.
- **13 potentially active** (with at least one eruption during the last 10 Ka).
- **8 active volcanoes** (with eruptions since 1532)
- **3 volcanoes are currently in eruption.**
RECENT VOLCANIC ERUPTIONS

GUAGUA PICHINCHA
TUNGURAHUA
REVENTADOR
COTOPAXI
GALAPAGOS (FERNANDINA,
Cerro Azul, Sierra Negra,
Wolf)
Why is important to monitor a volcano?

Fallecidos por erupciones a nivel mundial:
Entre 1750 y 1985: 216,000: 919/año
Cotopaxi 2,000 fallecidos en las erupciones de 1741 y 1877

Después de 1985: 600 fallecidos, 19/año

En América Latina
Después de 1985: 11 fallecidos, 0.4 / año
El monitoreo parte de la química predominante en el volcán y de su historia eruptiva.

Es importante entender sus procesos internos para conocer el estado del volcán.

Se requieren observaciones multi-parámetricas. Las redes sísmicas, geodésicas y geoquímicas son el núcleo del monitoreo.

Se debe tener transmisión de datos en tiempo real y un sistema rápido de análisis de información.

También se usan imágenes termales para la identificación de anomalías.

Los resultados deben ser compartidos a autoridades, medios de comunicación y a la comunidad.
Métodos de monitoreo volcánico

Reconocimiento, cuantificación y análisis de:

- La sismicidad de origen volcánico
- Deformación de los flancos del edificio
- Emisiones gaseosas
- Anomalías gravimétricas
- Señales infrasonido
- Imágenes satelitales
- Análisis físico-químico de fuentes termales
- Observaciones visuales
Eruption forecasting

Figure by C. Dan Miller
Milestones

- 1988-1989 First Seismic Network. UNDRO-USAID Project
- 1989-1990 Second Phase Seismic Network. OAS project
- 1993-present ORSTOM – IRD Cooperation
- 2004-2009 JICA Project Enhancing Volcano monitoring system at Cotopaxi and Tungurahua
- 2006-2011 Early Warning System at Tungurahua and Cotopaxi. BID
- 2008-2013 Senasctyt project for Enhancement of the IG and SENASV
- 2013-present Generation of Early Warning Alerts project
- 2014-present IRD and EPN agrees to consider Instituto Geofisico as a Mutual International Laboratory
- 2014-2015 Second phase of Enhancement of the IG (Spain’s funding)
- 2014-2017 JICA Project Early Warning Alerts for Tsunamis
Beginning instrumental monitoring of Andean volcanoes: Guagua Pichincha, Cotopaxi, Cuicocha, Cayambe, Tungurahua, Chimborazo, Antisana, Cerro Negro, and Quilotoa volcanoes.

Projects include short-period telemetered seismic stations at Guagua and EDM baselines and electronic tiltmeters.

OAS Project allowed to installed short period seismic networks in Cotopaxi and Tungurahua.
In 1992 an agreement with the Instituto Ecuatoriano de Electrificaciòn strengthened the monitoring of Tungurahua and Cotopaxi.

Telemetered short period seismic networks were installed in Tungurahua and Cotopaxi. Data was processed in Quito.

Background activity levels were established, which was helpful because of the onset of the 1999 eruptive activity at Tungurahua and Guagua Pichincha.
Starting in 1988 with Guagua Pichincha seismic crisis. The first short period seismic network was installed with monitoring purposes in Ecuador.

Analog signals are internally digitized and it is analyzed using software for digital processing.

Cooperation included lahar prevention systems in quebradas coming down from Cotopaxi.
Abstract

April 15, 1990, the first phreatic explosion was recorded by several instruments.
Seismic sources at Guagua Pichincha
GUAGUA PICHINCHA
GENERAL INFORMATION

- 1981 Initiation of phreatic activity

- 1998-1999 Intense phreatic activity

- Sept. 1999 – May 2000 dome ascent, and destruction sequence.

Volcán Guagua Pichincha
7 de Octubre 1999
1999 Guagua Pichincha Eruption

Last eruption 1660
Phreatic activity since 1981
Sub-plinian eruptions: Sept-Dec 1998
JICA – IG EPN
Cooperation in volcano monitoring

- Three cooperation projects for enhancing capacities of volcano monitoring 2002-2009 for Cotopaxi and Tungurahua.

- In 2006 permanent seismic Broad Band stations and infrasound sensors were installed at Tungurahua and Cotopaxi under a cooperative program supported by JICA, which allowed us to follow Tungurahua’s climatic eruptions of 2006 and subsequent eruptions up to the present.

- After 2015 eruption of Cotopaxi, a follow up Project for enhancing capacities of monitoring of Cotopaxi volcano was implemented.

- Projects include instrumentation, software, expert visits, and personal training.
Deploying broad band seismic sensors in volcano monitoring in order to detect seismic events generated by fluid resonances in cracks and conduits and magma transfer inside volcano building known as Long Period and Very Long Period events.

Detection of atmospheric disturbances caused by explosion and gas/ash emission. It provides information about discharge rates.

Processing protocols of volcanic signals

- Inversion of seismic waveforms in order using pre-established mechanisms and source geometries
TUNGURAHUA MONITORING ACTIVITIES

- Instrumental monitoring began in 1988 with a single short-period seismic station (10 events/month).
- In 1993 a network of four seismic stations and EDM measurements.
- A sustained low amplitude tremor was observed and reported in 1994.
- In 1999 four additional seismic stations were installed.
- A modern network of five broad band stations and infrasonic microphones was installed in 2006 with JICA support.
- A DOAS network of 4 instruments, 5 GPS receivers, 6 tiltmeters, video cameras, infrared camera, a network of ashmeters
Monitoring eruptive activity of Tungurahua volcano between 2006-2016

Using permanent seismic broad-band and collocated infrasound sensors, IG maintained and active monitoring of eruptive activity of Tungurahua. It provided information for issuing early warnings to community, authorities, and civil aviation offices.

Information from IG-OVT fostered early evacuations from endangered areas before the impact of pyroclastic flows, especially before devastating pyroclastic flows in August 2006.
VLP signals observed immediately before an eruption with pyroclastic flows
Waveform analysis of the VLP signals

- Assuming an isotropic source and vertical and horizontal cracks
- Waveform inversion in the frequency domain
- Grid search in space to find the best fit solution
- Products: Location of two successive VLP events at 05h38 and 05h44 on Aug. 17, 2006. It suggested a magma ascending velocity of 2 m/s.
Result of the waveform inversion
VLP2: Isotropic source
VLP waveform inversión assuming pre-defined source geometries
Procesos establecidos

-Análisis e identificación automática de eventos LP & VLP
Recent eruptive period (1999 – 2016) exhibits several episodes with strong degassing and large explosions. The most powerful eruptions occurred in July and August 2006. At this year, IG-EPN started the current permanent infrasound monitoring of Tungurahua. Infrasound signals were classified as explosions (the most frequent ones), jetting pulses and chugging events (Ruiz et al., 2007). ASHE monitoring system (Steffke et al., 2010) provided infrasound detections and early warnings to IG-EPN and institutions in charge aviation traffic control since 2006 to 2012.
14 July, 2013, 06H45 LT - Vulcanian Eruption--
- Occurred after 2 months of quiet and little degassing.
- Important deformation signal
- Two days of seismic ramping up; especially the last three hours.
- Scoria clot PDCs traveled down three quebradas immediately after explosion.
- Limited evacuations
- No deaths
Knowledge of the internal structure of the Tungurahua volcano

Methodology: seismic tomography. In these studies, a three-dimensional modeling of the propagation speed of the waves inside these volcanoes was carried out.
COTOPAXI: Summary of seismic activity

- Mid-term precursors (slow magma ascent and alteration of hydrothermal system):
  - 4 months before eruption onset (B.E.) Increment of 3-6 Hz LP events.
  - 2 months B.E. Tremor swarms with same frequencies appear in June
  - 2 months B.E. 0.5 – 1 Hz VLP events
  - 1 month B.E. decrease of seismicity
- Short-term precursor: Swarm of LP and VLP events one day before eruption (Shallow intrusion)
- Phreatic and Phreato-magmatic eruption on August 2015 with initial explosion pulses and sustained ash emissions. (Conduit clearing and magmatic eruption).
- After eruption: Infrasound signals with at least 5 sec. infrasound oscillation
- After eruption: Secondary lahars with spindle-shape tremors
Since 2002, seismicity is composed by shallow LP events near the crater and VT events around the cone.
Monitoring of the eruptive period of the Cotopaxi volcano between 2015-2016

Timely detection of the reactivation signals of Cotopaxi volcano. In April, 4 months before the eruption, the first signs of reactivation were detected after 9 years of continuous monitoring with JICA –IG network.

Follow-up of the eruptive activity, from its beginning in August 2015 until March 2016. Issuance of early warnings about increases in activity to the authorities, population and civil aviation.
Reactivación 2015 -2016

Pre anomalía
Abril 2015

Enjambre sismos LP
Abril -Mayo 2015

Tremores presurización
y sismos VLP
Junio – julio 2015

Enjambre sismos VT,
explosiones y
tremor emisión
14 Agosto 2015
Detecting and locating lahar sources on Cotopaxi volcano
Determination of internal structure of Guagua Pichincha volcano

Journal of Volcanology and Geothermal Research
Volume 161, Issue 4, 1 April 2007, Pages 333-351

Seismic, petrologic, and geodetic analyses of the 1999 dome-forming eruption of Guagua Pichincha volcano, Ecuador

Alexander García-Aristizábal, Hiroyuki Kumagai, Pablo Samaniego, Patricia Mothes, Hugo Yepes, Michel Monzier
COTOPAXI MONITORING / RESEARCH NETWORKS

SEISMIC: 5 short period, 11 broad band,

INFRASOUND: 4 mics and a temporal array of 3 mics

GEODETIC: 7 GPS, 5 tiltmeters

GEOCHEMISTRY: 4 DOAS, 1 CO₂

LAHAR DETECTORS: 11 AFM, 1 pluviometer

VISUAL: 5 digital cameras

THERMAL: FLIR Camera

GEOPHISICAL: 1 gravimeter

XXI IPGH General Assembly
AMPLITUD DISTRIBUTION (RSAM)

- Normal background
- LP tremor
- VLP eruption
- infrasound tornillo events
Summary of seismic activity


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- After eruption: Secundary lahars with spindle-shape tremors
LP EVENTS

XXI IPGH General Assembly
TREMOR EPISODES

XXI IPGH General Assembly
VLP EVENTS

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Hydro-magmatic eruption that opened the conduit and allowed more magmatic - dry activity
3150 cm^2 and 2786 cm^2
9 Pa p2p at BNAS 6km distance
Infrasound Tornillo Events

Tornillo 30 septiembre 2015  18h02 TU
Infrasound Tornillo Events

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Infrasound Tornillo Back-azimuth

Volcan Cotopaxi: Likely Infrasound Source

Infrasound array: ISUC
Analysis starts at: 2016/02/15 18:00
Window size = 20 s
High-pass filter; Corner = 0.1 Hz
Enhancement Volcano Monitoring Capacity Project 2015-2016

- Follow up of Enhancement Volcano Monitoring Capacity due to eruptive activity of Cotopaxi volcano.
- Two broadband seismic stations were installed in 2016 in Cotopaxi volcano flanks.
Local instrumentation and research projects

- Programs supported by the Ecuadorian Secretaria Nacional de Ciencia y Tecnologia (SENESCYT) and the Secretaria Nacional de Planificación resulted in further expansion of the IG's monitoring infrastructure.

- Thermal and video imagery, SO2 emission monitoring, geochemical analyses, continuous GPS and tiltmeters, and micro-barometric surveillance have been incorporated.

- Sangay, Soche, Ninahuilca, Pululahua, and Fernandina, Cerro Azul, Sierra Negra, and Alcedo in the Galapagos Islands are now monitored in real-time.
Challenges for future cooperation

- Maintain the current instrumentation and process for volcano monitoring and detection and analysis of large earthquakes for tsunami early warning.
- Search of new topics for proposing new cooperation projects with JICA in areas of damage prevention of 
- Satreps programs (JICA, JST) including scientific component and high social impact.
- Improve the preparation and training of IG's technical and scientific personnel
Red Nacional de Observatorios Volcánicos - ROVIG

- CHILES – CERRO NEGRO ............ S I D G
- SOCHE ........................................ S
- CHACHIMBIRO ............................. S
- IMBABURA ................................. S
- CUICOCHA ................................. S D G
- PULULAHUA ............................... S
- CAYAMBE ................................. S D G
- REVENTADOR ............................. S I D G
A modern and multi-parametric monitoring systems was installed in volcanoes in Ecuador.

IG identified anomalies at Guagua Pichincha, Tungurahua and Cotopaxi several years before their eruptions.

Monitoring provided information about eruption evolution, facilitating decisions from population and authorities.

It is important to maintain monitoring infrastructure and processing activities even at quite times.

The final result of volcano monitoring is to have a country better prepared for earthquakes and volcanic eruptions.