

Instituto Geofísico – Escuela Politécnica Nacional, the Ecuadorian Seismology and Volcanology Service

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ABSTRACT

Ninety-eight Quaternary volcanoes have been identified in the Ecuadorian Andes and the Galápagos Islands, from them, nine experienced at least one eruption in the last twenty years. Additionally, about 35 % of the Ecuadorian population live in areas that could be affected by future volcanic eruptions. The *Instituto Geofísico de la Escuela Politécnica Nacional* (IG-EPN) monitors and evaluates Ecuador's volcanic hazards: nineteen volcanic hazard maps and hundreds of related articles have been published as a result of its research. The monitoring networks include eighteen volcanoes, with more than 266 stations, which also form the basis for early warning systems at several volcanoes. Volcanic activity is widely communicated by the IG-EPN through periodic information published in different media (website and social networks). Ecuadorian volcanoes will erupt in the future and, therefore, the IG-EPN continuously updates its monitoring and hazard assessment practices and improves communication channels and protocols to successfully fulfil its responsibilities.

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1 INTRODUCTION

Ecuador is divided into four physiographical regions: Coast, Mountain Range, Amazon and the Galápagos Islands, and 98 volcanoes are distributed in the last three regions (Figure 1). The origin of volcanism in Ecuador is subject to the subduction of the Nazca plate underneath the South American plate, which produces the continental Northern Andean Volcanic Zone (NVZ) and to the presence of a hot spot south of the Galápagos Spreading Center that gives rise to intense volcanism of the Galápagos archipelago (Figure 1). Since 1983 volcanoes have been monitored in Ecuador, and in this time volcanic eruptions have occurred from both sources: on the mainland, Guagua Pichincha (1999–2001), Tungurahua (1999–2016), Reventador (2002–present), Cotopaxi (2015), and Sangay (continuous) volcanoes; and along the Galápagos Archipelago, Sierra Negra (2005, 2018), Fernandina (1984, 1988, 1991, 1995, 2005, 2009, 2017, 2018, 2019, 2020), Cerro Azul (1998, 2008), and Wolf (2015) volcanoes. Based on the statistical database of the *Instituto Nacional de Estadística y Censos* from 2010 [INEC 2010], at least 35 % of the Ecuadorian population settle in these regions and could be subject to the impacts of volcanic activity.

In this work, we present an overview of the volcanism of Ecuador, as well as the different techniques that the *Instituto Geofísico de la Escuela Politécnica Nacional* (IG-EPN), the institute in charge of monitoring and evaluation of volcanic hazards, applies for the daily moni-

toring of volcanoes on both the mainland and the Galápagos Islands. We also outline the hazard management that the IG-EPN scientists and technicians carry out together with authorities, and with communities principally.

1.1 Volcanic activity in Ecuador

Volcanoes in Ecuador are classified based on their last eruptive activity as:

1. Extinct or dormant: if their last eruption occurred during the Pleistocene.
2. Active: for volcanoes that last erupted during the Holocene. This includes volcanoes that erupted during historical time (since 1532, time of the Spanish Conquest).
3. In Eruption: for volcanoes that are currently erupting or had an eruption within the last two years (i.e. 2018–2020).

On the mainland, 76 volcanic centers have been identified (Figure 1A), 52 of them are extinct, 24 are active and 2 of them are currently in eruption (i.e., Reventador and Sangay). Offshore, the Galápagos Islands host 22 volcanoes distributed over the Archipelago (Figure 1B): the youngest volcanoes are located at the western islands, and the oldest at the eastern islands [Allan and Simkin 2000], 12 of these volcanoes are extinct, 10 are active and 2 of them had an eruption within the last two years (i.e., Fernandina and Sierra Negra) [Santamaría and Bernard 2018; Vásconez et al. 2018].

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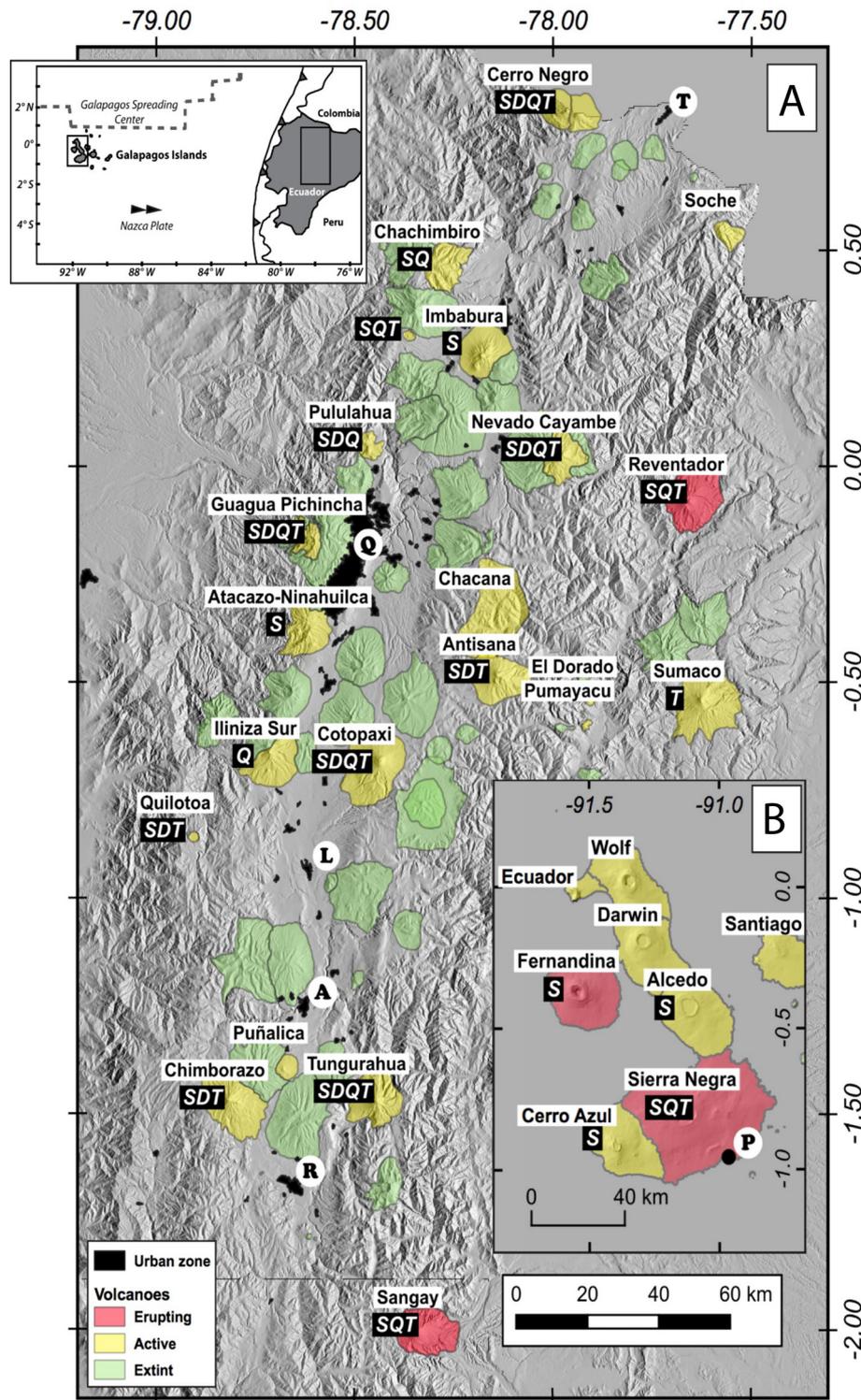


Figure 1: Ecuadorian volcanoes distributed in [A] mainland, and [B] the Galápagos Islands. Dormant or extinct volcanoes are shown in green, active volcanoes in yellow and erupting volcanoes (currently erupting or had an eruption within the last two years, i.e. 2018–2020) in red. The names of the volcanoes are written in black inside white boxes. Black bold letters in white circles represent the main cities, from north to south: T: Tulcán, Q: Quito, L: Latacunga, A: Ambato, R: Riobamba, P: Puerto Villamil. White letters in black boxes represent the different types of monitoring carried out on the volcanoes: S: Seismic (seismic and/or infrasound), D: Geodetic (GPS and/or tiltmeter), Q: Geochemistry (gas, fluids), T: Thermal/visual (airborne and/or ground-based thermal imaging).

1.2 History of the *Instituto Geofísico*

In 1972, the *Escuela Politécnica Nacional* (EPN) invited Dr. Minard Hall to become a professor of the Geology Faculty. His research (and additional work led by his students), resulted in the publication of the book "The Volcanism in Ecuador" (1977). This book, for the first time, highlighted the active nature of many volcanoes in the country, and the exposure of population to potential volcanic hazards. After an increase in fumarolic activity in Cotopaxi in 1975, and an earthquake in Pastocalle in 1976 (Mw=5.7), and thanks to the management and efforts of Dr. Hall, some monitoring instrumentation was installed. Successively, in 1983, the EPN created the *Instituto Geofísico* (IG-EPN) with the aim to have an institution to monitor the seismic and volcanic activity in Ecuador.

In 1985 two disastrous events took place in Latin America: the eruption of Nevado del Ruiz volcano in Colombia (~25000 deaths), and an earthquake in Mexico (M=8.0, 9500 deaths). Following these tragedies, IG-EPN staff resolved to carry out all the necessary actions to reduce the risk associated with these types of hazards in Ecuador, especially in terms of evaluation of seismic and volcanic hazards, and of monitoring. The results of these efforts are described in sections below and refer mainly to the creation of extensive field-based volcanic hazard maps, the implementation of volcano monitoring networks, and the experiences gained in early warning systems. The IG-EPN monitors a total of 20 volcanoes (Figure 1, Table 1): 16 located in mainland, and 4 in the Galápagos Islands.

2 VOLCANO MONITORINGS

Ecuadorian volcanoes have been continuously monitored since 1988 under the *Red de Observatorios Volcanológicos del Instituto Geofísico* [ROVIG; Alvarado et al. 2018]. In these 37 years, the monitoring network has been improved via new technologies and an increase in the number of stations. Nowadays, these new technologies include seismic (short period, broad band and lahar Acoustic Flow Monitor sensors), geodetic (tilt-meter, Global Positioning System), geochemistry (airborne and ground-based) and remote sensing (visual and thermal imaging) techniques. Currently (end of 2020), there are 266 stations installed in 20 continental and Galápagos volcanoes that help monitoring their daily activity (Table 1). The monitoring is organized based on the risk they pose to the population. Consequently, the surveillance has been grouped into:

- Observatories with surveillance level 1: 4 volcanoes, Tungurahua, Cotopaxi, Guagua Pichincha and Reventador. Level 1 observatories use multiple techniques: seismic (more than 4 stations), geodetic, acoustic sensors and geochemistry. In addition, Tungurahua, Cotopaxi and Reventador

have lahar (AFM) sensors and visual and infrared cameras; Guagua Pichincha has one visual camera. As an example, (Figure 2) shows the monitoring network of the Cotopaxi volcano towards 2016.

- Observatories with surveillance level 2: 5 volcanoes, Antisana, Cayambe, Chiles-Cerro Negro, Cuicocha and Sierra Negra. These observatories have at least two monitoring techniques such as seismic with more than one station, geodetic and occasional geochemical and thermal monitoring.
- Observatories with surveillance level 3: 10 volcanoes, Sangay, Pululahua, Chimborazo, Imbabura, Chalupas, Chacana, Quilotoa, Alcedo, Cerro Azul and Fernandina volcanoes. This level of surveillance involves at least one monitoring technique, mostly seismic. In some cases, it includes permanent GPS or geochemical and visual/thermal monitoring.

2.1 *Instituto Geofísico* staff and organization

The assignments that the IG-EPN has been carrying out since 1983 are achieved thanks to the daily work of 90 people grouped into five different teams: (1) Seismology, (2) Volcanology, (3) Technology, (4) Systems and (5) Administration. The staff people have academic backgrounds and experience in Seismology, Volcanology, Electronics, Physics, Informatics and Management. The expertise varies from college students to senior professionals, having achieved academic levels of technicians, engineers, MSc and PhD. Due to the fact that the IG is part of the EPN, which is a major degree-granting university in Ecuador, some staff teach in different faculties of the university. The responsibilities of each team is detailed below:

- The seismology team analyzes and interprets the seismic signals collected from the stations either of volcanic or tectonic origin.
- The volcanology team follows up and continuously evaluates the activity of the volcanoes by processing different monitoring methods in each volcano. They also keep up-to-date on the increasing activity, create eruptive scenarios, and produce hazard maps based on fieldwork and computational modeling.
- The technology team is in charge of the installation, maintenance and functioning of all the monitoring stations along the Ecuadorian territory, as well as of signal transmission to the IG-EPN offices.
- The systems team manages the storage and organization of all the incoming data acquired from the different stations located in the field to the IG-EPN

COTOPAXI VOLCANO MONITORING NETWORK INSTITUTO GEOFISICO-EPN

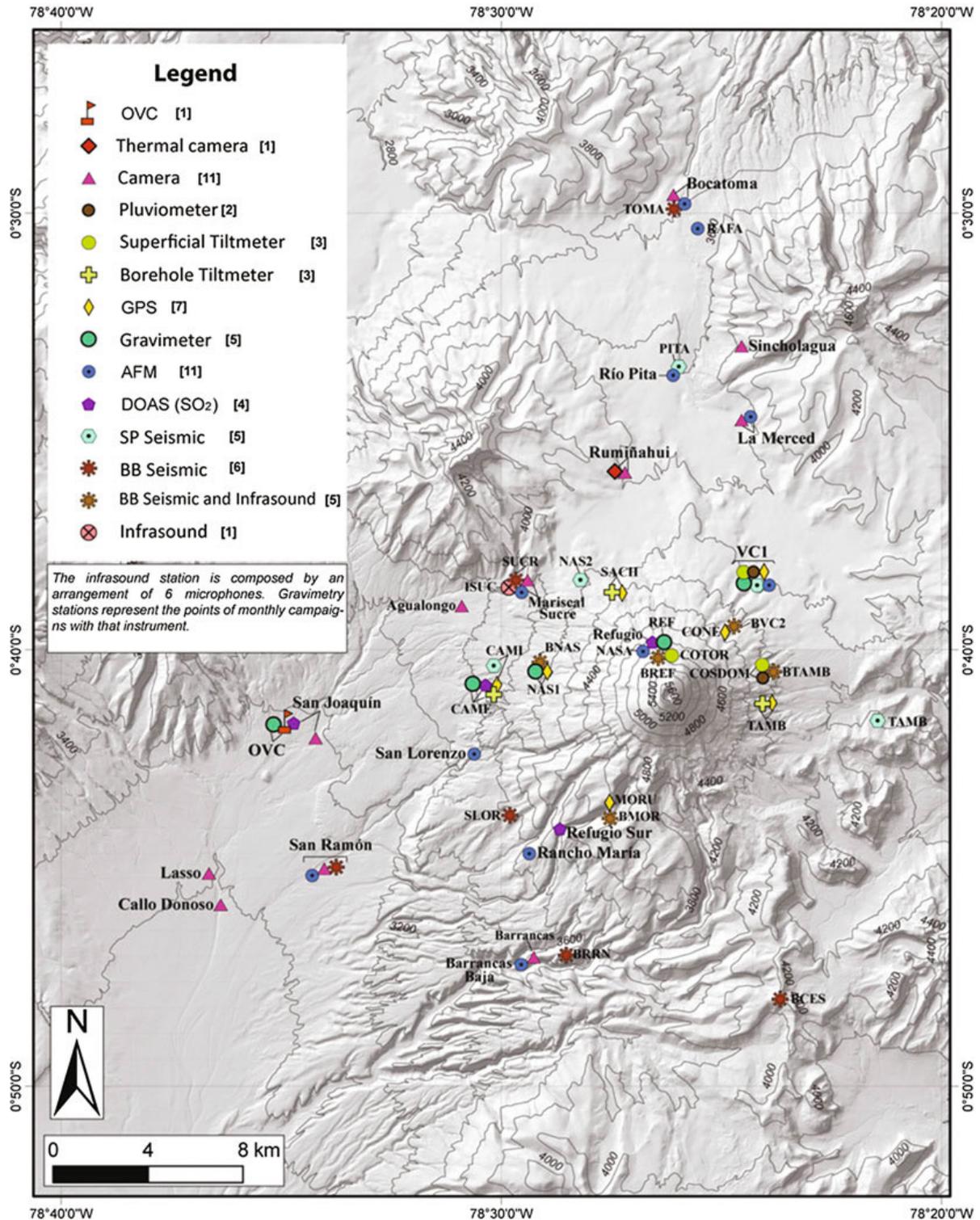


Figure 2: Map of the instrumental monitoring network around Cotopaxi volcano, April 2016 [Mothes et al. 2017]. The station name codes are included. Acronyms: OVC = Observatory Vólcan Cotopaxi, GPS = Geographic Positioning System, AFM = Acoustic Flow Meter, DOAS=Differential Optical Absorption Spectroscopy, SO₂ = Sulfur Dioxide, SP = Short Period seismometer, BB = Broad Band seismometer.

offices. They are also in charge of the maintenance and management of the social media networks (e.g. webpage, Facebook, Twitter).

- The administrative team is in charge of the logistics and of the administrative management of IG-EPN.

Since the beginning, the IG-EPN was established in Quito, at the EPN campus, and is the headquarters for the development of the different activities of all the workers. At the end of 1999, the Tungurahua volcano entered in a new eruptive phase, so in order to monitor its daily activity, the IG-EPN decided to install the *Observatorio del Volcán Tungurahua* (OVT) in October 1999, located 13 km north of the volcano. At the OVT, two volcanologists and other IG-EPN members worked in weekly shifts to provide custom surveillance on the volcano activity and to maintain the instrumentation around the volcano, until it was closed after 20 years of continuous operation. The location of the OVT enabled close relationship with the population and a better understanding of the superficial activity of Tungurahua whilst erupting [e.g. Mothes et al. 2015].

2.2 Data processing, storage and access

All the data generated by the instrumentation is sent continuously via radio, microwave, satellite or internet from the stations to the headquarters in Quito. These data are stored in servers at the IG-EPN and are accessed and daily processed by scientists. Depending on the monitoring technique, the processing follows different protocols: Seismic data from short and broad band seismometers, includes earthquakes classification, location and magnitude calculation; Ground deformation data from GPS and tilts, includes analysis of the deformation trend in a certain period of time; Gas data from DOAS, multiGAS is analyzed to determine the SO₂ amount released to the atmosphere; long term analysis of thermal anomalies is carried out via Infra Red images collected via fixed cameras; additionally regular visual observations allows to identify surface activity changes on the morphology, presence of ash columns and their dispersion in the atmosphere.

Processed seismic and volcanic data can be found in a dedicated webpage*. When the requirement is different from the available information provided in the webpage, the user can fill out a specific request form.

3 VOLCANO HAZARD MANAGEMENT

3.1 Hazard management tools and techniques

At the IG-EPN, volcanic hazard management is carefully thought out within the current worldwide princi-

ples of risk reduction [United Nations 2015], thus long-term and short-term hazards have been considered.

Long-term hazard assessment: the background information of the volcano is especially important in order to understand the volcanic activity and associated parameters that may eventually lead to an eruption. Likewise, the geological and historical activity data are essential for assessing the hazards of each volcano.

Short-term hazard assessment: in order to identify the precursory phenomena that may eventually precede volcanic activity, human surveillance and instrumental monitoring of the volcano are carried out. The analysis and interpretation of different monitoring systems, constitutes the basic elements in the short-term evaluation of the volcanic hazard. This information is very important in the prognosis of the development of the activity, in the elaboration of eruptive scenarios, and especially in the assembling of Early Warning Systems.

3.2 Early Warning Systems (EWS) for volcanoes

The Early Warning System (EWS) that the IG-EPN follows was defined in 2006 during the Early Warning Conference III [ISDR Early Warning Conference III 2006]. It is a system that empowers people and communities confronted with a hazard to act timely and adequately to reduce the negative effects. The EWS is made of three groups. The first group (IG-EPN), is responsible for assessing the hazard and volcano monitoring and recognizes and declares the occurrence of the hazard. A second group, made up of authorities, stakeholders and Civil Protection, is responsible for the decision and communication of the alert. A third group comprises the community at risk, and has been trained to respond to the alert.

This system was implemented during the recent eruption of Tungurahua volcano (1999–2016) and proved to be very effective in drastically reducing the impact associated with the eruptive activity (Figure 3). The communities were evacuated adequately upon receiving alerts and there were no fatalities related to the impact of lahars and lava flows. During the eruption of August 2006, however, five people who had been evacuated according to the provisions of the EWS decided to return to their homes where they were caught and killed by a PDC. The ash falls were abundant during this same eruptive period and, despite having produced no fatalities, they generated substantial economic losses [Tobin and Whiteford 2002].

In this regard, it is noteworthy to mention an unprecedented experience we had during the 17-yr-long Tungurahua eruption that is the organization of a network of volunteers, known as *vigías* [Stone et al. 2014]. Initially, the *vigías* (Spanish word for watchman) were volunteers from the communities around the volcano, responsible for making observations to support the monitoring of the OVT, and for maintaining the field

*<https://www.igepn.edu.ec/solicitud-de-datos>

Table 1: Monitoring techniques used by the IG-EPN for the surveillance of 20 volcanoes in Ecuador; 16 in mainland and 4 in the Galápagos Islands. Volcanoes are grouped depending on the surveillance level. A = Active; E = Extinct; IE = In Eruption.

Volcano	Surveillance level	Level of activity	Monitoring techniques					
			Seismic			Acoustic	Geodetic	
			Short period	Broad Band	Lahar sensors		Tilt-meter	GPS
Cotopaxi (5898 m)	1	A	6	9	11	2	6	9
Guagua Pichincha (4742 m)		A	4	3	-	1	2	1
Reventador (3539 m)		IE	2	2	1	2	-	-
Tungurahua (5016 m)		A	3	7	9	4	5	5
Antisana (5720 m)	2	A	1	3	-	-	-	2
Chiles (4707 m) - Cerro Negro (4429 m)		A	-	2	-	1	-	2
Cotacachi (4887 m) - Cuicocha (3318m)		A	-	3	-	-	-	2
Nevado Cayambe (5759 m)		A	1	2	-	-	2	2
Sierra Negra (1124 m)**		IE	-	2	-	-	-	-
Alcedo (5720 m)**		A	-	1	-	-	-	-
Cerro Azul (1689 m)**	3	A	-	2	-	-	-	-
Chacana (4000 m)		A	-	1	-	-	-	1
Chimborazo (6268 m)		A	-	3	-	-	-	1
Fernandina (1476m)**		IE	-	2	-	-	-	-
Imbabura (4545 m)		A	-	1	-	-	-	-
Pululahua (3316 m)		A	-	-	-	-	-	1
Quilotoa (3872 m)		A	-	-	-	-	-	1
Sangay (5302 m)		IE	-	1	-	-	-	-

Volcano	Monitoring techniques (continued)							Ash meter	Rain gauge
	Geochemistry			Remote sensing					
	Gas (SO ₂) DOAS	multiGAS*	Fluid	Ground-based IR cameras	Ground-based visual cameras	Airborne vis+IR			
Cotopaxi (5898 m)	3	×	×	2	11	×	30	2	
Guagua Pichincha (4742 m)	-	-	×	-	1	×	2	1	
Reventador (3539 m)	1	×	-	1	3	×	60	-	
Tungurahua (5016 m)	2	×	×	-	4	×	-	2	
Antisana (5720 m)	-	-	-	-	-	×	-	-	
Chiles (4707 m) - Cerro Negro (4429 m)	-	-	×	-	-	×	7	-	
Cotacachi (4887 m) - Cuicocha (3318m)	-	-	×	-	-	×	-	-	
Nevado Cayambe (5759 m)	1	×	×	-	-	×	-	-	
Sierra Negra (1124 m)**	1	-	-	-	1	-	4	-	
Alcedo (5720 m)**	-	-	-	-	-	-	-	-	
Cerro Azul (1689 m)**	-	-	-	-	-	-	-	-	
Chacana (4000 m)	-	-	-	-	-	-	-	-	
Chimborazo (6268 m)	-	-	-	-	-	×	-	-	
Fernandina (1476m)**	-	-	-	-	-	-	-	-	
Imbabura (4545 m)	-	-	-	-	-	×	-	-	
Pululahua (3316 m)	-	-	-	-	-	×	-	-	
Quilotoa (3872 m)	-	-	-	-	-	×	-	-	
Sangay (5302 m)	1	×	-	-	1	×	-	-	

* Airborne

** Galápagos volcanoes

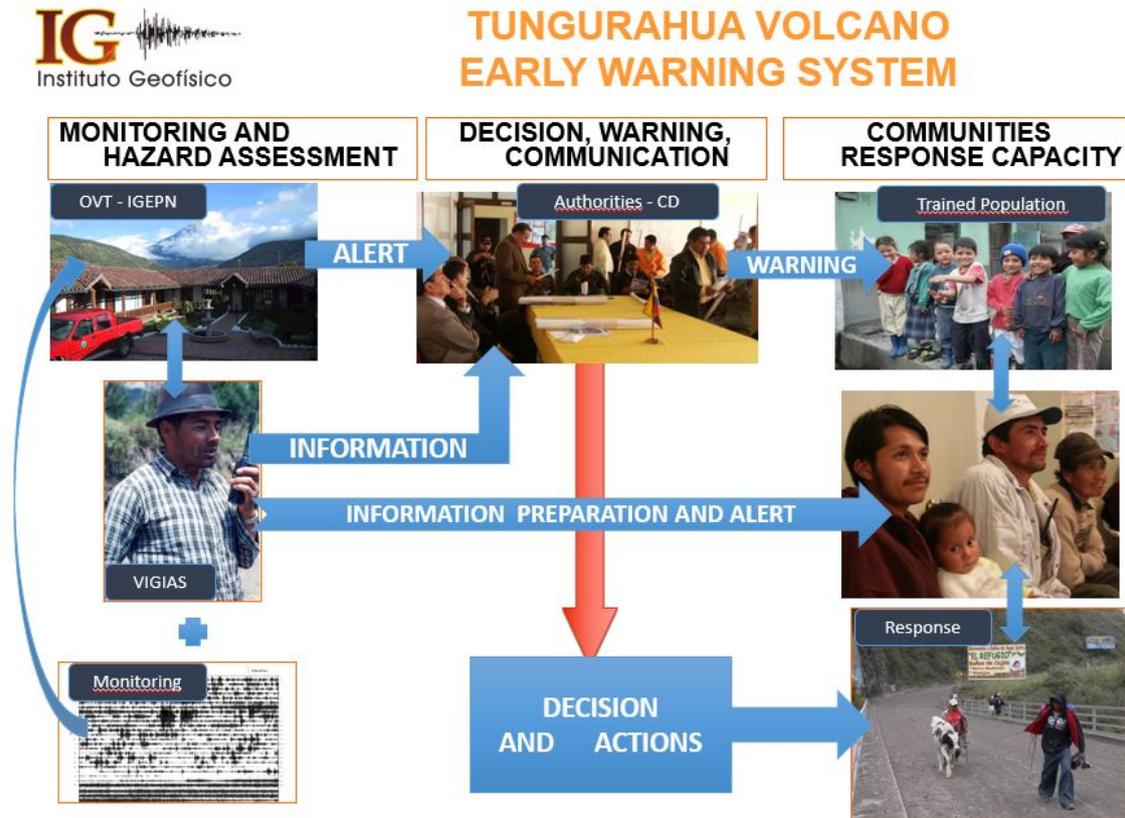


Figure 3: Early Warning System for Tungurahua eruption (1999–2016) [modified from Ramón 2010].

monitoring stations [Armijos et al. 2017]. They were the intermediaries between the scientists of the OVT and the communities who thereafter had the knowledge about the activity of the volcano. That way the *vigias* became the leaders of their communities and lead their communities to safer places once early warnings were issued, and in some cases even evacuated their communities before the alerts were issued. The *vigias* proved to be of great help in managing hazards and reducing risk.

3.3 Volcanic Hazard Mapping

In 1978, the first hazard map of Ecuador and of all South America was published for Cotopaxi volcano [Miller et al. 1978]. This map was then updated in 2004 and after the small hydro-magmatic eruption in August 2015, [the new map now extent of the eastern zone of the volcano; Vascónez et al. 2016]. Between 1988 and 1992, 11 more volcanic hazard maps were published for Antisana, Chimborazo, Cotopaxi (North and South), Cuicocha, Guagua Pichincha, Atacazo –Ninahuilca, Pululahua, Quilotoa and Tungurahua volcanoes as part of a United Nations Project. Later hazard maps were published for Cayambe [Samaniego et al. 2002] and Imbabura [Ruiz et al. 2005]. After an intense eruption in 2006, the hazard map for Tungurahua was updated

[Samaniego et al. 2008]. Reventador volcano began a new eruptive period in 2002, with the largest eruption (VEI = 4) recorded in the country in the last 150 years [Hall et al. 2004]. A hazard map was published in 2011 [Bourquin et al. 2011], which includes modeled extension and distribution of the products. The Sangay volcano hazard map was published in 2013 [Ordóñez et al. 2013]. In 2014, a volcanic hazard map for Chiles - Cerro Negro volcanic complex (located in the Ecuador-Colombia border) was jointly prepared by IG-EPN and the Geological Service of Colombia*. Very recently, the IG-EPN staff has updated the Guagua Pichincha volcano hazard map [Telenchana et al. 2019].

Updated volcanic hazard maps can be downloaded from the IG-EPN website†.

4 INFORMATION DISSEMINATION AND OUT-REACH

4.1 Volcanic activity reports

The IG-EPN keeps the Ecuadorian community permanently informed about the status of the volcanic activity in the country through different means. The fre-

*<https://www.igeepn.edu.ec/ccn-mapa-de-peligros>

†<https://www.igeepn.edu.ec/publicaciones-vulcanologia/mapas-de-peligros>

quency and destination of the information depends on the type of activity that a given volcano presents for a given region. In any case, this information is intended to be directed to the largest number of recipients possible. Under these considerations, the IG-EPN offers the following four types of reports to the general public:

1. *'Informes diarios'* (daily IG reports) are generated for the volcanoes that are going through an eruptive phase. The reports include the information detected by the monitoring network and by the satellite sensors, as well as the weather conditions, and the information reported by on-site observers.
2. *'Informes IG al Instante'* (Real-time IG reports) are published immediately after the various detection networks have warned of the occurrence of some surface volcanic manifestation, which includes the emission of eruption columns, gas and ash emissions, or the presence of incandescence.
3. *'Avisos para la Aviación'* (Aviation Notifications – through the Volcano Observatory Notice for Aviation VONA) are reports issued when volcanic activity has generated columns of volcanic ash that jeopardizes air navigation. Currently these reports are being produced for Reventador and Sangay volcanoes. The main recipients of these reports are the Ecuador's Civil Aviation authorities (Dirección General de Aviación Civil: DAC) and the Volcanic Ash Advisory Center (VAAC, Washington). These reports are also disseminated via the aforementioned means of the IG-EPN.
4. *'Informes Especiales'* (Special Reports) are generated when there is extraordinary volcanic activity, as for example, the onset of an eruption, a drastic increase in surface activity, or the decrease or cessation of this activity.

In cases where activity on any of the volcanoes warrants it, the IG-EPN calls on Ecuador's different media to hold press conferences, in which the community is informed about the situation. On those occasions the media frequently attends the IG-EPN headquarters where spokespeople provide explanations and interviews about the volcanic event.

These reports are published on the IG-EPN website*, are sent by email to various recipients (e.g. local and regional authorities, Servicio Nacional de Gestión de Riesgos y Emergencias, Institutions, communities and stakeholders), and are published in IG-EPN's social networks (e.g. Facebook†, Twitter‡, YouTube§).

*www.igepn.edu.ec

†<https://www.facebook.com/IGEPNecuador>

‡<https://twitter.com/IGecuador>

§<https://www.youtube.com/user/institutogeofisico>

5 INTERACTION WITH OTHER PUBLIC INSTITUTIONS

The IG-EPN is the officially designated entity responsible for monitoring and disseminating information regarding seismic and volcanic activity in Ecuador. The IG-EPN interacts directly with many public institutions such as the *Servicio Nacional de Gestión de Riesgos y Emergencias* (SNGRE), and the *Servicio Integrado de Seguridad ECU 911*. Also, IG-EPN brings information to the local governments about the cities that might potentially be affected by or confronted by eruptive activity.

Important infrastructure has been developed in areas of the country that are susceptible to the impacts of seismic and volcanic activity. The IG-EPN, via its outreach activities, maintains cooperative agreements with several public and private institutions that are responsible for these public works, so that they are informed and alerted in detail about the types of hazards that they might need to face. An example of such a cooperative arrangement is represented by the agreement with the Galapagos National Park, through which the Park is provided with up-to-date seismic and volcanic monitoring information, as well as with the corresponding hazard assessment, especially in case of frequent eruptions where information during the crises is offered. Similarly, cooperation agreements with institutions in the electricity and oil sectors are maintained.

6 NEEDS, CHALLENGES, AND FUTURE PERSPECTIVES

In Ecuador, the short-term hazard assessment, which includes monitoring activities and periodic equipment maintenance, takes up most of IG-EPN's time, human and financial resources. Ensuring the proper functioning of the current monitoring network (more than 500 seismic and volcanic monitoring stations nationwide) has become the main priority, and the main challenge over the years. The monitoring data are needed to guarantee accurate and real-time information for the population living in high-risk areas. In particular, the resources limitations become more evident during crises, limiting the institutional response.

Nowadays, several novel monitoring techniques have been established, mainly based on remote sensing. These new techniques demand facilities and experts and therefore both technical training and transfer of knowledge are needed. These challenges could be tackled through international cooperation, mainly via partnership projects that focus on solving the local needs and take into account the different cultural realities. Finally, by enhancing the communication channels, simplifying the terminology, and by being physically present in communities (like with the OVT), we can improve the relationship and trust between scientists

and stakeholders in order to facilitate good decision-making, especially during crises.

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AUTHOR CONTRIBUTIONS

Patricio Ramón, Silvia Vallejo, and Francisco Vásconez led the writing of the manuscript. Patricia Mothes, Daniel Andrade, Santiago Santamaria, Hugo Yepes, and Silvana Hidalgo contributed with information from monitoring systems. All authors reviewed and made suggestions that improved the manuscript.

DATA AVAILABILITY

All available volcanic hazard maps in Ecuador and volcano activity reports can be downloaded from the Geophysical Institute website <https://www.igepn.edu.ec/>. Additionally, thermal anomalies are regularly checked on <http://modis.higp.hawaii.edu/> and on <http://www.mirovaweb.it/> pages, and degassing data on <https://so2.gsfc.nasa.gov/>.

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