

# Volcano monitoring in Latin America: taking a step forward

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## ABSTRACT

Monitoring the state of active volcanoes is the foundational component of volcanic risk reduction strategies. To a large extent, these responsibilities rest with volcano observatories. Based on the 11 Reports that constitute this Special Issue—“Volcano Observatories in Latin America”—we provide a comprehensive overview of the work that has been carried out by the observatories in Latin America, a region in which tens of millions of people are exposed to volcanic activity. Since the first steps taken in the 1980s, volcano observatories of the region have made significant progress in assessing and monitoring volcanic activity. Currently, 17 institutions officially contribute to monitoring 135 volcanoes in 10 countries. Along with the improvements in the instrumental, technical, and operational capabilities, advancements have been made in long-term hazard assessment and hazard communication. But despite all the progress accomplished, several challenges and limiting factors still remain, such as the lack of financial resources and training opportunities. Efforts should be focused on increasing the number and quality of monitoring networks.

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## 1 INTRODUCTION

Latin America is a region with numerous active volcanoes coupled with large populations exposed to the hazards they pose. Recent eruptions that took place in the region, such as Chaitén (2008–2010, Chile), Cordón Caulle (2011–2012, Chile), Calbuco (2015, Chile), Fuego (2018, Guatemala) and Ubinas (2019, Peru) have demonstrated the impact of volcanic activity on modern societies [e.g. Craig et al. 2016; Elissondo et al. 2016; Reckziegel et al. 2016; CONRED 2018]. In this complex scenario, it is essential to monitor and understand volcanic behaviour in order to constrain volcanic hazards and assess or mitigate associated risk. Volcano observatories are institutions developed to identify, monitor, and perhaps forecast, the occurrence of volcanic eruptions [Pallister et al. 2019; Lowenstern and Ewert 2020]. In many cases, these institutions are also responsible for assessing and communicating volcanic hazards, along with the development of educational and outreach programs. Consequently, volcano observatories are a key component in the development

of disaster risk reduction strategies.

Although the first volcano observatories in the world were founded more than one hundred years ago—e.g. *Osservatorio Vesuviano* (Italy) in 1841, Hawaiian Volcano Observatory (USA) in 1912—in Latin America these institutions are relatively young and, in many cases, their creation occurred as a consequence of a volcanic crisis or a disaster. For example, the creation of the first volcano observatory in Colombia—now called *Observatorio Volcanológico y Sismológico de Manizales* (SGC-OVSM)—took place in 1986, after the 1985 Nevado del Ruiz eruption and the associated lahar that buried the city of Armero and killed over 20000 people [see Gómez Martínez et al. 2021, this issue]. But despite their relative youth, volcano observatories in the region have grown quickly, enhancing their technical and scientific capabilities rapidly. However, this did not happen without facing several difficulties, some of which still persist. This is the story told by this Special Issue: “Volcano Observatories in Latin America.”

This Special Issue represents an unprecedented collaborative effort between scientists, volcano observa-

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tories, the *Asociación Latinoamericana de Volcanología*\* (ALVO), and the journal *Volcanica* [see [Chevrel et al. 2021](#), Editorial: this issue], to summarize and share with the (scientific) community the work that is being carried out by the volcano monitoring institutions in Latin America. For the first time, all volcano observatories of the region—from Mexico to the Southern Cone—converged on a single project. Often overextended by daily surveillance duties and responsibilities, publishing in scientific journals is generally not at the top of the priorities list of volcano observatories. This Special Issue is therefore a rare window of opportunity to learn about these institutions.

Another important milestone of this project is the dual-language format of the publications, with versions in English and Spanish<sup>†</sup>. Guided by *Volcanica*'s commitment to removing barriers and making science more accessible [[Farquharson and Wadsworth 2018](#)] and ALVO's enthusiasm for promoting Latin American volcanology, we hope this innovative format contributes to reaching a larger audience. This Preface frames the 11 *Reports* that constitute this Special Issue. Here, we provide the reader with an overview of the topics covered in the different *Reports*. We summarize and contextualize the information in those *Reports*, in order to assess the current state of volcano monitoring in Latin America.

## 2 ACTIVE VOLCANISM IN LATIN AMERICA

Latin America is one of the most active volcanic regions in the world. Although more than one definition is possible, here Latin America is considered as the region of America comprised of the 19 countries where Spanish or Portuguese is currently the dominant language. This therefore exclude the active volcanoes of the Caribbean that are in English, French, or Dutch speaking countries. According to [Delgado Granados et al. \[2015b\]](#), at least 1265 eruptions with a Volcanic Explosivity Index (VEI)  $\geq 2$  have occurred in Latin America during the Holocene. Furthermore, [Delgado Granados et al. \[2015b\]](#) reported a rate of 4.5 eruptions per year over the last 150 years. Although most Holocene eruptions were  $\text{VEI} \leq 3$  (~85 %), stratigraphic records also show evidence of larger eruptions, with the capacity of affecting at local, regional and hemispherical scale. One of the largest Holocene eruptions worldwide, the ~4410 BP Cerro Blanco rhyolite eruption in the Central Andes (Argentinian Puna) emitted  $>100 \text{ km}^3$  of tephra, blanketing a wide area of Argentina, Paraguay and Brazil [[Fernandez-Turiel et al. 2019](#); [Báez et al. 2020](#)]. Another

example is the explosive eruption of Huaynaputina volcano in 1600 CE, in southern Peru. This is considered the largest historic eruption in South America, with a total of  $13\text{--}14 \text{ km}^3$  of tephra covering vast areas of southern and west-central Peru, western Bolivia, and northern Chile [[Prival et al. 2020](#)].

### 2.1 Where are the active volcanoes?

The occurrence of volcanism in Latin America is mainly concentrated along the Pacific edge ([Figure 1](#)). According to what volcano observatories report in this Special Issue, there are 302 active volcanic centers in the region (i.e. having erupted in the last 10000 years). This includes volcanic complexes, stratovolcanoes, calderas and monogenetic fields. A summary of their distribution by country is shown in [Figure 2](#).

In South America, volcanic activity takes place chiefly in the Andean Range, a  $>7500\text{-km}$ -long continuous mountain chain that extends from the southern tip of Argentina and Chile to Venezuela in the north. However, not all of the Andean Range is volcanically active. Volcanism occurs in four separate regions named the Northern (NVZ;  $5^\circ \text{ N--}2^\circ \text{ S}$ ), Central (CVZ;  $14\text{--}27^\circ \text{ S}$ ), Southern (SVZ;  $33\text{--}46^\circ \text{ S}$ ) and Austral (AVZ;  $49\text{--}55^\circ \text{ S}$ ) Volcanic Zones [[Stern 2004](#)]. While the first three zones are related to the subduction of the Nazca plate beneath the South American plate, the AVZ results from the subduction of the Antarctic plate. The second source of volcanism in South America is the Galápagos hot spot, represented by the 22 volcanoes that shape the Galápagos Archipelago [[Ramón et al. 2021](#), this issue].

In Central America, most active volcanoes are located north of the Talamanca Range (southern Costa Rica), and result from the subduction of the Cocos plate under the Caribbean plate. The Central American Volcanic Arc (CAVA) extends for over 1000 km, from central Costa Rica to the border between Guatemala and Mexico. Volcanoes along the CAVA delineated a series of 100 to 300 km linear segments, with an average spacing of 27 km [[Carr et al. 2003](#)]. South of the Cocos Ridge, volcanic activity is scarce and there is controversy among scientists as to whether it should be considered part of the CAVA [[Carr et al. 2003](#); [Wegner et al. 2011](#)]. The only confirmed evidence of Holocene volcanism there is associated with Barú volcano, in western Panama. Its last known eruption occurred 400–500 years ago [[Sherrod et al. 2008](#)]. The only Central American countries with no evidence of active volcanism are Honduras and Belize.

In Mexico, the occurrence of volcanism responds to a complex interplay between several tectonic plates [[Espinasa-Pereña et al. 2021](#), this issue]. At the southern end of the country, the subduction of the Cocos plate under the Caribbean plate also creates the Chiapanecan volcanic arc. In the central region, the interaction between the North American plate with the Co-

\* A detailed description about ALVO's history and main objectives is provided by [Delgado Granados et al. \[2015a,b\]](#). Link to ALVO's institutional video: [https://youtu.be/bEwzA\\_ozDo](https://youtu.be/bEwzA_ozDo).

<sup>†</sup> Here, Latin America is considered as the region of America comprised of the 19 countries where Spanish or Portuguese is currently the dominant language. Latin American volcano observatories are all located in Spanish-speaking countries.

cos and Rivera plates results in the occurrence of the Trans-Mexican Volcanic Belt, which crosses the country from west to east. Volcanism also occurs in the north-western coast of Mexico, which is associated with the spreading setting of the East Pacific Rise. Lastly, a volcanic province develops along the east of the country, which includes few recent monogenetic fields and the San Martín Tuxtla volcano. For a detailed description of the volcano distribution and the associated tectonic settings in the different countries, please refer to the respective works in this Special Issue.

## 2.2 Volcano-human interaction

Volcanic activity in Latin America has shaped not only the landscape morphology but also the history and culture of its people. It is already well-known that volcanic eruptions can generate a wide range of negative impacts on people and assets. For instance, the 1600 CE Huaynaputina eruption caused serious economical and human losses, including the burial and destruction of all the communities within 20 km of the volcano [Marín et al. 2021]. While it is estimated that volcanic activity in the region has caused almost 50000 fatalities since 1600 CE [Auker et al. 2013], its influence and impacts can be traced back to prehistoric times [Dull et al. 2001; Hall and Mothes 2008]. Besides negative impacts, volcanoes have also played an important role in the development of cultural identities. This can be recognized, for instance, through the myths, legends, and worldviews that have survived to our time and continue to evolve [Masse and Masse 2007; Marín et al. 2020]. In addition, volcanoes and their products have provided a source of resources (e.g. obsidian knives, arrows, mirrors, and grinding stones), as recognized at many archaeological sites [Chevrel et al. 2015; Stern 2018].

Volcano-human interaction has evolved as the ways humans inhabit the territory have changed. From the initial dispersed rural communities to the modern settlements, the complexity has increased in multiple and myriad ways. As a general rule, urban settlements have expanded, increasing in size, number, and density of inhabitants. However, the complexity reaches beyond this, for instance, infrastructure, means of transport, telecommunication and, more broadly, new technologies, have critically modified the dynamics of human settlements. In many cases, urban areas have developed nearby active volcanoes. There are several examples of this in Latin America, including many capital cities: Mexico City, Quito (Ecuador), San Jose (Costa Rica), Managua (Nicaragua), San Salvador (El Salvador) and Guatemala City.

The number of people living nearby volcanoes has increased, resulting in a larger number of people exposed to volcanic hazards. According to Loughlin et al. [2015], only 0.35 % of the population of South America (~1.25 million people) live within 10 km of an active volcano, while in Central America and Mexico this

number raises to 3.6 % (~5.6 million). When the radius is extended to 100 km, the exposed population increases to 9.79 % (~35.3 million) and 23.57 % (~36.6 million), respectively. In El Salvador and Nicaragua the percentage of the population living nearby an active volcano goes up to 30 % [Castro and Gutiérrez 2021, this issue] and 70 % [Espinoza et al. 2021, this issue], respectively. More people are therefore living in increasingly complex and dynamic settlements. This scenario poses a challenge to society as a whole, but especially to governing authorities, who are responsible for the safety of the population. In this context, volcano observatories can contribute significantly to the reduction of risk [Auker et al. 2013; Lowenstern and Ewert 2020].

## 3 KEEPING AN EYE ON VOLCANOES: WHO AND HOW?

After the pioneering efforts of Mexico during the end of the 19th century and first half of the 20th [Espinosa-Pereña et al. 2021, this issue] and Costa Rica in 1964 [Avard et al. 2021, this issue], the first permanent volcano observatory in Latin America was the IG-EPN<sup>‡</sup> (Ecuador), founded in 1983 [Ramón et al. 2021, this issue]. The youngest is the OAVV-SEGEMAR<sup>‡</sup> (Argentina), operating only since 2017 [García and Badi 2021, this issue]. Currently, 17 volcano observatories officially contribute to monitoring volcanic activity in 10 countries (Table 1; Figure 1). They represent 25 % of the volcano observatories worldwide (see World Organization of Volcano Observatories' (WOVO) website for the complete list of volcano monitoring institutions<sup>§</sup>). The only two countries of the region with evidence of active volcanism that lack volcano observatories are Bolivia and Panama.

In 7 of the 10 countries, monitoring is carried out by a single observatory. Only in Mexico, Costa Rica, and Peru more than one institution participates in the monitoring—with different degrees of responsibility. Most of the volcano observatories belong to national geological surveys (or other national institutions with an equivalent role). However, there are some exceptions. In Ecuador (IG-EPN) and Costa Rica (OVSICORI-UNA and RSN-UCR)<sup>‡</sup> monitoring is carried out by universities. In Mexico, volcano surveillance results from a joint effort between the National Disaster Prevention Center (CENAPRED<sup>‡</sup>, by its acronym in Spanish) and national universities (OSV-UV, CUEIV and CMVS-UNICACH)<sup>‡</sup>. In some duties, these institutions are supported by the *Universidad Nacional Autónoma de México* (UNAM).

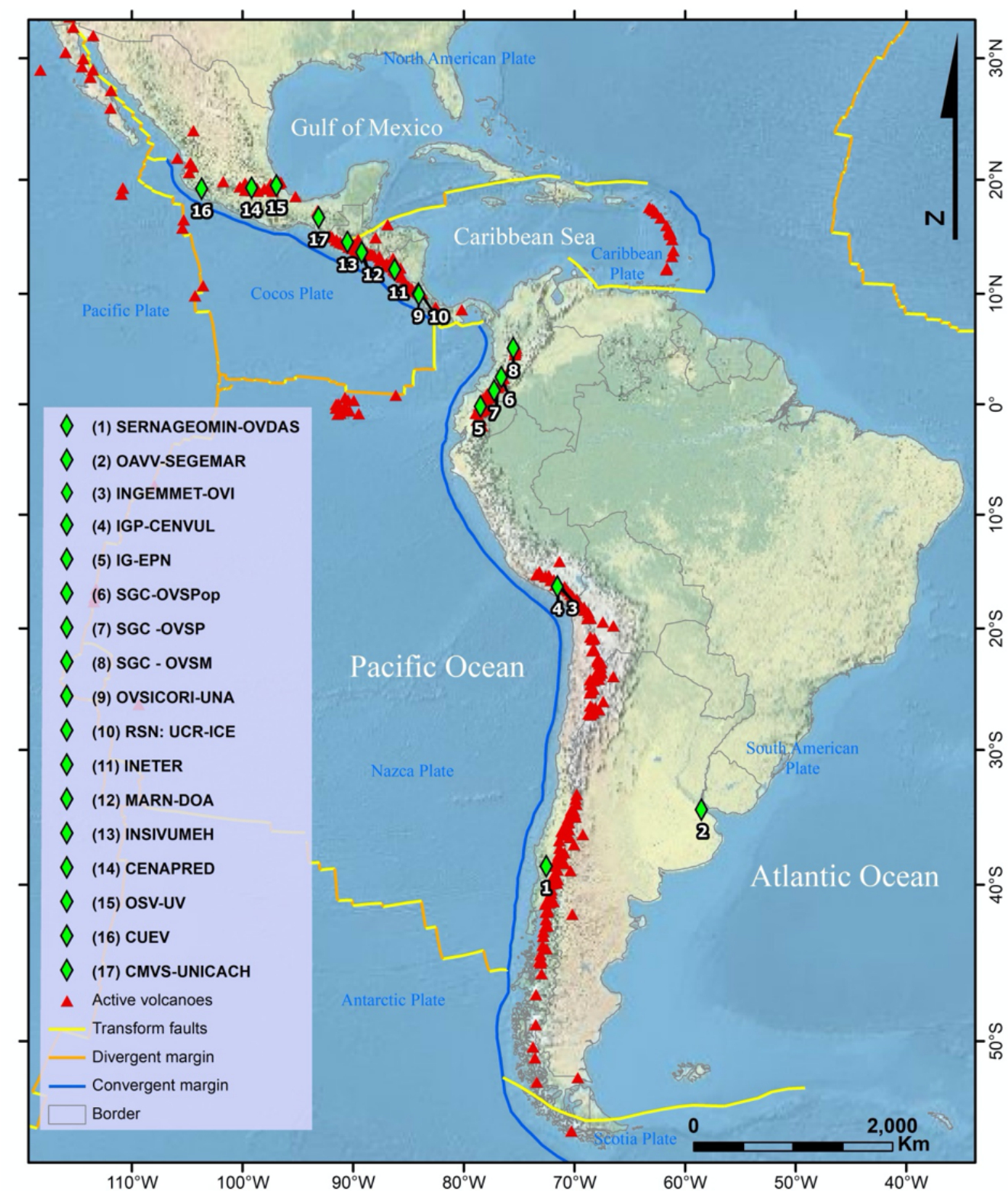
### 3.1 Volcano surveillance

At the time of the writing of this Special Issue, a total of 135 volcanoes are being monitored—with at least

<sup>‡</sup> All acronyms are defined in Table 1.

<sup>§</sup> <https://wovo.iavceivolcano.org/observatories>





**Figure 1:** Map showing the active volcanoes (red triangles) and volcano monitoring institutions (green diamonds) in Latin America. A detailed list of these institutions is provided in [Table 1](#). Although represented in the map, active volcanoes from the Caribbean volcanic arc (upper right cluster of volcanoes) are not included in the Latin American region as defined here<sup>†</sup>. The map in this figure is sourced from Esri®.

**Table 1:** Latin American volcano observatories, listed from south to north.

Map code	Acronym	Monitoring institution	Country	Website	Reference
1	SERNAGEOMIN-OVDAS	Servicio Nacional de Geología y Minería - Observatorio Volcanológico de los Andes del Sur	Chile	a	Amigo [2021]: “Volcano monitoring and hazard assessments in Chile”
2	OAVV-SEGEMAR	Observatorio Argentino de Vigilancia Volcánica - Servicio Geológico y Minero Argentino	Argentina	b	García and Badi [2021]: “Towards the development of the first permanent volcano observatory in Argentina”
3	IGP - CENVUL	Instituto Geofísico del Perú - Centro Volcanológico Nacional	Peru	c	Machacca et al. [2021]: “Monitoring of active volcanoes in Peru by the Instituto Geofísico del Perú: Early warning systems, communication, and information dissemination”
4	INGEMMET - OVI	Instituto Geológico, Minero y Metalúrgico - Observatorio Volcanológico INGEMMET		d	Aguilar Contreras et al. [2021]: “Hazard assessment studies and multiparametric volcano monitoring developed by the Instituto Geológico, Minero y Metalúrgico in Peru”
5	IG-EPN	Instituto Geofísico Escuela Politécnica Nacional	Ecuador	e	Ramón et al. [2021]: “Instituto Geofísico – Escuela Politécnica Nacional, the Ecuadorian Seismology and Volcanology Service”
6	SGC- OVSPop	Servicio Geológico Colombiano - Observatorio Volcanológico y Sismológico de Popayán	Colombia	f	Gómez Martínez et al. [2021]: “Active volcanism in Colombia and the role of the Servicio Geológico Colombiano”
7	SGC - OVSP	Servicio Geológico Colombiano - Observatorio Volcanológico y Sismológico de Pasto		f	
8	SGC - OVSM	Servicio Geológico Colombiano - Observatorio Volcanológico y Sismológico de Manizales		f	

Continued on next page.

<sup>a</sup> <https://www.sernageomin.cl/red-nacional-de-vigilancia-volcanica/><sup>b</sup> <https://oavv.segemar.gob.ar/><sup>c</sup> <https://www.igp.gob.pe/servicios/centro-vulcanologico-nacional/><sup>d</sup> <http://ovi.ingemmet.gob.pe/><sup>e</sup> <https://www.igepn.edu.ec/><sup>f</sup> <https://www.sgc.gov.co/volcanes/index.html>

**Table 1: [cont.]:** Latin American volcano observatories, listed from south to north.

Map code	Acronym	Monitoring institution	Country	Website	Reference
9	OVSICORI-UNA	Observatorio Vulcanológico y Sismológico de Costa Rica - Universidad Nacional	Costa Rica	g	Avard et al. [2021]: “Volcano hazard and surveillance in Costa Rica”
10	RSN: UCR-ICE	Red Sismológica Nacional: Universidad de Costa Rica – Instituto Costarricense de Electricidad		h	
11	INETER	Instituto Nicaragüense de Estudios Territoriales	Nicaragua	i	Espinoza et al. [2021]: “Nicaraguan volcanic monitoring program of the <i>Instituto Nicaragüense de Estudios Territoriales</i> ”
12	MARN - DOA	Ministerio de Medio Ambiente – Dirección General del Observatorio de Amenazas y Recursos Naturales	El Salvador	j	Castro and Gutiérrez [2021]: “Volcanic monitoring and hazard assessment in El Salvador”
13	INSIVUMEH	Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología	Guatemala	k	Roca Palma et al. [2021]: “Volcano observatories and monitoring activities in Guatemala”
14	CENAPRED	Centro Nacional de Prevención de Desastres	Mexico	l	Espinasa-Pereña et al. [2021]: “Monitoring volcanoes in Mexico”
15	OSV - UV	Observatorio Sismológico y Vulcanológico de Veracruz - Universidad Veracruzana		m	
16	CUEV	Centro Universitario de Estudios Vulcanológicos -Universidad de Colima		n	
17	CMVS -UNICACH	Centro de Monitoreo Vulcanológico y Sismológico de Chiapas - Universidad de Ciencias y Artes de Chiapas		o	

g <http://www.ovsicori.una.ac.cr/>

h <https://rsn.ucr.ac.cr/>

i <https://www.ineter.gob.ni/>

j <https://www.marn.gob.sv/monitoreo-volcanico/>

k <http://insivumeh.gob.gt/vulcanologia/>

l <https://www.gob.mx/cenapred>

m <https://www.uv.mx/osv/>

n <https://portal.ucol.mx/cueiv/>

o <https://monitoreo.unicach.mx/>

one technique or instrument—in Latin America. This represents 45 % of the active volcanoes in the region. As shown in Figure 2, active volcanoes are not equally distributed among the countries; neither are the number and percentages of them being monitored. Chile, Ecuador, and Colombia are together responsible for about 65 % of the total monitored volcanoes in the region. Only Colombia and Costa Rica monitor all the

active volcanoes in their territories. At the other end of the spectrum, Argentina, Mexico, and Guatemala monitor less than 25 % of their active volcanic systems. Bolivia and Panama do not monitor any of their active volcanoes.

The reasons for the low monitored/active ratios observed in some countries are multiple. However, to a large extent they are related to a lack of resources or

the fact that some of those volcanoes are located in remote areas with no populations nearby. In order to optimize resources, some countries like Argentina, Chile, Guatemala, and Mexico have developed Relative Risk Rankings, in which not only the hazards but also the exposure parameters are considered. In this way, monitoring efforts are focused on the volcanoes most likely to pose significant risk. For more details see the respective *Reports* in the Special Issue.

Volcano observatories perform permanent surveillance on 128 out of the 135 monitored volcanoes in Latin America. Only 7 volcanoes are subject to periodic (non-permanent) monitoring: 4 in Mexico, 1 in El Salvador, and 2 in Chile. Real-time monitoring has involved the deployment of over 1300 ground-based sensors around volcanoes. Seismology is the most used technique, with more than 600 seismometers installed all across the region. In most cases, this is complemented with geochemical (e.g. Multigas, DOAS), geodetic (e.g. GPS and tiltmeters) and infrasound stations. However, volcanoes with low-surveillance level are, in the vast majority of the cases, only monitored with seismic stations [e.g. Amigo 2021; Ramón et al. 2021, this issue]. All the observatories have adopted the use of fixed cameras as a complementary tool for visual surveillance. A detailed description of the tools and software used by the volcano observatories to acquire, process and analyse the monitoring data can be found in the different *Reports* of this Special Issue, including those developed by the institutions themselves [e.g. Gómez Martínez et al. 2021, this issue].

In addition to real-time monitoring, all the observatories carry out periodic geochemical sampling campaigns (gas and water). Also, when explosive events take place, ash collection is a common practice. For this purpose, Ecuador, Peru, and Chile have deployed low-cost ash collector networks [e.g. Figure 2B from Aguilar Contreras et al. 2021, this issue]. Lastly, satellite images are a very useful resource for monitoring ash dispersion, temperature anomalies, as well as lava flows over long periods of time, especially for remote volcanoes.

To perform the aforementioned tasks, volcano observatories employ over 450 people across Latin America. This includes scientists (e.g. geophysicists, geologists, chemists) as well as technical, administrative and logistical staff. A key component of volcano observatories is the interdisciplinary nature of their working team.

### 3.2 Long-term hazard assessment

Long-term hazard assessment is a fundamental part of the implementation of volcanic risk reduction strategies [Pallister et al. 2019]. In particular, hazard maps have proved to be an invaluable tool to communicate volcanic hazards. These maps show the areas that could be impacted by a volcanic phenomenon during or after an eruption.

In Latin America, 30 % ( $n=90$ ) of the active volcanoes have a hazard map (Figure 2). This is 15 % fewer than the number of monitored volcanoes in the region. Similar to the statistics on surveillance, almost two-thirds of the volcanoes with hazard maps ( $n=53$ ) are in Chile, Ecuador, and Colombia. There are also a few examples of bi-national hazard maps: Chiles-Cerro Negro volcanic complex (Ecuador-Colombia border) and Planchón-Peteroa, Laguna del Maule, and Lanín volcanoes (Chile-Argentina border).

In Figure 3, we present the evolution of hazard maps published through time in the region. The first map was published in 1978 for Cotopaxi volcano, Ecuador. However, it was not until 1985 that volcanic hazard maps started to be published systematically. Since then, three maps on average have been published every year. Together with Ecuador, Colombia, Guatemala, and Costa Rica were the first countries to produce hazard maps. With a few exceptions, it was not until the turn of the century that Chile, Nicaragua, El Salvador, Mexico, and lastly, Peru and Argentina, started developing hazard maps for their volcanoes. Some of the earliest published maps have already been updated (e.g. Nevado del Ruiz, Cotopaxi, Fuego, Popocatepetl). Although the first maps published were mainly deterministic (i.e., based on geological mapping and directly-observed historical events), the development of modelling-based [e.g. Gómez Martínez et al. 2021, this issue] and probabilistic maps [e.g. Castro and Gutiérrez 2021, this issue] is becoming increasingly common.

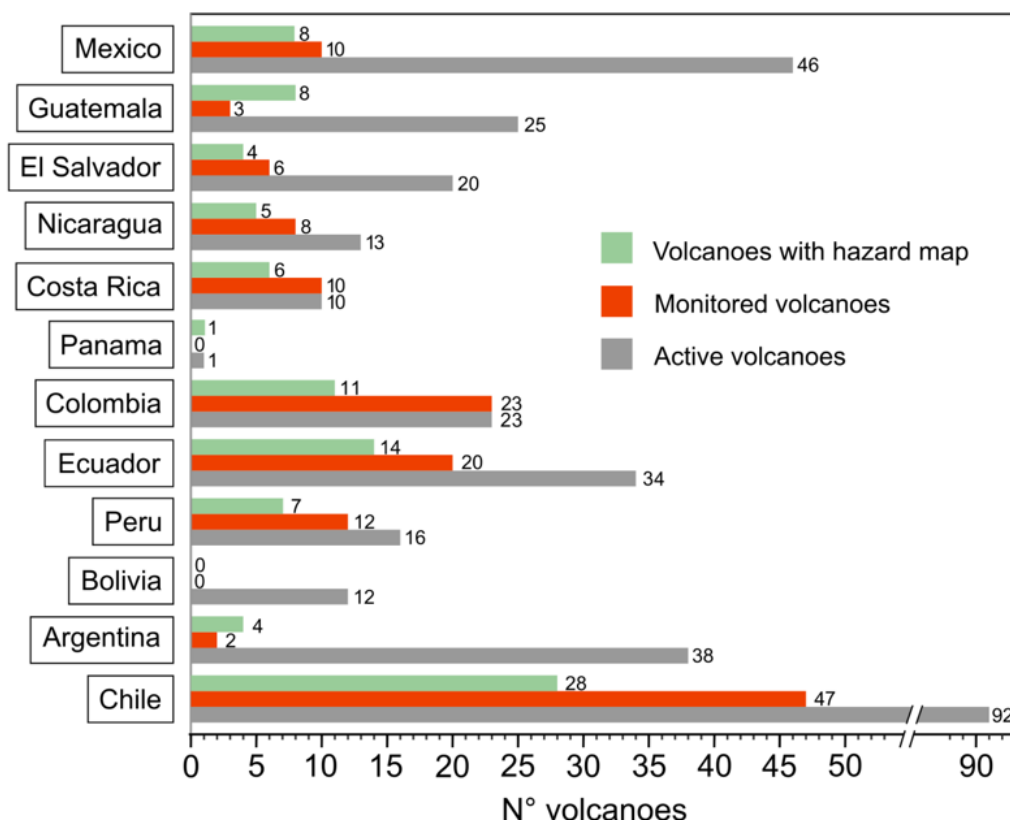
The responsibility for generating and publishing hazard maps in Latin America commonly lies with specialized divisions that are part of the institutions which host the volcano observatories. However, in countries like Mexico and Costa Rica, such resources have mostly been developed by scientists that do not belong to the monitoring institutions. Nevertheless, in recent years, this scenario has started to change, with the legally responsible institutions—CENAPRED and the Costa Rican civil protection (i.e. *Comisión Nacional de Emergencias*: CNE)—taking a more active role.

### 3.3 Volcano hazard communication and outreach

Volcano observatories are responsible for communicating hazard information [Pallister et al. 2019]. Effective communication is crucial during eruptive crises and equally important during quiescent periods. The main target audience is decision-makers and risk management institutions, but it can also include general public and the media; all of them with different levels of responsibilities and interests. For this reason, volcano monitoring institutions need to develop integral communication strategies, using several tools and diverse communication channels.

Latin American volcano observatories report the activity of the volcanoes under their surveillance, both





**Figure 2:** Plot showing the number of volcanoes monitored in Latin America, together with the hazard maps available. For each country, the number of active, monitored and “with hazard map” volcanoes are shown, from bottom to top. Data of active and monitored volcanoes were collected from the different *Reports* of this Special Issue. For details about the hazard map data, see the [Supplementary Material \[EN\]](#).

to decision-makers and civil protection institutions as well as to the media and general public. To do this, they publish volcanic activity reports with variable periodicity (e.g. daily, weekly, monthly), depending on the country and the volcanic activity. The reports include information about the different monitored parameters (e.g. seismicity, deformation, gas/ash emission, column height) and the alert level. All volcano observatories have adopted a color-coded activity level system, which provides information on the state of unrest. Although some differences can be found, most of the alert levels range from green to yellow, orange, and red. None of the volcano observatories of the region assumes the role of ordering civil actions (e.g. evacuations), and their responsibilities are limited to providing recommendations based on scientific evidences.

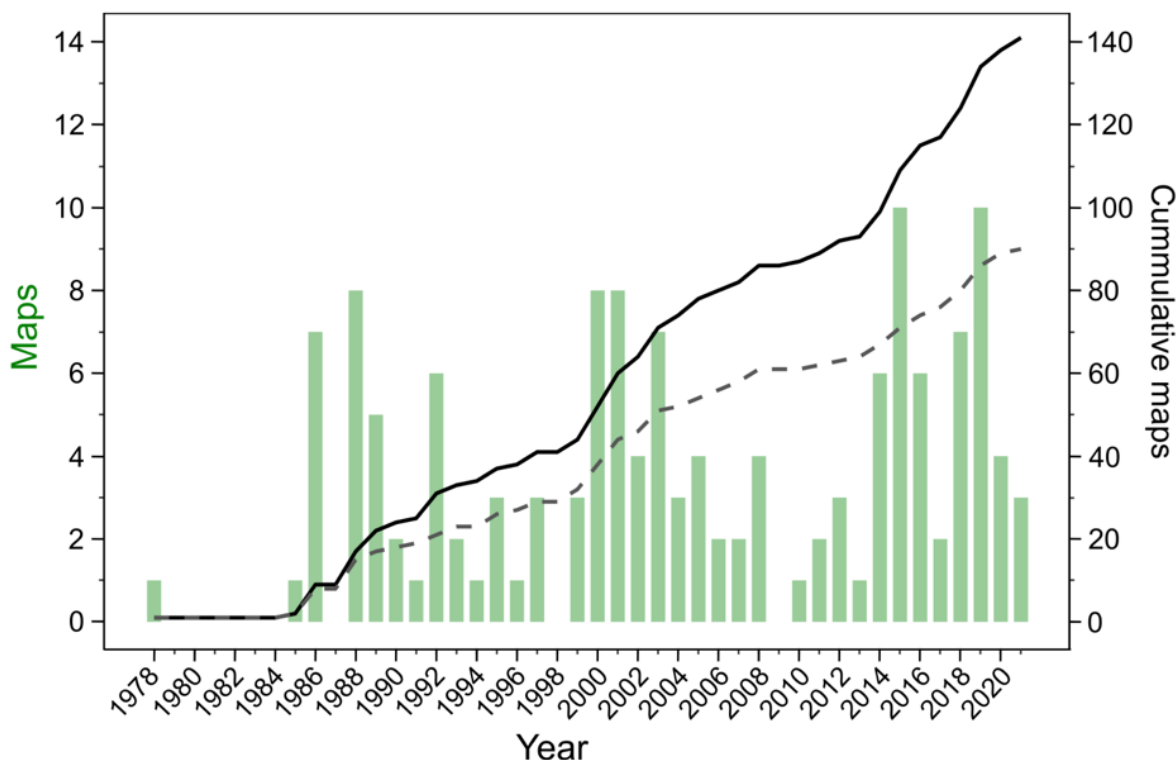
Reports are disseminated through several channels. All volcano observatories publish them on their websites (see [Table 1](#)), where they can be accessed by everyone. Additionally, most of the observatories send the reports to pre-defined email lists, which include key institutions and stakeholders (e.g. civil protection, monitoring partners, local, and regional authorities). In the last few years, social media—via platforms such as Twitter, Facebook, and Instagram—has become one of the main means of rapid dissemination of this informa-

tion. In Mexico and Peru, observatories have implemented the use of mobile apps [see [Espinasa-Pereña et al. 2021](#); [Machacca et al. 2021](#), this issue].

Volcano observatories’ websites are also a repository for basic information about volcanoes, as well as diverse educational material, such as brochures, books, maps, and infographics. Most of the volcano observatories also provide access to the latest version of their hazard maps. All this information is published in Spanish, the official language for all the Latin American countries with monitoring institutions. Nevertheless, many other native languages are spoken in the region. This is something that some observatories are already considering when designing their communication strategies. Examples of this are the workshops in Quechua—widely spoken in the central Andes—offered by the OVI<sup>+</sup> (Peru), and the last hazard map of Popocatepetl published in Nahuatl, a native language spoken in central Mexico.

In this Special Issue, volcano observatories report a wide range of strategies to strengthen bonds with the communities. In addition to the communication through the virtual channels mentioned above, many of the institutions also carry out on-site outreach activities. This is particularly important considering that in the region there are still communities with limited





**Figure 3:** Published volcanic hazard maps for the Latin American volcanoes. The vertical bars show the number of hazard maps published per year. The solid black curve represents the cumulative number of hazard maps published, while the dashed line shows the cumulative number of published hazard maps, but excluding updates (i.e. number of volcanoes with hazard maps). For details about references used to build this figure, see the [Supplementary Material \[EN\]](#).

internet access. The list of activities includes: socialization of volcanic hazard maps [e.g. [Roca Palma et al. 2021](#), this issue], outreach fairs [e.g. [Gómez Martínez et al. 2021](#), this issue], guided tours through the observatories [e.g. [Aguilar Contreras et al. 2021](#), this issue], and volcanic unrest and eruption drills [e.g. [Amigo 2021](#), this issue]. In most cases, these activities are coordinated with the respective civil protection agencies. Also, monitoring institutions have increasingly encouraged citizen participation in surveillance duties. For instance, countries like Ecuador and El Salvador have provided training and developed networks of local observers, as part of their Early Warning Systems strategies. In Costa Rica, volcano observatories use social media to collect information about eruptions and affected areas.

### 3.4 Cooperation with other institutions

After a necessary first stage characterized by external assistance from international research groups and cooperation agencies, such as the U.S. Geological Survey's Volcano Disaster Assistance Program (USGS-VDAP), French National Research Institute for Sustainable Development (IRD, for its acronym in French), and Japan International Cooperation Agency (JICA), most of the

observatories have started to develop their own monitoring strategies. A large majority have also expanded their cooperation networks to other international and national institutions involved in volcanology (e.g. universities, geological surveys). All volcano observatories in the region work hand in hand with the civil protection agencies of their respective countries, key to any success of volcanic risk reduction strategies. The epitome of this intra-country cooperation is the Risk Management Awareness Center created in 2011, in Arequipa, Peru [see [Aguilar Contreras et al. 2021](#), this issue]. Peru, Mexico, and Costa Rica, which all have more than one institution assuming volcano monitoring responsibilities in the country, have an additional coordination challenge. This Special Issue reflects the significant progress made in the last two countries, with more than one institution converging in a single *Report*.

Intra-regional cooperation between monitoring institutions has also improved in recent years. One example is the assistance of the Chilean government (through SERNAGEOMIN<sup>‡</sup>) to the Guatemalan government (through INSIVUMEH<sup>‡</sup>) after the 3 June 2018 Fuego eruption<sup>¶</sup>. Another example of this is the cooperation agreement signed between Argentina (through

<sup>‡</sup><https://www.sernageomin.cl/sernageomin-capacita-a-delegacion-guatemalteca-en-la-elaboracion-de-ranking-de-volcanes/>

OAVV) and Chile (through SERNAGEOMIN) to monitor and manage the activity of volcanoes located on the border [García and Badi 2021, this issue]. This agreement acquires its real relevance when considering that a total of 18 active volcanoes are shared between these two countries. As one of the first steps in this cooperation effort, SERNAGEOMIN and OAVV have deployed an instrumental network around Copahue volcano and exchange real-time monitoring information. Colombia (through SGC<sup>‡</sup>) and Ecuador (through IG-EPN) have signed a ten-year framework cooperation agreement in 2014 to investigate, monitor and assess volcanic hazards of Chiles-Cerro Negro volcanoes [Gómez Martínez et al. 2021, this issue]. The bi-national hazard maps mentioned in Subsection 3.2 are a result of these two cooperation agreements (excluding the one of Planchón-Peteroa volcano).

Intra-regional cooperation has been also stimulated through the Meetings of Latin American Volcano Observatories (*Encuentros de Observatorios Vulcanológicos de Latinoamérica*). These events seek to provide a space for exchange between volcano observatories and their cooperating partners, as well as an opportunity to analyse the progress made by these institutions and remaining weaknesses [Rodríguez et al. 2018; Aguilar Contreras et al. 2021, this issue]. Organized by ALVO, in cooperation with OVI and the USGS-VDAP—and with the institutional support of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and WOVO—the first two meetings were held in Arequipa (Peru), in October 2015 and April 2018.

#### 4 CHALLENGES AND PERSPECTIVES

Latin America has undoubtedly taken a step forward in assessing and monitoring volcanic activity. During the last couple of decades volcano observatories' capabilities have improved, both quantitatively and qualitatively. This is evident when comparing the data presented here with the one reported by Alvarado et al. [1999] for the end of last century. The number of instrumented volcanoes has increased from 57 to 135 and there are more institutions devoted to volcano surveillance. The creation of the observatories in Chile, Peru, and—more recently—in Argentina, was of great importance in order to extend monitoring networks to the southern end of the continent. Another gauge of development is the continuous increase in the elaboration and publication of hazard maps (Figure 3). From a qualitative perspective, the region has experienced advances in monitoring, computational and communication strategies, and technologies. All this has allowed most of volcano observatories to manage eruptive crises with little or no external aid.

Despite all the progress made, there is still a long way to go. More than 50 % of the active volcanoes of the region are not monitored yet and a larger number lack a

hazard map. It should be a priority to start monitoring volcanic activity in Bolivia and Panama. Countries in the region with no active volcanoes, like Honduras, Brazil, and Venezuela, should not be overlooked, as they can also be impacted by ash fallout. An additional challenge is posed by volcanoes located on borders between countries [Donovan and Oppenheimer 2019]. The auspicious first joint efforts that have been made by Argentina-Chile and Colombia-Ecuador need to be intensified as well as reproduced in other countries with similar scenarios, such as Mexico and Guatemala [Espinasa-Pereña et al. 2021, this issue].

In terms of hazard communication, the eruption of Fuego volcano (June 3, 2018) and its painful associated impacts have shown us that we still need to improve. We recognize two main limiting factors for the development of volcano surveillance in Latin America: the lack of available financial resources—to maintain existing monitoring networks, acquire new instruments and hire personnel—and training opportunities. The offer of postgraduate programs in volcanology by Latin American universities is still scarce, which translates to a shortage of trained scientists available to cover the needs of the volcano observatories. Possible short-term solutions to this problem might be found through international and regional cooperation projects with other volcano observatories, as suggested in many of the *Reports*.

Cooperation efforts must be continuously reinforced. It should be a priority of all the institutions to work on strengthening bonds with other national and international partners. In this regard, initiatives like ALVO, the Young Latin American Volcanologists network (JVLA, by its acronym in Spanish [Forte et al. 2018]) and more recently, the International Network for VOLcanology Collaboration (INVOLC) have the opportunity to foster new kind of bonds between countries and institutions, based on equality, respect, and solidarity. Finally, we hope this Special Issue contributes to bringing the volcanological community closer as well as inspiring new ways of sharing knowledge.

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## AUTHOR CONTRIBUTIONS

P. F. drafted the manuscript and all authors contributed to the content, style and structure. All authors contributed to the materialization of this Special Issue.

## DATA AVAILABILITY

All data are available in the [Supplementary Material \[EN\]](#) provided alongside the online version of this Preface. For availability of specific data related to the countries mentioned in this Preface, the reader should refer to the respective *Reports* of this Special Issue.

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