REPORT

VOLCANICA

Volcano observatories and monitoring activities in Guatemala

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Abstract

The tectonic and volcanic environment in Guatemala is large and complex. Three major tectonic plates constantly interacting with each other, and a volcanic arc that extends from east to west in the southern part of the country, demand special attention in terms of monitoring and scientific studies. The *Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología* (INSIVUMEH) is the institute in charge of executing these actions at the national and civil level.In recent years, INSIVUMEH has formed a volcanology team consisting of multi-disciplinary personnel that conducts the main volcanological monitoring and research activities. These activities include: seismic and acoustic signal analysis, evaluation and analysis of the volcanic hazards, installation and maintenance of monitoring equipment, and the socialization and dissemination of volcanic knowledge. Of all the volcanic structures in Guatemala, three volcanoes (Fuego, Pacaya, and Santiaguito) are in constant eruption and require all of the available resources (economic and human). These volcanoes present a wide range of volcanic hazards (regarding type and magnitude) that make daily monitoring a great challenge. One of the greatest goals achieved by the volcanology team has been the recent development of a Relative Threat Ranking of Guatemala Volcanoes, taking into account different parameters that allow improved planning in the future, both in monitoring and research.

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1 Introduction

The country has a diverse geology as a result of a complex interplay between three major tectonic plates (from north to south): North America, Caribbean, and Cocos. One of the most distinctive expressions associated with this complex tectonic setting is the occurrence of surficial volcanism.

Guatemalan volcanoes are located in the northernmost segment of the Central American Volcanic Arc (CAVA), which is the result of the subduction of the Cocos plate beneath the Caribbean plate [Carr et al. 2003]. The CAVA can be subdivided into two areas: the volcanic front and the behind-the-front (or BVF) areas. The volcanic front in Guatemala is divided into the Western, Central, and Eastern segments [Stoiber and Carr 1973]. Most of the volcanic centers in the volcanic front are large composite cones and stratovolcanoes built from calc-alkaline basalts, andesites, and dacites [Carr et al. 1979]. The greatest concentration of BVF volcanism in Central America is in southeastern Guatemala [Walker et al. 1995]. This is expressed through two major cone fields: Ipala Graben and Cuilapa-Barberena [Walker 1981]. Relatively small calderas, composite cones and shield volcanoes also exist in the BVF of southeastern Guatemala [Walker et al. 1995].

Different attempts have been made to list and classify the Guatemalan volcanoes, from 324 Quaternary eruptive vents according to Bohnenberger [1969], to 39 volcanoes in the official Geographic Dictionary [Gall and Nacional 1976], to 36 in the Smithsonian's Global Volcanism Program (GVP) volcanoes catalog, to a recent estimation of 43 volcanoes as listed in 2019 by the volcanology group of the *Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología* (INSIVUMEH). Out of these 43, a total of 25 volcanoes are considered active or potentially active and are currently the subject of a Relative Threat Ranking implemented by INSIVUMEH's Volcanology group (Figure 1 and Table 1). This ranking follows the methodology proposed by Ewert [2007] for the "System for Ranking Relative Threats of U.S. Volcanoes". Currently, INSIVUMEH efforts are focused entirely on the volcanoes that pose the greatest threat (very high–threat group), but in the short-term other volcanoes that also pose a threat (high- and moderate-threat group) will be included in daily monitoring.

During historical times and according to INSIVUMEH and the GVP, only seven of the Guatemalan volcanoes have had eruptive stages (Tacaná, Santa María/Santiaguito, Cerro Quemado, Atitlán, Acatenango, Fuego, and Pacaya), with the occurrence of fumaroles, phreatic explosions, lahars, lava flows, tephra emissions, pyroclastic flows, dome/sector collapses, and lateral blasts. Despite the occurrence of this variety of volcanic activity and associated

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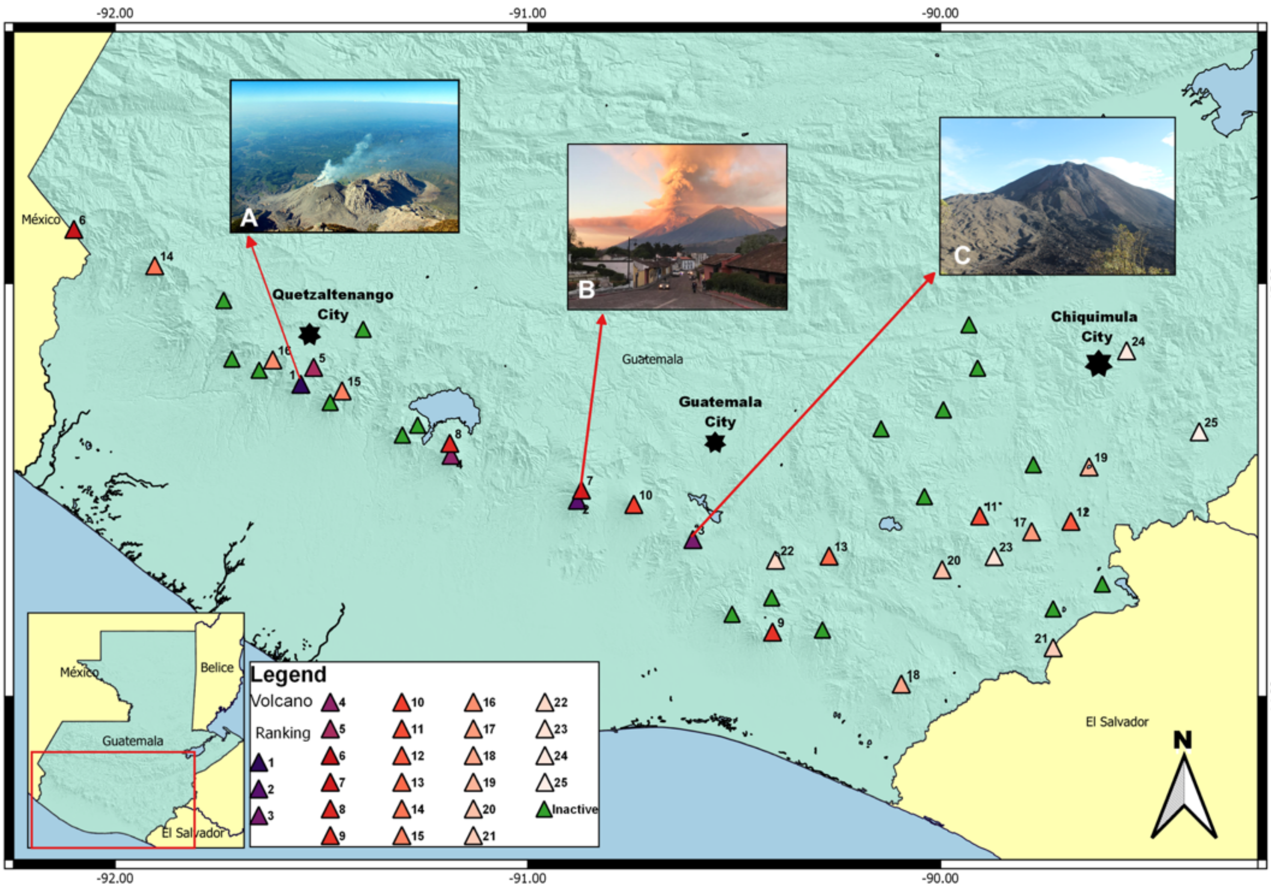

Figure 1: Map of the Guatemalan volcanoes. A total of 43 volcanoes are marked, with the currently (18) inactive volcanoes shown in green, the (25) active and potentially active included in the Relative Threat Ranking are shown in different colors in order to identify their positions in the ranking. The three continuously erupting volcanoes are: Santa Maria/Santiaguito, Fuego, and Pacaya volcanoes (shown as [A], [B] and [C] respectively).

hazards, a large number of human settlements have been established around the volcanoes since colonial times, primarily due to the fertile soils, and access to natural resources and transit corridors. According to the 2018 Population and Living Places Census, up to 3.5 million people live in areas 30 km away or less from a volcano, and more than 2 million in the vicinity of Santa María/Santiaguito, Fuego, and Pacaya alone, the three volcanoes where INSIVUMEH performs real time monitoring of their activity and periodic volcanic hazard assessments.

1.1 INSIVUMEH: the volcano monitoring institution of Guatemala

INSIVUMEH was created due to the need to have a scientific institute in the wake of the M7.5 earthquake that occurred on February 4, 1976. The INSIVUMEH groups several disciplines, however, the volcanology discipline started in 1987, after the volcanic crisis of Tacaná volcano in 1985–86, as well as due to the constant eruptions of Pacaya volcano, 30 km away from Guatemala City. In 1986, the first volcanology course was carried out in Central American. This course was funded by the *Centro de Coordinación para la Prevención de los Desastres en América Central y República Dominicana* (CEPREDENAC) who, together with Michigan Technological University (MTU) and especially Dr. William Rose, imparted their knowledge on personnel from the countries of Guatemala, Costa Rica, Nicaragua, El Salvador, Honduras, and Panama. The second volcanology course was held in Guatemala in 1987. Also 1987, the United States Geological Survey (USGS) visited Guatemala, where the creation of the volcanology section at INSIVUMEH was consolidated, with 12 people working on deformation, volcanic seismology, and geology. The deformation equipment and seismic stations were donated by the USGS, including the installation of one short-period seismic station at Fuego, Pacaya, and Santiaguito volcanoes. Two more volcanology courses were carried out by the same institutions group in Nicaragua (1989) and Guatemala (1990). As an important result of this collaboration, in 1990 CEPREDENAC made possible the construction of

Table 1: Each volcano has an entry at the Smithsonian Global Volcanism Program website, with information about its geology, eruptive history, activity reports, and more (when available) that can be found at `https://volcano.si.edu/volcano.cfm?vn=` followed by the unique GVP Number as shown in the table.

Ranking position	GVP number	Name	Threat group	Last active
1	342030	Santa Maria/Santiaguito		2019 CE
2	342090	Fuego	Very high	2019 CE
3	342110	Pacaya		2019 CE
4	342060	Atitlán		1853 CE
5	342040	Cerro Quemado		1818 CE
6	341130	Tacaná	High	1972 CE
7	342080	Acatenango/Yepocapa		1853 CE
8	342070	Tolimán		Unknown
9	342120	Agua		Unknown
10	342100	Tecuamburro		960 BCE
11	342141	Tahual	Medium	Unknown
12	342180	Ixtepeque		Unknown
13	342121	Jumaytepeque		Unknown
14	342020	Tajumulco	Low	Unknown
15	342800	Zunil		Unknown
16	342809	Siete Orejas		Unknown
17	342160	Suchitán		Unknown
18	342130	Moyuta		Unknown
19	342190	Ipala+Monte Rico	Low	Unknown
20	342140	Amayo-Las Flores		Unknown
21	342170	Chingo	Very low	Unknown
22	342111	Cuilapa Barberena		Unknown
23	342150	Cerro Santiago-Jutiapa Group		Unknown
24	342200	Chiquimula Volcanic Field		Unknown
25	342210	Quezaltepeque Volcanic Field		Unknown

the first volcanic observatory in Guatemala, with the purpose of monitoring the volcanic activity of Santiaguito volcano. These facilities were built at Finca El Faro, a farm located at 6 km from the volcanic complex. A second observatory was built by INSIVUMEH as a consequence of an important eruptive event at Fuego, in 1999. This was located at 9 km from Fuego's crater, in a rural community called Panimaché. Since the first day of operations, both observatories have been supported by INSIVUMEH. The following years, continuous cooperation plans with international institutions, such as USGS, made it possible to strengthen and improve the monitoring network and volcanic monitoring capacities, respectively. The Volcanology group is currently monitoring volcanic activity at these three continuously erupting volcanoes (see for example Figure 2).

1.2 Fuego, Pacaya, and Santiaguito volcanoes: main characteristics of the three erupting volcanoes of Guatemala

Pacaya volcano is a large volcanic complex situated on the southern boundary fault zone of the Amatitlan Caldera, 30 km south of Guatemala City [Kitamura and Matías 1995]. This complex includes the Pacaya composite cone, Cerro Grande and Cerro Chiquito, and the Cerro Chino scoria cone [Gomez 2012] as well as an ancestral Pacaya stratovolcano, rhyodacitic through andesitic domes, flows, and tephra [Conway et al. 1992]. The current Pacaya summit is formed by two overlapping cones, the first cone built after the collapse of "Old Pacaya" and the second one, known as the Mackenney cone, that formed in 1965 on the west flank of this cone [Gomez 2012]. Pacaya erupted in 1961 for the first time since 1880 and has been continuously active since 1965, with explosive phases—i.e. Strombolian activity with

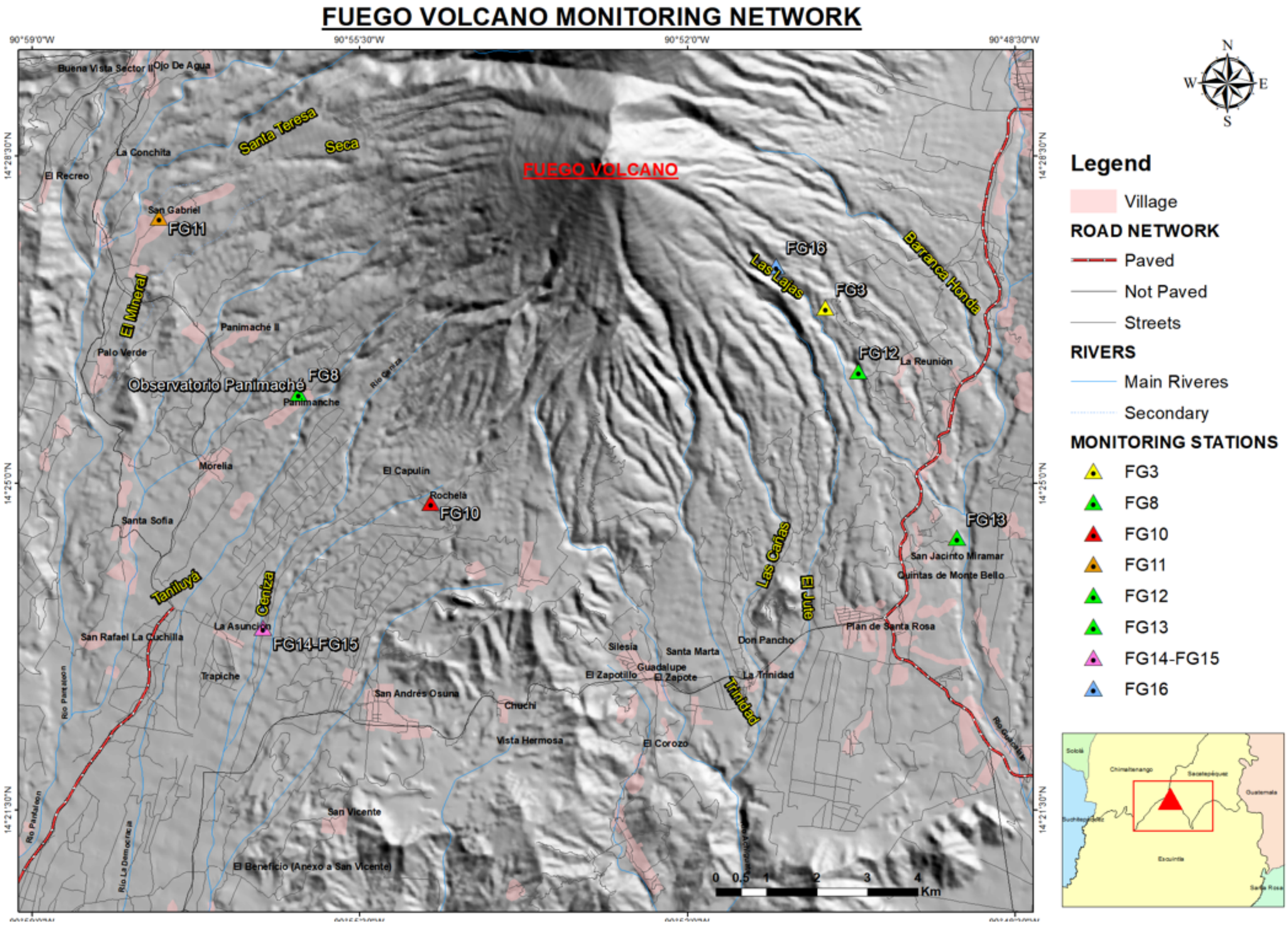

Figure 2: Monitoring network at Fuego Volcano. Color-coded triangles represent the location of the multi-parametric stations, respectively as yellow for stations with one seismometer and radio transmitting telemetry; green for stations with one seismometer, camera, rain gauge, infrasound sensors, and 3G telemetry; red for stations with one seismometer, 3G telemetry, camera, and infrasound sensors; orange for stations with one seismometer sensor and 3G telemetry; and purple for stations with one seismometer, 3G telemetry, and rain gauge. All stations are located on the south flank and close to the canyons. This complete network was deployed after the eruption on June 3, 2018. The inset map at the right bottom represents the geographical location of Fuego Volcano, which is exactly the intersection of 3 departments: Chimaltenango in cyan, Sacatepéquez in aquamarine, and Escuintla in green.

ejection of bombs or Vulcanian activity with ashfalls—alternating with effusive phases [Bardintzeff and Deniel 1992]. The GVP lists at least 36 Holocene eruptive periods, with VEIs up to 3. The 2010 May eruption caused a major disturbance due to the heavy tephra fall in the towns surrounding the volcano, which led to the closing of La Aurora International Airport for six days [Chigna et al. 2010]. Pacaya volcano currently has lava flows in the northwest flank, as well as exhibiting explosive activity.

Fuego volcano is located directly south of Acatenango volcano and is 45 km from Guatemala City*. The Fuego complex is composed of the younger Fuego and older Meseta vents [Chesner and Rose 1984]. The end of Meseta's activity was marked by a debris avalanche around 8500 years ago, then the activity migrated south and began building Fuego, which became the focus of activity in the complex up to present day [Basset 1996]. Fuego has had at least 60 historical sub-Plinian eruptions and several longer periods (i.e. months to years) of low-level Strombolian activity [Lyons et al. 2009], with highly explosive VEI 4 events punctuating extended periods of lower level activity [Berlo et al. 2011]. The most recent continuous low-level Strombolian activity began with a VEI 2 eruption on May 21, 1999, characterized by frequent, short (hundreds of meters) lava flows, pyroclastic explosions, lahars, and paroxysmal, extended-duration (i.e. 24–48 h) eruptions that produce longer lava flows (hundreds to thousands of meters), pyroclastic flows, and sustained eruptive columns; this activity leads to small eruptions nearly every day and an "open vent" condition [Lyons et al. 2009]. The eruption of June 3, 2018, according to

*http://www.insivumeh.gob.gt/folletos/folleto_fuego.pdf

INSIVUMEH scientists and field observations, appear to have included a sector-collapse in the southeast part of the upper volcanic structure, generating a considerable number of PDCs that ran down and overflowed the Las Lajas ravine. Fuego volcano currently maintains an average of 15 gas and ash emissions per hour, and produces avalanches that travel long distances, and lahars.

The Santa María-Santiaguito volcanic complex includes the symmetrical composite cone of Volcán de Santa María and the east-west-elongated Santiaguito dome complex [Escobar-Wolf et al. 2010], located 110 km west and 11 km south of the cities of Guatemala City and Quetzaltenango, respectively [Lamb et al. 2019]. In 1902 Santa Maria produced a devastating Plinian eruption, generating at least 8.5 km^3 dense rock equivalent (DRE) of dacite as ash- and pumice lapilli–fall deposits, and leaving an explosion crater and collapse scar on the southern base of the edifice [Rhodes et al. 2018]. In 1922, the Santiaguito volcanic complex began to grow inside the crater formed during the 1902 eruption and remains active, having erupted more than 1.2 km^3 of dacitic magma [Escobar-Wolf et al. 2010]. The Santiaguito complex comprises four domes–El Caliente (1922–1939; 1972–present day), La Mitad (1939–1949), El Monje (1949–1958), and El Brujo (1958–1986) [Rhodes et al. 2018]. Activity has been focused at the El Caliente vent in recent years and consists of semi-continuous extrusion of blocky lava flows interspersed with frequent gas-and-ash explosions. Occasional escalations in explosive activity have included dome collapse and PDCs [Lamb et al. 2019].

2 How do we monitor these volcanoes?

2.1 Capabilities

Table 2 lists the instruments used at each of the three continuously erupting volcanoes. Fuego volcano is currently the most instrumented and this has allowed INSIVUMEH to better monitor surface volcanic activity and the internal dynamics of the volcano. The combination of infrasound sensors, seismic sensors, and webcams has allowed us to better study lahars and lava flows. Lahars generate both types of signals (i.e. seismic and acoustic), so that amplitude and frequency content of both are likely to change when a lahar is moving downstream. These changes can be used to describe and characterize the lahar activity along the canyons. Effusive volcanic phases generate one or more lava flows that last days or even months, so that seismic and acoustic sensors record continuous signals (i.e. tremor) related to permanent outgassing and magma movements produced by these flows. Such continuous signals allow us to define, among other parameters, the duration and intensity of an effusive phase. The activity in the crater of Fuego volcano is studied through five infrasound arrays that allow us to locate, characterize, and detect parameters such as the pressure of each of the material emissions (gas and/or magma) that produce acoustic signals. Goals for 2022 to2023 include the automation of basic tasks such as counting and classifying the frequent volcanic earthquakes from Fuego using Machine Learning techniques. For Pacaya volcano, seismic data are mainly studied using basic but well-proven methods like RSAM (Real-time Seismic-Amplitude Measurement) that track "tremor" type seismic activity. From 2020 to 2022, three Global Positioning System (GPS) sensors, one webcam, and two more seismic sensors (one short period and one broadband) are slated to be added to the Pacaya network. Santiaguito volcan seismicity is monitored and studied using three broadband sensors donated by Liverpool University, UK, and one short period sensor. In the near future, INSIVUMEH plans to rehabilitate three short-term stations that are currently not working and that operate by analog telemetry at the Santiaguito volcano area.

The data collected by the monitoring instruments are received in real time and stored at INSIVUMEH's data center. The storage format is miniSEED (Standard for the Exchange of Earthquake Data), although there are backups in different formats (SAC, SEISAN, Earthworm). The data are shared with other institutions in real time (for example: the VDAP-USGS, University of Liverpool, UK, *Ministerio de Medio Ambiente y Recursos Naturales* El Salvador, *Instituto Nicaragüense de Estudios Territoriales* Nicaragua, and *Servicio Sismológico Nacional* México) through the SeedLink communication protocol, which is possible after establishing an agreement between the interested parties and INSIVUMEH. However, data is also shared with individuals through official requests. Individuals and technical or academic organizations can request the data through the channels established by the institution (i.e. the office of free access to INSIVUMEH information*).

In addition to ground-based sensor data, the analysis of satellite images has been a very useful tool for monitoring thermal radiance and ash dispersion, as well as for monitoring lava flows over long periods of time. Additionally, the evaluation of volcanic hazards is carried out and updated by computational simulations of volcanic phenomena during volcanic crisis, such as ash fall and lava flows. These simulations use digital elevation data previously obtained with overflights carried out by volcanology personnel.

2.2 Technical-scientific staff

Currently, in the central facilities of INSIVUMEH, the area of volcanology is composed of a group of five people with different capacities and skills that perform different activities. Geologists (four people) and volcanologist (one person) perform the evaluation of volcanic

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Table 2: Description of the volcano monitoring networks

Volcano	Instruments				
	Seismometer		Acoustic sensor	Camera	Meteorological station
	SP	BB			
Fuego	1	7	18	5	3
Pacaya	1	1	-	1	1
Santiaguito	1	3	-	1	-

threats through different techniques, including the simulation of volcanic phenomena and drone flights. They also carry out field activities for data collection and/or sampling, and communicate and describe the volcanic threat to institutions, organizations, and to the general public. Physicists (two people) monitor and analyze geophysical signals, primarily with seismic and infrasound data. The maintenance and installation of monitoring equipment is performed by electronics technicians (two people) and electronics engineering students (two people).

In addition to the volcanology staff at the central INSIVUMEH facility, there are local observatories near to every erupting volcano (Fuego, Pacaya, and Santiaguito) that provide additional volcano surveillance and monitoring. There are technical personnel in each observatory who perform monitoring activities, such as visual and field surveys, prepare activity reports (three times a day) aimed towards the volcanology group at central facilities in the city, and provide assistance to personnel that come from the central facilities in the city for field visits.

3 Volcano hazard management

INSIVUMEH participates in the management of volcanic risk in Guatemala as the scientific entity of the *Secretaria Ejecutiva de la Coordinadora Nacional para la Reducción de Desastres* (SE-CONRED), the fundamental duty of INSIVUMEH is to provide technical and timely information during preparation, mitigation, and response to volcanic hazards, fulfilling three fundamental functions: 1) real-time monitoring, 2) the development of hazard maps, and 3) the dissemination of knowledge of the hazard to the population. To do this, INSIVUMEH implements two fundamental tools that are at the service of the population: volcanological activity bulletins and the generation of hazard maps. The official volcanic hazard maps have been developed in collaboration with international agencies, such as the USGS, with whom a map of Pacaya volcano was created in 1987 following a short geological campaign during which the main volcanic deposits around the volcano were mapped [Banks 1987]. INSIVUMEH has also collaborated with institutions such as the Japan International Cooperation Agency (JICA), and foreign universities like MTU and the University of Edinburgh (UK), to generate hazards maps of other volcanoes in the country. Currently, eight Guatemalan volcanoes have hazard maps: Tacaná, Santa María/Santiaguito, Cerro Quemado, Atitlán, Acatenango, Fuego, Agua, and Pacaya.

Due to the frequent and dynamic eruptive activity in the last 30 years of Fuego, Pacaya, and Santiaguito volcanoes, INSIVUMEH has developed two types of map products: volcanic crisis maps and official volcanic hazard maps. The first are made during a paroxysm, pointing out threats such as ash dispersion or the direction of a new pyroclastic flow. These maps are useful to inform the population of the immediate they are exposed to in a given event. The latter are probabilistic maps that represent the areas prone to the background presence of individual volcanic hazards. One of the main examples of the generation of crisis maps are those that were produced after the eruption of Fuego volcano on June 3, 2018 due to the large amount of material that ended up in the rivers around the volcano, and the possibility of a new paroxysm. These maps were the result of simulations produced by the software `LaharZ` [Schilling 1998], using specific parameters of the volcano such as topography, the starting points of lahars, and historical activity. The maps formulated three new scenarios: two for lahars (moderate rain and heavy rains) and a third for pyroclastic flows. The official maps are available on the INSIVUMEH website*. INSIVUMEH also worked with the nongovernmental organization Map Action, to produce an interactive 3D map. The interactive map is a very useful tool for the population to have a better idea of how they would be affected by the different hazards. This tool can be viewed online†.

The hazard maps for Pacaya, Fuego, and Santiaguito volcanoes are constantly updated after field surveys and when new photogrammetry data are acquired by drone flights performed around the volcanic edifice. These maps also include recent eruptive events, historical data, and modeling of different volcanic products such as lahars and lava flows. Capabilities have also been developed for the use of volcanic hazard mod-

* https://insivumeh.gob.gt/geofisica/vulcanologia/mapas-de-amenaza-volcanica/

† https://arcg.is/18irm9

els, such as: LaharZ [Schilling 1998], Downflow [Tarquini and Favalli 2011], Q-lavHA [Mossoux et al. 2016], MrLavaLoba [Tarquini et al. 2018], ECMapPro [Aravena and Cioni 2019], Ash3D [Schwaiger et al. 2012], Tephra [Bonadonna 2005], TephraProb [Biass et al. 2016], and Eject! [Mastin 2001].

4 Information dissemination and outreach

4.1 Volcanological information

INSIVUMEH has a monitoring network that serves to generate real-time information that is subsequently processed and analyzed by volcanology personnel. Four types of reports are generated:

1. Daily bulletins: summarize the volcanic information of the active volcanoes erupting in the country including essential information such as atmospheric conditions (data generated by the climate department of INSIVUMEH) and the eruptive behavior of the last 24 hours. General recommendations are framed in this type of bulletin.

2. Special bulletins: issued at the time of an increase in activity, an activity that is not considered usual, such as the dispersion of ash, a new paroxysm, or the descent of lahars. In addition, special recommendations (such as to follow the activity more closely and be aware of any sudden changes) are included to the institutions that must perform a specific task, such as the SE-CONRED, DGAC (General Directorate of Civil Aviation), CAMINOS (General Directorate of Roads), COVIAL (Road Maintenance Enforcement Unit), and the general public, prioritizing in the communities located in the vicinity of the area.

3. Weekly newsletters: summarize the volcanic activity observed during a week to highlight significant changes on a larger scale. These newsletters include a brief recommendation (such as, stay away from areas identified as high-threat, extend the current alert level) to institutions with immediate responsibility.

4. Monthly reports: gather the information of the volcanic activity that was recorded during the month and include statistics of the recorded events and general data in a time window larger than that of a weekly newsletter.

The information of the reports and newsletters are freely accessible and available on the INSIVUMEH website under the “Volcanological Bulletins” tab*. Access can also be requested by email†.

* https://insivumeh.gob.gt/vulcanologia/
† acceso.informa@insivumeh.gob.gt

The pertinent information of the daily, weekly, and monthly bulletins, and special newsletters is shared by email to government institutions such as CONRED, the General Directorate of Civil Aeronautics, the Guatemalan Tourism Institute, the General Directorate of Roads, and the national parks in volcanic areas and municipalities, in order for them to distribute the information to the people and communities that may be affected by the hazards.

4.2 Outreach

Information described above is disseminated through social networks (Facebook: @insivumeh, Twitter: @insivumehgt) to the public, so that the necessary considerations are taken, depending on the volcanic product that is being generated and how that product can affect the general population (e.g. in case of volcanic ash fallout). Population is kept informed daily with an update of the volcanic activity of the three erupting volcanoes, specifying the changes registered in real time.

The primary information of volcanic hazard maps is shared to institutions, such as the SE-CONRED, who subsequently carries out the vulnerability analysis and thus adds an extra value or parameter to obtain risk maps, where homes, evacuation routes, safe areas, shelters, etc. are identified.

In order to more effectively disseminate and convey hazard information, INSIVUMEH appoints technical specialists in the field to explain maps and volcanic hazards to the communities. In addition, socialization of volcanic hazard maps (ash dispersion, lava flows, lahars, PDCs, ballistic falls) with civil protection support (SE-CONRED) is achieve through different activities, like social media and socialization campaigns held at the local observatory facilities.

5 Needs, challenges, and future perspectives

It has not been a long time since the eruption of Fuego volcano on June 3, 2018, but enough to carry out the corresponding analysis that highlights the lack of a robust and reliable volcanic monitoring system for the very high– and high-threat group of volcanoes in Guatemala and the need for continuous capacity building programs. On this matter, the support and strengthening delivered by the Volcanic Disaster Assistance Program (VDAP), as part of the cooperation with the USGS, during this large paroxysm and also the last couple of years, have been invaluable. Improvements to the monitoring network during July, August, and September made it possible to handle and process a substantial amount of data for the following three eruptions that occurred during October and November 2018. This allowed to provide more reliable information in real time to the population and institutions in charge of risk management and disaster prevention (i.e. CONRED). On the other hand, training on how to use methodologies for an adequate, timely, and practical management of a volcanic crisis provided by VDAP have also been developed. Mention should be made of the "Tree of Events" methodology, which allows to adequately infer which is the most probable eruptive scenario in an active volcano, taking into account recent and historical geological factors, type of threats that the volcano is capable of producing, among others. After dedicated and constant work alongside volcanologists from VDAP, this methodology was adapted for every volcano of the very high–threat group in the national volcano ranking. Although the success of this methodology is based on the amount of available information and the knowledge of the historical and current activity of each volcano, this could provide a very valuable perspective regarding the possible impact of the threats generated in a volcanic paroxysm.

Monitoring volcanoes that maintain a state of nearly continuous eruption represents a major challenge, since it involves an investment of human resources of different skills and specialties, as well as high-quality instrumental technology. Following the eruption of Fuego volcano on June 3, 2018, INSIVUMEH was able to acquire monitoring equipment that produces higher resolution data and allows a broader analysis regarding the threats presented on the southern flank of this volcano. However, the number of personnel hired for instrumental monitoring and threat assessment is not capable of analyzing all of the new data, thus new hires are needed to fill gaps. It is also necessary to include more technical personnel for the installation, repair, and mobilization of monitoring equipment in the field (e.g. seismometers, multi-parameter stations, etc.). Regarding Pacaya and Santiaguito volcanoes, seismic monitoring is maintained using one and four seismic stations, respectively. Previous results from campaign data on these two volcanoes indicates that more stations are needed to further capture the breadth of signals produced by these volcanoes for a comprehensive monitoring effort.

One of the most significant monitoring goals for the short- and medium term-is to establish a multi-parameter baseline of volcanic activity for each of the three erupting volcanoes. This requires a large amount of continuous data and the use of computational tools with which can determine (in near-real-time) the state of volcanic activity. For Fuego volcano, a baseline has been developed and has been continuously updated for about one year, primarily based on seismic and infrasound data. However, these recent advances need to be continuously refined due to the dynamic nature of Fuego's activity, thus maintaining continuous data flow from the network is essential. Pacaya and Santiaguito volcanoes do not yet have these monitoring technologies.

The Relative Threat Ranking of Guatemala Volcanoes is currently being finalized, which will serve as a guideline for future monitoring planning for all volcanoes that also represent some degree of threat to the population. The results from this project will dictate the steps to follow in the effort of the hazard assessments, as well as the instrumental monitoring of all of the active and potentially active volcanoes. The initiative will prioritize the volcanoes that are currently in the very high– and high-threat groups and will place the volcanoes that are in the medium, low- and very low–threat groups into a medium- to long-term plan of action.

Another important aspect that is currently being addressed is the establishment of procedural protocols during volcanic crisis through the use of tools such as a color scale for volcanic alert levels and probabilistic analysis of volcanic behavior (known as "event trees"). These are currently being developed at INSIVUMEH, along with threat maps for different scenarios. All these efforts present a roadmap for a more robust and transparent decision making process, thus the challenge in the short term is to make systematic use of all of these protocols when they are required.

Acknowledgements

More than a simple "thank you", this is a posthumous recognition of all the people that were affected by the eruption of Fuego Volcano on June 3, 2018, as well as to CONRED co-worker, Juan Galindo, who passed away trying to save others. We hope that this eruption presents a cautionary lesson and call to action for national and international institutions and organizations of the world. We are calling on the local government to invest in volcanic prevention and surveillance. Do not forget the past, because the same will happen in the future.

Author contributions

Introduction was prepared by Mérida R., Chun C., and Chigna G. Sections on How do we monitor these volcanoes? and Needs, challenges, and future perspectives were prepared by Roca A. and Argueta P. Volcano hazard management and Information dissemination and outreach sections were prepared by González D. and Juárez F., respectively.

Data availability

Volcano bulletins are available at https://www.insivumeh.gob.gt/vulcanologia/. Seismic and acoustic data is available upon request at accesso.informa@insivumeh.gob.gt. OSAI MAP Santiaguito Volcano can be downloaded at https://jicabosai.cepredenac.org/application/files/9715/4048/4757/BOSAI_MAP_for_Santiaguito.pdf while BOSAI MAP of Pacaya Volcano can be found at https://jicabosai.cepredenac.org/application/fil es/5315/4048/4754/BOSAI_MAP_for_Pacaya.pdf.

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