

# Nicaraguan volcanic monitoring program of the *Instituto Nicaragüense de Estudios Territoriales*

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## ABSTRACT

The *Instituto Nicaragüense de Estudios Territoriales* (INETER) is the institution responsible for volcano monitoring in Nicaragua. The Volcanology Division of the General Directorate of Geology and Geophysics currently monitors six active volcanoes by means of seismology, gas measurements, optical webcams, and visual and satellite observations. The volcano monitoring network that INETER maintains is in continuous expansion and modernization. Similarly, the number of technical and scientific personnel has been growing in the last few years. 2015 was the busiest year of the last two decades: Momotombo volcano erupted for the first time in 110 years, a lava lake was emplaced at the bottom of Masaya volcano's Santiago crater, and Telica volcano experienced a phreatic phase from May to November. Although we have increased our monitoring capabilities, we still have many challenges for the near future that we expect to resolve with support from the national and international geoscientific community.

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## 1 INTRODUCTION

Approximately 3600000 inhabitants live and/or work at the base of an active volcano in Nicaragua. According to the last official census of Nicaragua [Goffin 2006], this corresponds to about 70 % of the Nicaraguan population. As a consequence, the risk derived from volcanic activity is very high in Nicaragua. In this challenging context, the study and surveillance of volcanic activity has become a priority for the development of effective risk reduction strategies.

### 1.1 Geological setting

The dynamics and evolution of the Cocos plate, off the west coast of Central America, is complex and related to slab dip and possibly to the distribution of mechanical coupling within the overriding plate and upper plate deformation [La Femina et al. 2009; French et al. 2010]. This has important implications for the generation of thrust earthquakes at the subduction interface and destructive intraplate earthquakes [Norabuena et al. 2004; La Femina et al. 2009; French et al. 2010].

At present, the Cocos plate subducts beneath the Caribbean plate northeastward at a rate of 76–91 mm yr<sup>-1</sup> (relative to the Caribbean plate) along the Middle American Trench [DeMets 2001]. This subduction process is responsible for the volcanic activity observed in the modern Central American Volcanic Arc, which extends 1100 km from the Mexican-Guatemalan border to Panama [Carr 1984; Jordan et al. 2007; Seginor et al. 2011]. This volcanic arc has seven stepping

sections that vary in length from 100 km to 300 km [Carr 1984]. The spacing of volcanoes within these segments appears to be random with a few along-arc gaps. The longest gap, about 80 km long, is between Cosigüina and San Cristóbal volcanoes in northwestern Nicaragua [Carr 1984; Seginor et al. 2011, Figure 1].

The significant variations in geochemistry found along the Central American Volcanic Arc make it an ideal place to test the hypotheses put forward on the origin of the different features of arc geochemistry [Carr et al. 2007b]. The volcanic arc segment between Cosigüina and Masaya volcanoes has some of the globally highest levels of slab fluid tracers, such as <sup>10</sup>Be/<sup>9</sup>Be and Ba/La. The abundance of tracers dramatically drops southeast of Masaya volcano and gradually decreases across El Salvador and Guatemala. The abundance of slab fluid tracers in Costa Rica is very low and they are isotopically distinct, specifically between Arenal and Irazú volcanoes [Carr et al. 2007b].

The active Nicaraguan volcanic front lies within the Nicaraguan Depression, which also hosts the two major Nicaraguan lakes (Managua, also known as Xolotlán; and Nicaragua, also known as Cocibolca). The active Nicaraguan volcanic front is about 700 km long and runs from Maderas volcano near the Costa Rican border to the Gulf of Fonseca in El Salvador [McBirney and Williams 1965]. There has been a lot of controversy as to the early history of the volcanic front. The most recent hypothesis was proposed by Funk et al. [2009], who stated that the Nicaraguan Depression initially formed in Lake Nicaragua during the late Oligocene to early Miocene and that it propagated northward toward the Gulf of Fonseca during the Miocene to Pliocene.

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**Figure 1:** Active volcanic structures monitored by the Volcanology Directorate, INETER. Coordinate system WGS84. Red triangles indicate unmonitored active volcanoes.

The alluvial and lacustrine sediments that fill the flat topography of the Nicaraguan Depression have buried the earliest erupted lavas of the active volcanic front, making it difficult to determine a time of onset. However, the oldest lavas sampled by Carr et al. [2007a], from the most eroded sectors of the active Nicaraguan volcanoes, revealed an  $^{40}\text{Ar}/^{39}\text{Ar}$  age of 65 to 330 ka.

## 1.2 Volcanic activity in Nicaragua

Based on the geological record of their eruptive history in the last 10,000 years, there are 13 active volcanic structures in Nicaragua (Figure 1). During the last century, eight volcanoes have erupted in Nicaragua: Cosiguina, San Cristóbal, Telica, Cerro Negro, Momotombo, Apoyeque, Masaya and Concepción.

In Nicaragua, additionally around 173 inactive volcanoes have been mapped\*. These are divided into two large groups depending on whether they were active in the Tertiary or Quaternary. At least 53 Tertiary volcanic structures (whose last eruption took place more than 2.6 Ma ago) were identified in the Highlands of Nicaragua, which corresponds mostly to the northern

and central region of Nicaragua. It is, however, possible that more volcanoes were present in that region but are no longer identifiable, as they have been buried by eruptive deposits from nearby volcanoes, and others that were eroded over time. About 120 inactive volcanoes of the Quaternary period are found along the current active volcanic arc.

In the last three decades, the most notable volcanic activity in Nicaragua has been observed at Cerro Negro, Momotombo, Telica and Masaya volcanoes. Cerro Negro volcano is a basaltic cinder cone (728 m a.s.l.). It erupted three times during the 1990s, for which the Volcanic Eruption Index (VEI) decreased from 3 in 1992, to 2 in 1995, and finally to 1 in 1999 [Hill et al. 1998; INETER 1999; La Femina et al. 2004]. The eruptions from Cerro Negro volcano are usually Strombolian, and sometimes form satellite vents. The volcano only showed low-level seismic unrest following the 1999 eruption [INETER 1999; 2004].

Momotombo volcano is a basaltic stratovolcano (1297 m a.s.l.) and erupted on 1 December 2015 after 110 years of repose. This last event was a slug-driven Strombolian eruption that lasted three days and formed a 3.5 km-long lava flow. Subsequently, energetic explo-

\*<https://web-geofisica.ineter.gob.ni/vol/volnic.html>

sions, ranging from violent Strombolian to weak Vulcanian, occurred almost on a daily basis until early April 2016. Following this unrest, activity at Momotombo volcano has been characterized by seismicity and low SO<sub>2</sub> emissions, below 600 tonnes/day (t d<sup>-1</sup>) [INETER 2015a; b].

In December 2015, a basaltic lava lake was emplaced at the bottom of the Santiago crater of Masaya volcano [INETER 2015a; b]. Prior to this emplacement, the last time a lava lake was seen at Santiago crater was in December 1999, although it was not officially reported. Aiuppa et al. [2018] found that, before appearance of the lava lake, the volcanic gas plume composition became unusually CO<sub>2</sub>-rich, and the CO<sub>2</sub> flux peaked in November 2015 (average: 81.3 ± 40.6 kg s<sup>-1</sup>; maximum: 247 kg s<sup>-1</sup>). These authors proposed that the elevated gas bubble supply destabilized the shallow (<1 km) Masaya magma reservoir, leading to an upward migration of vesicular (buoyant) resident magma, and ultimately to the (re)formation of the lava lake on 11 December 2015 (constrained by satellite-based MODIS thermal observations). Currently, the Masaya lava lake is still active, and the lake level has descended by a small amount (the drop has not yet been quantified, however) since 2015–2017. In the last couple of years, the SO<sub>2</sub> flux oscillated between 500 and 2000 t d<sup>-1</sup> [INETER 2016].

Telica volcano is a basaltic stratovolcano (1036 m a.s.l.) and underwent a phreatic eruptive phase that lasted six months, from May to November 2015, and consisted of 891 explosions, 104 of which were ash-laden [INETER 2015a]. This eruptive phase was of low energy, and the ash clouds reached less than 1 km above the volcano's crater. One of the most violent explosions was registered on 22 November 2015; incandescence was observed on the crater floor and generated ash columns that rose ~8 km, ejected large blocks at least 1 km away [Roman et al. 2019]. After this activity, Telica typically produces ash emissions about twice a year, and has a variable SO<sub>2</sub> flux below 800 t d<sup>-1</sup>, as measured by mini-DOAS instruments.

The other active volcanoes of the country produce explosions of gas and ash almost on a yearly basis, except for Concepción volcano which has not erupted since 2010. Nevertheless, it is not uncommon for Concepción to show volcano-tectonic earthquake swarms without other manifestations of unrest, even if SO<sub>2</sub> emission levels are very low [i.e. below 250 t d<sup>-1</sup>; Saballos et al. 2013; 2014].

## 2 INETER AND ITS GENERAL DIRECTORATE OF GEOLOGY AND GEOPHYSICS

The *Instituto Nicaragüense de Estudios Territoriales* (INETER) was created on 5 October 1981 and today comprises more than 500 employees, including specialists, technicians and scientists.

INETER is in charge of research and of the inventory and evaluation of the physical resources of the country; executing the studies of territorial planning; carrying out studies for the prevention and mitigation of the effects caused by dangerous natural phenomena; carrying out meteorological and geophysical studies; regulating and carrying out cartographic and geodetic works; and regulating, operating, updating and executing the national physical cadastre. INETER operates the system of basic geodetic, meteorological, hydrological, hydrogeological, tidal, accelerographic and seismological networks, as well as monitoring networks for natural phenomena and, consequently, it organizes specialized databases for the information generated by these networks.

INETER comprises six general directions amongst which the Dirección General de Geología y Geofísica (DGGG), is subdivided into the areas of volcanology, seismology and geology. The DGGG maintains a 24/7 surveillance on the active volcanoes and seismicity across the Central American region, including the tsunami alerts advisory. The DGGG of INETER works in tandem with institutions in Nicaragua that focus on natural disaster risk reduction and management at all levels, including the direct interaction with local communities in high hazard zones to teach them the actions they should take during the occurrence of a particular natural phenomena that may threaten their lives. Ongoing studies by INETER (and in collaboration with other national and foreign institutions) are also focusing on the inactive volcanic structures.

The DGGG is composed of 35 people. There is a general director, an administrative staff member, three scientist advisors, and several technicians divided into the areas of seismology (nine), geology (six), volcanology (eight), electronics (six), and information technology (two). INETER maintains a permanent 24/7 shift, composed of personnel from the seismology department and the electronics group. The electronics team is responsible for the installation, repair and maintenance of volcanic and tectonic seismic networks, as well as seismic data processing. The eight experts of the INETER's Volcano Division, who have technician, BSc, MSc and Ph.D degrees, carry out the tasks of volcano monitoring, research and the assessment of volcanic hazards.

## 3 HOW DO WE MONITOR OUR VOLCANOES?

The surveillance of Nicaragua's active volcanoes began at INETER following the eruption of Cerro Negro volcano in April 1992. Since then, eight active volcanoes, including those with intermittent activity (volcanoes presenting thermal anomalies and gas emissions, such as SO<sub>2</sub>, coming from a shallow magmatic body, and micro-seismicity associated with fluid circulation beneath the volcano) in the last forty years, are

being monitored 24/7: Cosigüina, San Cristóbal, Telica, Cerro Negro, Momotombo, Apoyeque, Masaya and Concepción volcanoes.

Different monitoring techniques are used at these eight volcanoes (a summary of the instrumentation deployed at each volcano is shown in Table 1). Seismic monitoring is performed with short period and broadband seismometers, and there are between two and seven instruments at each volcano (Figure 2; Table 1). The seismic data are processed daily, and the classification of earthquakes, their location, and the calculation of their magnitude are performed using SEISCOMP-PRO (automatic and manual earthquake location) and EARTHWORM (volcano monitoring). The digital helicorders of each seismic station are available online\*.

In the web server, all the earthquakes that are located both nationally and regionally, as well as those outside the Central American region, are automatically published and processed. As of October 2019, the Seismology Directorate has the responsibility of the Regional Tsunami surveillance (through the *Centro de Asesoramiento de Tsunami para América Central*—CATAC) that was developed in collaboration with the Japan International Cooperation Agency†. There are also webcams that take images at different time intervals (between three and five minutes) that can be accessed via the internet‡. During volcanic crises, images are taken every minute. Additionally, there is at least one Global Navigation Satellite System (GNSS) station per volcano, and Momotombo volcano has the largest number of GNSS stations, with five in total. The GNSS data are currently post-processed using GYPSY-OASIS II software, and plans are in place to perform real-time processing in the near future.

To measure gas emissions, Masaya volcano has a fixed DOAS and a MultiGAS (e.g. H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S, etc.) instrument that record and transmit data on a daily basis. Figure 2 shows the location of the monitoring instruments on the volcanoes, as well as the seismic instruments that are part of the Nicaraguan monitoring network.

The data transmitted in real-time to INETER headquarters in Managua arrive at different servers for instant display through the internet, the automatic (and post processing) location of seismic events, and storage. Data are displayed on INETER's website§. More products such as hazard maps, maps showing the location of the most recent earthquake events, monthly and annual bulletins, and project summaries are also available through the webpage. Local and international researchers can have access to the raw data owned by INETER through collaborative agreements.

\*<http://geofisica-ew1.ineter.gob.ni/sismogramas/welcome.html>

†<http://catac.ineter.gob.ni/>

‡<https://webserver2.ineter.gob.ni/webcam/index.html>

§<https://webserver2.ineter.gob.ni>

## 4 VOLCANO HAZARD MANAGEMENT

Data gathered during field work on the active volcanoes of Nicaragua are used to produce geologic maps and also as input data for numerical software to simulate volcanic hazards. These field data are also valuable for the validation of numerical probabilistic models that are then employed to simulate different volcanic activity scenarios. The final products are maps of multiple hazards from lava flows, tephra fall, ballistic impacts, pyroclastic flows, lahars, and active faulting (Figure 3). We have recently updated the hazard maps for five of the main active volcanoes: San Cristóbal, Telica, Momotombo, Masaya and Concepción, using different probabilistic numerical models, with geological data and different parameters of the field work to evaluate possible volcanic hazard scenarios. These maps are not currently available on the website, and distribution must first be authorized by the director of INETER. Whenever possible, we try to validate the models with field data. The modeling tools that are frequently used for hazard assessment are those freely available offline and online at the [vhub.org](http://vhub.org) website (Titan2D, Tephra2, Energy Cone). Other methods published in the scientific literature such as Scoops3D [Reid et al. 2015], DOWNFLOW [Favalli 2005], and LAHARZ\_py [Schilling 2014] are employed to develop probabilistic scenarios. Layers of georeferenced thematic data (GIS) are usually combined to produce thematic maps on a given scale for a specific geographic region.

During the main volcanic crisis so far, when Telica, Momotombo and Masaya volcanoes erupted coincidentally from September 2015 to March 2016, the scientific team at INETER took the following line of actions: Continuous real time observations related to seismicity, degassing GNSS deformation and webcam surveillance. Volcanic probabilistic event trees were constructed for each volcano on a daily basis. Proper and continuous communication with the above appropriate authorities took place during the crisis.

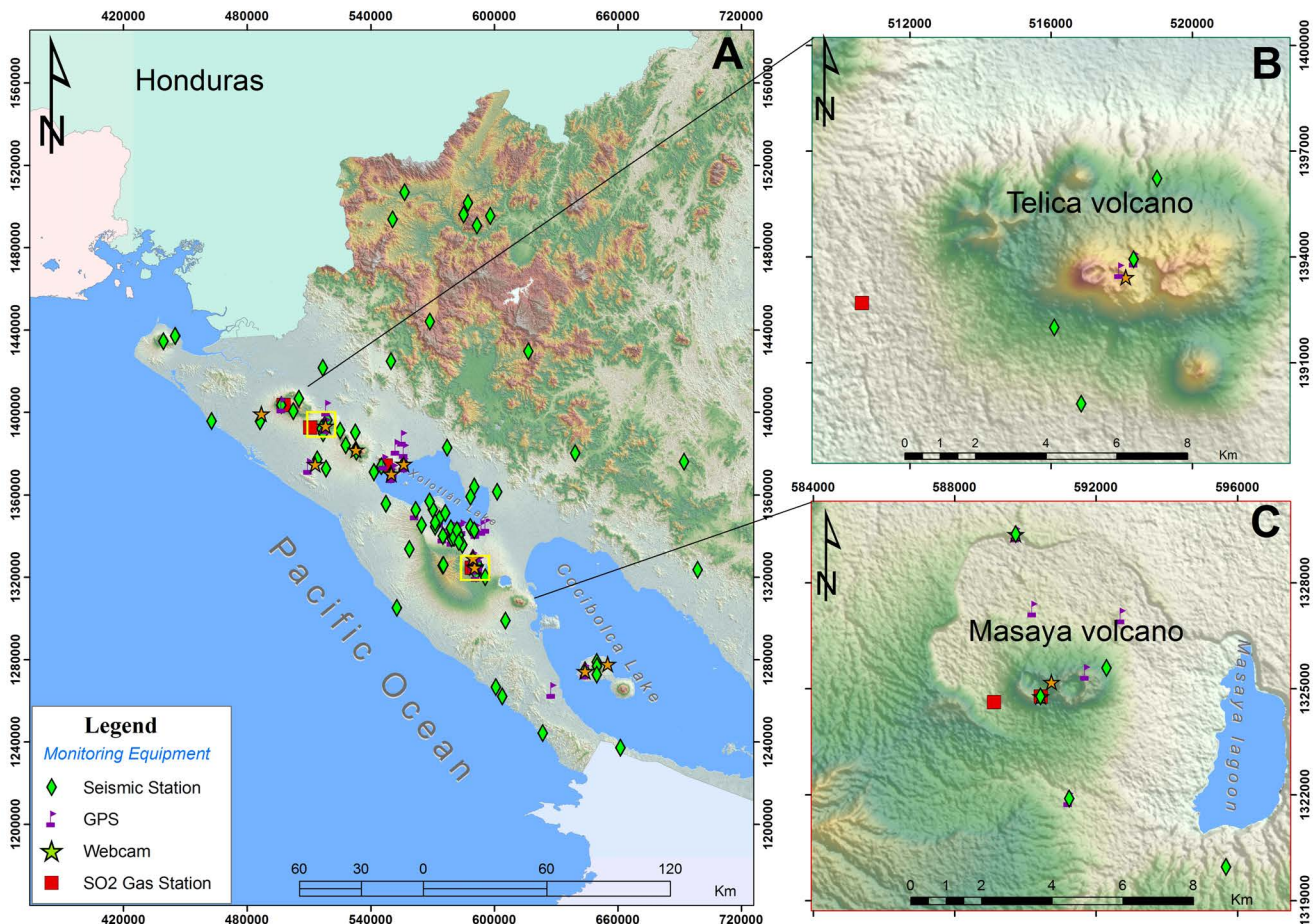
The different degrees or levels of volcanic hazard (low, medium and high) are defined for each active volcano based on its historical behavior and the different associated geological hazards, and taking into account the population exposed at different affected distances.

## 5 INFORMATION DISSEMINATION AND OUTREACH

During a volcanic crisis, we implement the already established protocol, which specifies that the Volcanology Division at INETER is the entity in charge of interpreting the level of severity of the ongoing events characterizing the crisis. Based on that, the head of the volcanology direction informs the head of DGGG, which in turn informs INETER's highest authorities, suggesting the measures to be taken. INETER then passes the infor-

**Table 1:** Monitoring instruments per volcano operated by INETER, Nicaragua.

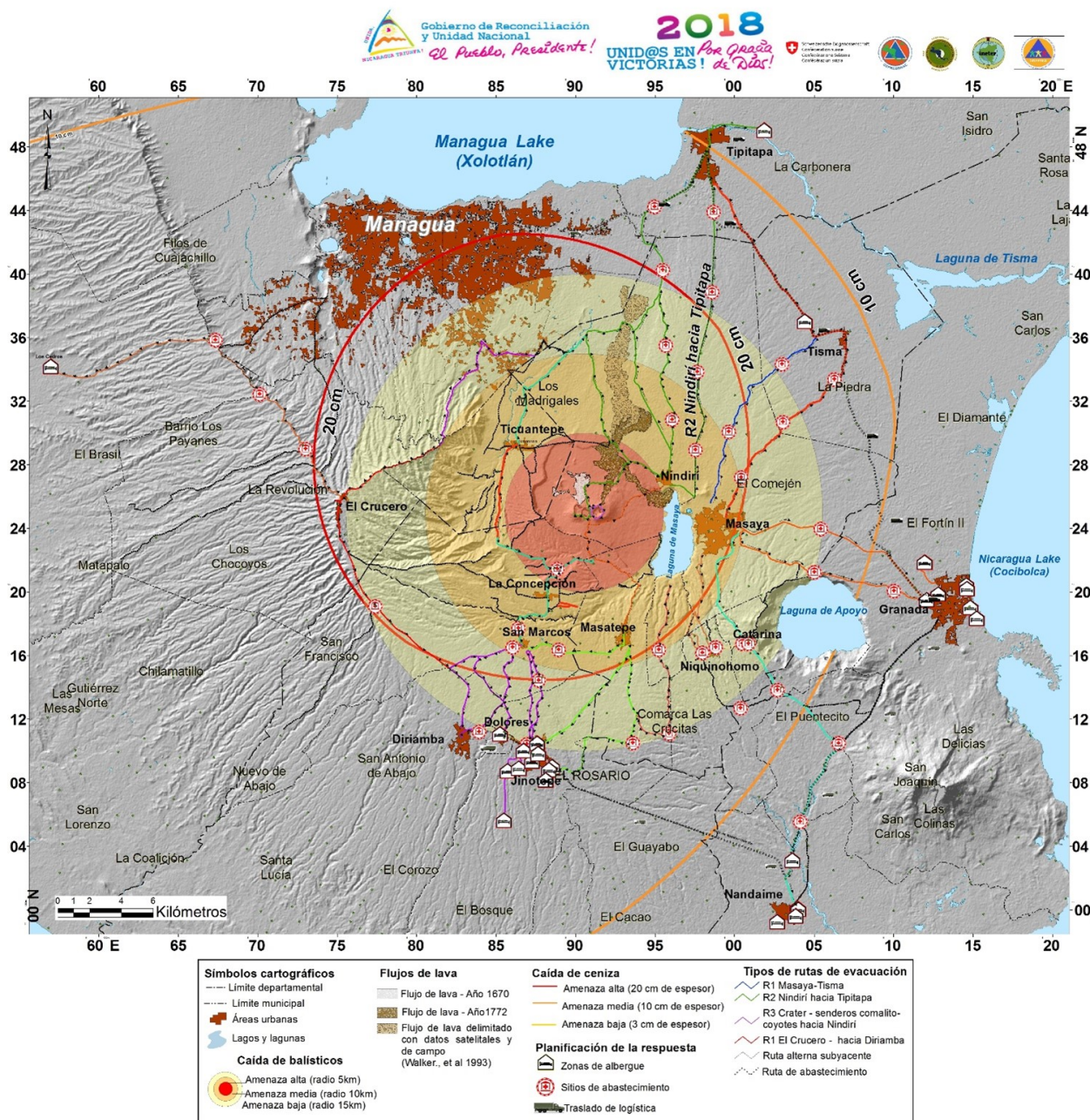
Volcano	Monitoring instruments					Total
	Webcam	MultiGAS	Fixed DOAS	GNSS	Seismic station	
San Cristóbal	2	-	1	2	3	8
Telica	2	-	1	4	7	14
Cerro Negro	1	-	-	-	6	7
Momotombo	3	-	1	7	5	16
Masaya	3	1	1	3	5	13
Concepción	2	-	-	2	4	8

**Figure 2:** National monitoring network of INETER. Monitoring networks on [B] Telica and [C] Masaya volcanoes. Coordinate system WGS84.

mation to the presidency of the Republic of Nicaragua and to the *Sistema Nacional de Prevención de Desastres* (SINAPRED) in charge of national prevention and mitigation of disasters, who inform the public about the volcanic crisis and direct the measures to be taken.

As part of SINAPRED, INETER interacts with a number of governmental, educational and private institutions, including civil defense, local authorities, people living in communities in volcanic hazard zones, schools, tourism companies, etc. At INETER, we conduct different outreach activities within the communities threatened by volcanic hazards together with the

local governmental and involved private sectors. On a regular basis we run drills so that the people know what to do during a given scenario related to volcanic activity. For instance, we are currently working with the communities around Telica, San Cristóbal, Concepción and Maderas volcanoes to develop eruption response plans. These response plans are presented to the communities using several methods, such as public presentations on hazards related to the volcano in question, using our three levels of volcano hazard (low, medium, and high), and the production of an evacuation route map, which clearly shows the routes each



**Figure 3:** Map of multiple hazards at Masaya volcano: ballistic impacts, tephra fall, lava flows, and evacuation routes are shown (blue, green and purple lines).

community should take to an existing shelter in a “safe” place where there will be logistics already established between the governmental and the private sector.

Some results are included in the monthly and yearly bulletins that are made available on our webpage\*, while others are shared with other institutions like SINAPRED and are accessible through their webpage†. Any remaining results are available on our data server‡. All communication of the generated information is

published through the website§ and television programs via the president’s office.

INETER also works in collaboration with the international scientific community, mainly universities and research centers in the United States of America (United States Geological Survey (USGS), Volcano Disaster Assistance Program (VDAP), University of South Florida, Pennsylvania State University, University of Arlington at Texas, University of New Mexico, University of Columbia, University NAVSTAR Consortium (UNAVCO), Carnegie Institute of Washington, among

\*<https://webserver2.ineter.gob.ni/sis/bolsis/bolsis.html>

†<http://www.sinapred.gob.ni/>

‡<https://webserver2.ineter.gob.ni>

§<https://www.ineter.gob.ni/>

others), in Europe (University of Bristol, King's College London, University of Edinburgh, University of Manchester, University of Kiel, GEOMAR Helmholtz Centre for Ocean Research Kiel, Universidad de Cádiz), and in Latin America (*Universidad Nacional Autónoma de México*, *Centro Nacional de Prevención de Desastres* (CENAPRED) in Mexico, *Servicio Nacional de Geología y Minería* (SERNAGEOMIN) in Chile, *Universidad de Puerto Rico en Mayagüez*, *Ministerio de Medio Ambiente y Recursos Naturales* of El Salvador, *Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología* (INSIVUMEH), *Coordinadora Nacional para la Reducción de Desastres* (CONRED) in Guatemala, *Observatorio Vulcanológico y Sismológico de Costa Rica* (OVSICORI) in Costa Rica). This international collaboration benefits INETER and Nicaragua in different ways, since it provides training to INETER's personnel, funding for field work and equipment maintenance, technology transfer, etc.

## 6 NEEDS, CHALLENGES, AND FUTURE PERSPECTIVES

After Cerro Negro volcano's eruption in April 1992, the volcanic instrumentation, permanent surveillance and monitoring of six of the main active volcanoes begun at INETER. This includes: seismic volcanic monitoring, SO<sub>2</sub> and CO<sub>2</sub> measurements, temperature measurements, webcam surveillance, GNSS, and response maps for each volcano's hazards for different eruptive scenarios, including lahars triggered by eruptive or geodynamic events at the volcanoes.

Since then, we have managed at least 19 volcanic crises, the outstanding ones were the six months between the middle of 2015 and beginning of 2016, when Telica, Momotombo and Masaya volcanoes erupted. Currently, the main needs to strengthen the Volcanology Division of the DGGG at INETER are:

- Increasing the number of experts and technicians. The personnel of the Volcanology Division, along with an adviser, continuously deal with different projects at the same time, and also have to respond to crises and emergency situations that arise.
- Funding for systematic training and continual professional development is needed in order to stay up to date with the advances in volcanology.
- Economic resources for field work and equipment maintenance is required.

INETER's Volcanology Division has several challenges for the near future, notably:

- Organization of real-time data transmission for all the monitoring equipment deployed in the field.
- Automation of preliminary data processing in near real-time for all incoming data.

- Increase the scientific capacity of all personnel. This includes the need for all personnel to speak English fluently.

We are working on projects with the national and international community to modernize our monitoring networks. Our goal is to enhance our capacity to respond in a timely manner to volcanic crises and to anticipate, as much as possible, the occurrence of dangerous volcanic phenomena to save the largest number of lives.

## ACKNOWLEDGEMENTS

We want to acknowledge the Executive Directorate of INETER which managed the liaison with the Nicaraguan government to provide unprecedented resources to foster our national volcano monitoring program. We are also very grateful to the international scientific community that has established cooperation agreements with INETER, through which we have been able to acquire complementary instrumentation, funding for maintenance of the monitoring instruments, and training for our personnel involved in the volcano monitoring program. We want to thank J. W. Quedo for providing assistance to prepare the figures in this manuscript.

## AUTHOR CONTRIBUTIONS

Each author contributed to the development of the document according to his or her expertise.

## DATA AVAILABILITY

All additional data or results from the volcanic hazard maps and monitoring equipment are available at <https://web-geofisica.ineter.gob.ni/vol/dep-vol.html>.

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## REFERENCES

Aiuppa, A., J. M. de Moor, S. Arellano, D. Coppola, V. Francofonte, B. Galle, G. Giudice, M. Liuzzo, E. Mendoza, A. Saballos, G. Tamburello, A. Battaglia, M. Bitetto, S. Gurrieri, M. Laiolo, A. Mastroli,

- and R. Moretti (2018). “Tracking Formation of a Lava Lake From Ground and Space: Masaya Volcano (Nicaragua), 2014-2017”. *Geochemistry, Geophysics, Geosystems* 19 (2), pp. 496–515. doi: [10.1002/2017gc007227](https://doi.org/10.1002/2017gc007227).
- Carr, M. J. (1984). “Symmetrical and segmented variation of physical and geochemical characteristics of the central american volcanic front”. *Journal of Volcanology and Geothermal Research* 20 (3-4), pp. 231–252. doi: [10.1016/0377-0273\(84\)90041-6](https://doi.org/10.1016/0377-0273(84)90041-6).
- Carr, M. J., L. C. Patino, and M. D. Feigenson (2007a). “Petrology and geochemistry of lavas”. *Central America: Geology, Resources and Hazards*. Ed. by J. Bundschuh and G. E. Alvarado. Vol. 2. CRC Press. doi: [10.1201/9780203947043](https://doi.org/10.1201/9780203947043).
- Carr, M. J., I. Saginor, G. E. Alvarado, L. L. Bolge, F. N. Lindsay, K. Milidakis, B. D. Turrin, M. D. Feigenson, and C. C. Swisher (2007b). “Element fluxes from the volcanic front of Nicaragua and Costa Rica”. *Geochemistry, Geophysics, Geosystems* 8 (6). doi: [10.1029/2006gc001396](https://doi.org/10.1029/2006gc001396).
- DeMets, C. (2001). “A new estimate for present-day Cocos-Caribbean Plate motion: Implications for slip along the Central American Volcanic Arc”. *Geophysical Research Letters* 28 (21), pp. 4043–4046. doi: [10.1029/2001gl013518](https://doi.org/10.1029/2001gl013518).
- Favalli, M. (2005). “Forecasting lava flow paths by a stochastic approach”. *Geophysical Research Letters* 32 (3). doi: [10.1029/2004gl021718](https://doi.org/10.1029/2004gl021718).
- French, S. W., L. M. Warren, K. M. Fischer, G. A. Abers, W. Strauch, J. M. Protti, and V. Gonzalez (2010). “Constraints on upper plate deformation in the Nicaraguan subduction zone from earthquake relocation and directivity analysis”. *Geochemistry, Geophysics, Geosystems* 11 (3). doi: [10.1029/2009gc002841](https://doi.org/10.1029/2009gc002841).
- Funk, J., P. Mann, K. McIntosh, and J. Stephens (2009). “Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median Trough, El Salvador, based on seismic-reflection profiling and remote-sensing data”. *Geological Society of America Bulletin* 121 (11-12), pp. 1491–1521. doi: [10.1130/b26428.1](https://doi.org/10.1130/b26428.1).
- Goffin, C. (2006). *VIII Censo de Población y IV de Vivienda*. Tech. rep. Managua, Nicaragua: Instituto Nacional de Estadísticas y Censos.
- Hill, B. E., C. B. Connor, M. S. Jarzempa, P. C. L. Femina, M. Navarro, and W. Strauch (1998). “1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions”. *Geological Society of America Bulletin* 110 (10), pp. 1231–1241. doi: [10.1130/0016-7606\(1998\)110<1231:eocnvn>2.3.co;2](https://doi.org/10.1130/0016-7606(1998)110<1231:eocnvn>2.3.co;2).
- Instituto Nicaragüense de Estudios Territoriales (1999). *Boletín Vulcanológico Mensual, Agosto, 1999*. URL: <https://webserver2.ineter.gob.ni/vol/bolvol/1999/08/index9908.htm>.
- (2004). *Boletín Vulcanológico Mensual, Febrero, 2004*. URL: <https://webserver2.ineter.gob.ni/boletin/2004/02/eventos-especiales0402.htm>.
- (2015a). *Boletín Vulcanológico Anual, 2015*. URL: [https://webserver2.ineter.gob.ni/boletin/2015/Anual\\_2015/Boletin\\_anual\\_vulcanologia\\_2015.pdf](https://webserver2.ineter.gob.ni/boletin/2015/Anual_2015/Boletin_anual_vulcanologia_2015.pdf).
- (2015b). *Boletín Vulcanológico Mensual, Diciembre, 2015*. URL: <https://webserver2.ineter.gob.ni/boletin/2015/12/index1512.htm>.
- (2016). *Boletín Vulcanológico Mensual, Febrero, 2016*. URL: <https://webserver2.ineter.gob.ni/boletin/2016/02/boletin-1602.pdf>.
- Jordan, B. R., H. Sigurdsson, S. N. Carey, R. Rogers, and J. Ehrenborg (2007). “Geochemical variation along and across the Central American Miocene paleoarc in Honduras and Nicaragua”. *Geochimica et Cosmochimica Acta* 71 (14), pp. 3581–3591. doi: [10.1016/j.gca.2007.05.013](https://doi.org/10.1016/j.gca.2007.05.013).
- La Femina, P. C., C. B. Connor, B. E. Hill, W. Strauch, and J. A. Saballos (2004). “Magma-tectonic interactions in Nicaragua: the 1999 seismic swarm and eruption of Cerro Negro volcano”. *Journal of Volcanology and Geothermal Research* 137 (1-3), pp. 187–199. doi: [10.1016/j.jvolgeores.2004.05.006](https://doi.org/10.1016/j.jvolgeores.2004.05.006).
- La Femina, P. C., T. H. Dixon, R. Govers, E. Norabuena, H. Turner, A. Saballos, G. Mattioli, M. Protti, and W. Strauch (2009). “Fore-arc motion and Cocos Ridge collision in Central America”. *Geochemistry, Geophysics, Geosystems* 10 (5). doi: [10.1029/2008gc002181](https://doi.org/10.1029/2008gc002181).
- McBirney, A. R. and H. Williams (1965). *Volcanic History of Nicaragua*. Vol. 55. University of California publications in geological sciences. University of California Press.
- Norabuena, E., T. H. Dixon, S. Schwartz, H. DeShon, A. Newman, M. Protti, V. Gonzalez, L. Dorman, E. R. Flueh, P. Lundgren, F. Pollitz, and D. Sampson (2004). “Geodetic and seismic constraints on some seismogenic zone processes in Costa Rica”. *Journal of Geophysical Research: Solid Earth* 109 (B11). doi: [10.1029/2003jb002931](https://doi.org/10.1029/2003jb002931).
- Reid, M. E., S. B. Christian, D. L. Brien, and S. T. Henderson (2015). *Scoops3D: software to analyze 3D slope stability throughout a digital landscape*. doi: [10.3133/tm14a1](https://doi.org/10.3133/tm14a1).
- Roman, D. C., P. C. LaFemina, R. Bussard, K. Stephens, C. Wauthier, M. Higgins, M. Feineman, S. Arellano, J. M. Moor, G. Avar, M. M. Cruz, M. Burton, M. Varnam, A. Saballos, M. Ibarra, W. Strauch, and V. Tenorio (2019). “Mechanisms of Unrest and Eruption at Persistently Restless Volcanoes: Insights From the 2015 Eruption of Telica Volcano, Nicaragua”. *Geochemistry, Geophysics, Geosystems* 20 (8), pp. 4162–4183. doi: [10.1029/2019gc008450](https://doi.org/10.1029/2019gc008450).
- Saballos, J. A., V. Conde, R. Malservisi, C. B. Connor, J. Álvarez, and A. Muñoz (2014). “Relatively short-term correlation among deformation, degassing, and seismicity: a case study from Concepción volcano, Nicaragua”. *Bulletin of Volcanology* 76 (8). doi: [10.1007/s00445-014-0843-5](https://doi.org/10.1007/s00445-014-0843-5).

- Saballos, J. A., R. Malservisi, C. B. Connor, P. C. L. Ferreira, and P. Wetmore (2013). "Gravity and geodesy of Concepción Volcano, Nicaragua". *Understanding Open-Vent Volcanism and Related Hazards*. Geological Society of America, pp. 77–88. doi: [10.1130/2013.2498\(05\)](https://doi.org/10.1130/2013.2498(05)).
- Saginor, I., E. Gazel, M. J. Carr, C. C. Swisher, and B. Turrin (2011). "New Pliocene–Pleistocene  $^{40}\text{Ar}/^{39}\text{Ar}$  ages fill in temporal gaps in the Nicaraguan volcanic record". *Journal of Volcanology and Geothermal Research* 202 (1-2), pp. 143–152. doi: [10.1016/j.jvolgeores.2011.02.002](https://doi.org/10.1016/j.jvolgeores.2011.02.002).
- Schilling, S. P. (2014). *Laharz\_py: GIS tools for automated mapping of lahar inundation hazard zones*. DOI: [10.3133/ofr20141073](https://doi.org/10.3133/ofr20141073).