REPORT VOLCANICA

Volcano hazard and surveillance in Costa Rica

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Abstract

Costa Rica hosts ten volcanic complexes and is highly tectonically active due to its location at the interaction between the Cocos, Nazca, and Caribbean plates and the Panama microplate. Three of the five historically active volcanoes had frequent eruptions in 2019. The institutions in charge of monitoring the volcanoes of Costa Rica are the *Observatorio Vulcanológico y Sismológico de Costa Rica* from *Universidad Nacional* (OVSICORI-UNA) and the *Red Sismológica Nacional* (RSN: UCR-ICE that groups the *Escuela Centroamericana de Geología* from the *Universidad de Costa Rica*, and the *Observatorio Sismológico y Vulcanológico de Arenal y Miravalles* from the *Instituto Costarricense de Electricidad*; acronyms ECG, UCR, OSIVAM, and ICE). These institutions are focused on the most dangerous volcanoes, i.e. those closest to the Great Metropolitan Area (2.2 million inhabitants), which includes San José (the capital), and those near hydroelectrical and geothermal plants. In 2020, those institutions operated a network of 59 seismic stations on volcanoes, 5 infrasound stations, 25 permanent GPS sites, 2 permanent DOAS, 3 permanent MultiGAS, 13 webcams, and performed systematic analyses in geochemistry and petrology laboratories. Those institutes routinely communicate results with the authorities in charge of crisis management nationally and internationally (*Comisión Nacional de Prevención de Riesgos y Atención de Emergencias* and *Volcanic Ash Advisory Centre*, respectively) and are always looking for more scientific collaborations.

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1 Introduction

1.1 Tectonic setting

Costa Rica is a small country (51,100 km^2) located in the Central American isthmus. The interaction between the Caribbean, Cocos, and Nazca plates and the Panama microplate has created a very complex tectonic setting (Figure 1). The Cocos plate subducts beneath both the Caribbean plate and the Panama microplate at 78 mm/year [Protti et al. 2012]. Three types of surface roughness on the Cocos plate originate from the interaction of the Cocos-Nazca Spreading Center and the Galápagos hotspot: smooth to the north, irregular over the seamount province in the center, and marked by the Cocos submarine volcanic range, a 1 to 2.5 km-high, 320 km-wide seamount chain to the south. Geodynamic changes and variations in slab morphology in the subducting plate have produced the Guanacaste (to the north), the Central (in central Costa Rica) volcanic ranges, and the non-volcanic Talamanca range (to the south). Among the ten volcanic complexes that form the modern volcanic arc (mostly grown over the last 600 ka, Figure 2A), Rincón de la Vieja, Arenal, Poás, Irazú, and Turrialba volcanoes have experienced historic activity (since 1700). Poás, Irazú, and Turrialba volcanoes, together with the dormant Barva and Platanar-Porvenir volcanoes, are within 50 km of the Greater Metropolitan Area (where the capital city San José and the cities of Heredia, Alajuela, and Cartago are situated). The Greater Metropolitan Area is home to ~45 % of the country's population (~2.2 million inhabitants) and hosts a large part of the infrastructure and economic activities of the country. All the volcanic complexes are part of national parks (which does not always prevent agriculture, nor farmers from living high on the volcano) that together exceed 450000 visitors per year.

1.2 Recent volcanic activity

Arenal volcano dramatically began an eruptive period with a Pelean eruption on July 29, 1968, that killed 78 people. The magmatic activity continued for 42 years and ended in October 2010 [Mora et al. 2013; Alvarado

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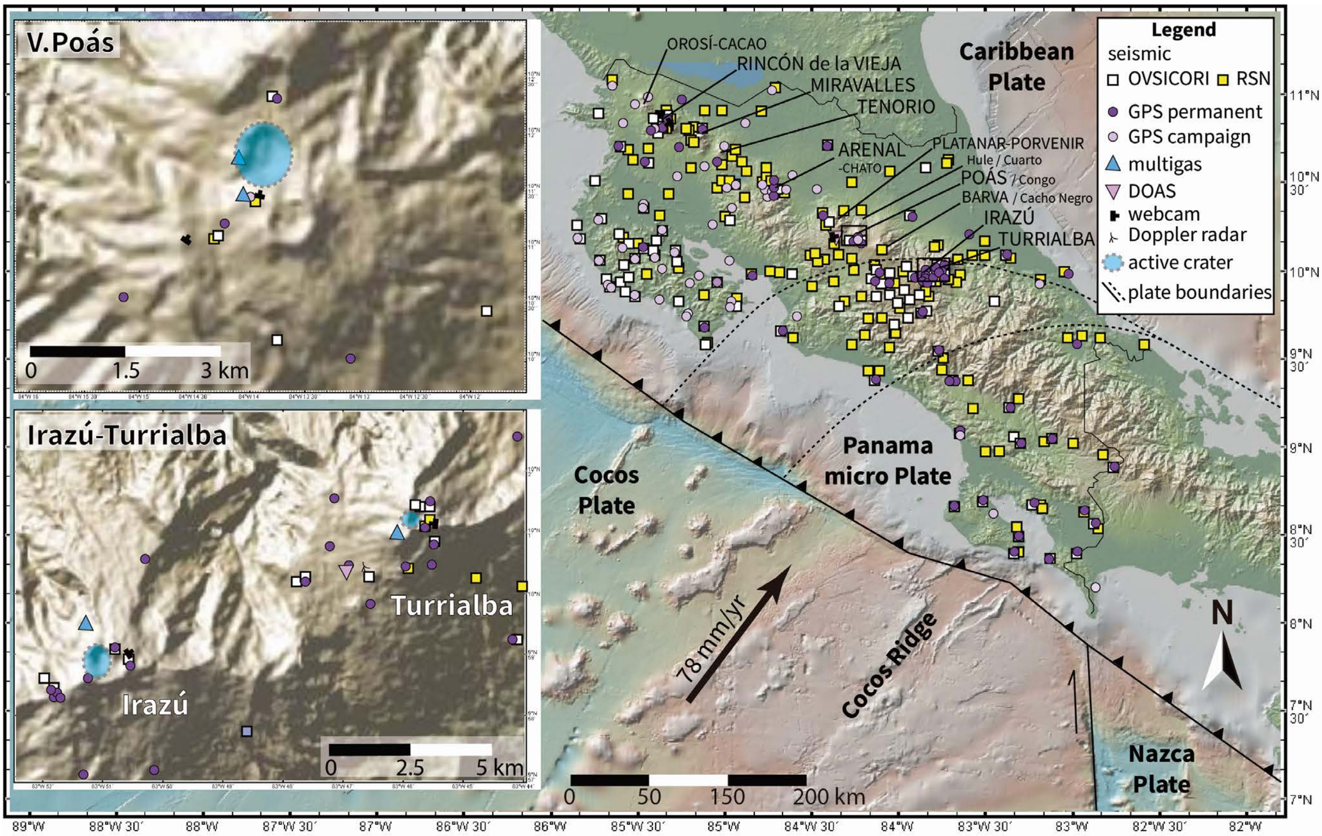

Figure 1: General map of Costa Rica showing the tectonic setting and the network managed by OVSICORI-UNA and RSN (UCR-ICE) in 2019 for both tectonic and volcanic surveillance. The network is detailed in Table 1. The maps on the left show details of the Poás and Irazú-Turrialba volcanic complexes.

2021], killing another three people (the last two were victims of pyroclastic flows in 2000). Activity at the volcano has since remained very low and is dominated by low degassing of hydrothermal gases and edifice stabilization [Muller et al. 2014].

Turrialba volcano reawakened in 1996 with seismic swarms followed by four phreatomagmatic ash emissions (1 to 5 % juvenile) between 2010 and 2013. A phreatomagmatic to Vulcanian eruptive period escalated after October 2014 [Alvarado et al. 2016; de Moor et al. 2016b] and climaxed with Vulcanian explosions in 2016 (Figure 2B). Two years of discontinuous phreatomagmatic and Strombolian activity followed that period before decreasing significantly (OVSICORI-UNA Annual bulletin 2020, and RSN bulletins).

Poás and Rincón de la Vieja volcanoes are dominated by hydrothermal manifestations such as hot hyperacidic lakes with sporadic phreatic/phreatomagmatic eruptions, and vigorous degassing. Both volcanoes have presented periods of phreatomagmatic eruptions (Figure 2A–B) since at least 1966 for Rincón de la Vieja and 2006 for Poás [de Moor et al. 2016a; Battaglia et al. 2019]. More recently, both volcanoes showed a high level of activity in 2017 (Figure 2A) with energetic phreatomagmatic eruptions and a low-level Strombolian stage for Poás [Madrigal and Lücke 2017; Salvage et al. 2018]. Another significant phreatomagmatic period has been observed at Rincón de la Vieja volcano in 2020.

2 Costa Rica volcano surveillance and research network

The national emergency due to the eruption of Irazú volcano (1962–1965) led to the first volcanic surveillance studies, that comprised the deployment of seismological and geophysical equipment, the construction of a local and temporal volcanological observatory in 1964 (the second in Latin America, after Paricutín, Mexico), the study of lahars and ash pollution, as well as mitigation and alert measures against lahars. That was the impetus for the creation of the Civil Defence that later became the *Comisión Nacional de Prevención del Riesgo y Atención de Emergencias* (CNE) in 1969 [Alvarado 2021].

The country's monitoring institutes dedicated to seismology and volcanology are the *Observatorio Sismológico y Vulcanológico de Arenal y Miravalles* from the *Instituto Costarricense de Electricidad* (OSIVAM-ICE), the *Escuela Centroamericana de Geología* from the *Uni-*

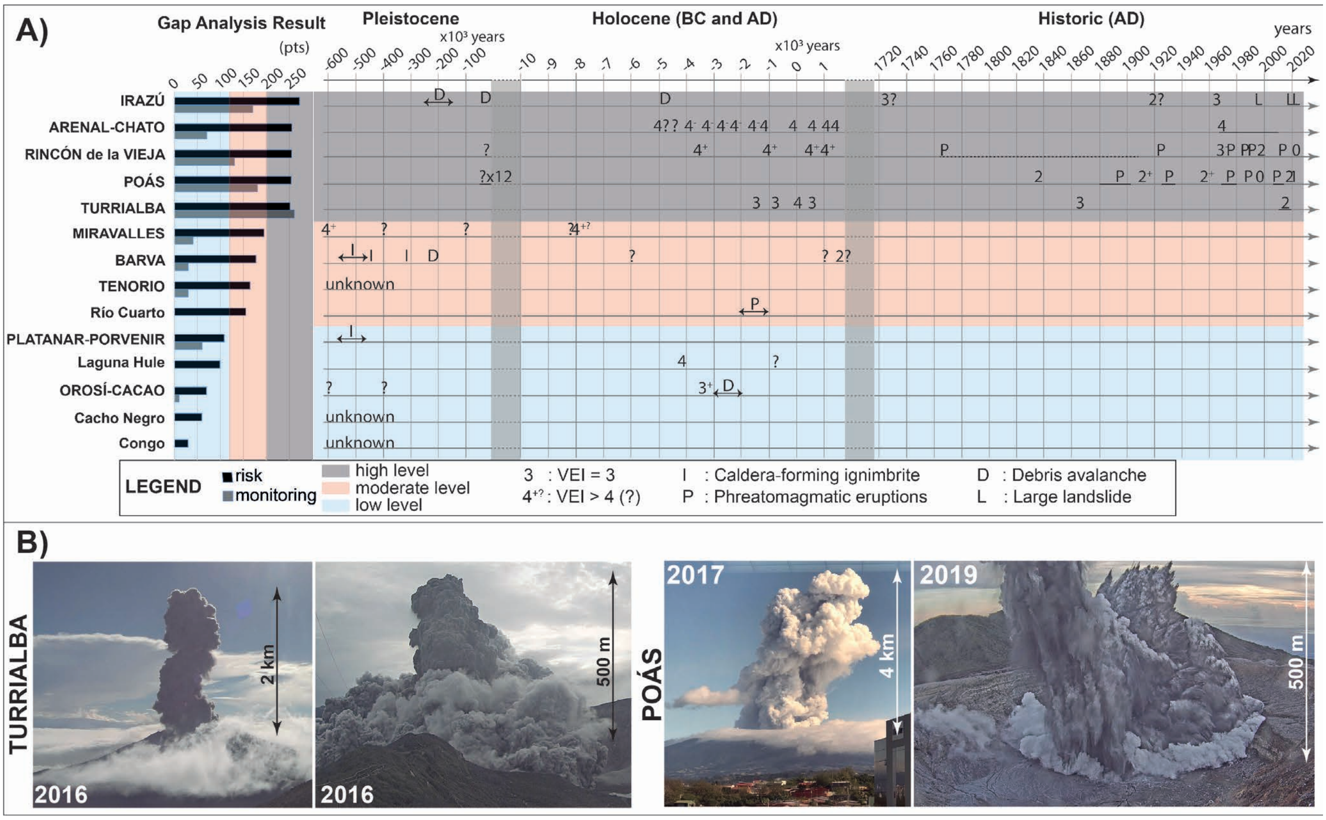

Figure 2: [A] Chronology of the known or estimated eruptive activity in Costa Rica with corresponding possible VEI (Volcanic Explosivity Index; compiled from many sources), and the results of a Gap Analysis in 2020 (see details in Section 5). Dates are negative Before Christ (BC) and positive Anno Domini. Grey vertical bands show a change in the time scale, question marks refer to uncertainties on the magnitude of the event when associated to a number, or to the date of the deposit for which no VEI can even be estimated. P: corresponds to a period of frequent phreatomagmatic eruptions for which no VEI can be estimated. I and D: ignimbrite and debris deposits (respectively) with no VEI estimation. L: large landslide not associated to eruptive activity but still representing a hazard. "Unknown" refers to a complete lack of knowledge of past activity. [B] Left: Phreatomagmatic eruptions at Turrialba volcano in 2016 showing a 2,000 m-high eruptive column on the left and small pyroclastic currents due to column collapse on the right. Right: phreatomagmatic eruptions at Poás volcano on April 14, 2017 (left) taken from the Central Valley 30 km away, showing a 4 km-high vapor-rich plume. This eruption modified the topography of the crater with the destruction of the 1955 dome. On the right, a moderate phreatomagmatic eruption (the jet reached a height of about 500 m) taken from the edge of the crater 600 m away on September 30, 2019. Centimeter-sized ballistics reached the MultiGAS station 400 m downwind from the vent. All pictures were taken by the OVSICORI-UNA webcams except Poás 2017 (credit: Jorge Villalobos Chavarría).

versidad de Costa Rica (ECG UCR), and the *Observatorio Vulcanológico y Sismológico de Costa Rica* from the *Universidad Nacional* (OVSICORI-UNA). OSIVAM-ICE and the UCR together form the *Red Sismológica Nacional* (RSN: UCR-ICE), as several of the seismic stations of OSIVAM-ICE are included in the RSN network. The creation of monitoring networks became a necessity since the last Arenal eruptive episode continued over four decades after the catastrophic onset in 1968. All of these institutes are research institutes created to monitor, document and study tectonic, volcanic and geothermal activity in the country.

The awakening of the Arenal volcano in 1968, and the occurrence of the Tilarán earthquake in April 1973 (Mw 6.5), motivated ICE to implement, in May 1974, the first telemetered (analog) seismic network in Costa Rica, in the Guanacaste region, due to the importance of the Arenal-Corobicí-Sandillal Hydroelectric Complex in the vicinity of Arenal volcano. The network was expanded to include coverage of geothermal plants near dormant Miravalles volcano in 1994, and then at Borinquen and Las Pailas at the foot of active Rincón de la Vieja volcano. Arenal, being one of the most active volcanoes in Latin America at that time, also motivated the creation of the *Observatorio Vulcanológico del Arenal* on July 29, 1988, later renamed OSIVAM-ICE in 1996 as a result of expansion of the monitoring systems. At present, OSIVAM-ICE has a seismological network for monitoring volcanic, human-induced and tectonic seismicity for the safety of power-generating infrastructure in the Guanacaste Range, including Rincón de la Vieja, Miravalles, Tenorio, and Arenal volcanoes, with more than 43 seismic stations. Twenty-five of these stations (4 broadband, 21 short-period) are for monitoring the volcanic activity by OSIVAM-ICE and shared into the RSN.

Since 1983, RSN (originally created in 1982) corresponds to the collaboration of ECG from UCR, and ICE. As of 2019, RSN (UCR and ICE together) manages a network of about 210 seismic stations throughout the country (Figure 1). The RSN's volcano monitoring is mostly based on seismology (18 broadband and 21 short-period stations) and direct observation using webcams (6 cameras), with complementary data collection from the field that is analyzed at the UCR. The UCR branch of RSN is mainly focused on Poás, Turrialba, and Irazú volcanoes while the ICE branch of RSN is focused on Rincón de la Vieja, Tenorio, Miravalles, and Arenal due to strategic electrical infrastructure managed by ICE close to those volcanic edifices. The monitoring network of RSN (UCR and ICE) is detailed in Table 1. RSN contains a laboratory of geochemistry and a laboratory of petrology for aqueous and rock samples, that together with other laboratories at University of Costa Rica, makes RSN able to carry out specific research [Lücke and Calderón 2016]. Gravity measurement campaigns are conducted by RSN for specific research at volcanoes [Argüello et al. 2019]. Most of the work of RSN on volcanoes has been focused on their geology, stratigraphy, and hazards.

The OVSICORI-UNA was formally created in 1985 as a research institute of UNA, although field work and volcano monitoring was carried out through a program that was part of the Department of Geography since 1977. As of 2019, OVSICORI-UNA manages a network of almost 90 broadband seismic stations with telemetry for near real-time data analysis that provide coverage of the whole country (Figure 1). This dense seismic network can locate even negative magnitude tectonic earthquakes. The volcano monitoring covers all ten potentially active volcanic complexes with a primary focus on Turrialba, Irazú, and Poás, due to their potential threats and the high exposure of the population or economic activities in the case of enhanced magmatic-hydrothermal activity. OVSICORI-UNA's volcano monitoring is mainly based on stations that provide permanent continuous near real-time data, which are summarized in Table 1. Besides seismic, GNSS and Multi-GAS networks, various geochemical parameters (pH, OxidoReduction Parameter, salinity, temperature, and heat flux) are automatically monitored in near real-time in springs around Rincón de la Vieja and Barva volcanoes (Campbell Scientific spring geochemistry station [Sáenz-Vargas 2020]). The institute hosts geochemistry and petrology laboratories that periodically complement the monitoring database with gas, aqueous and rock samples analyses.

OVSICORI-UNA and RSN have collaborated since 2010, sharing seismological data in real time and frequently communicating about data interpretation and hazard assessment. Collaborative projects are currently underway in order to: 1) automate seismic monitoring for generating fast time-frequency analysis and location of continuous and discrete seismic signals for assessing rapid changes in the dynamics of volcanic systems and having fast communication to authorities; 2) carrying out research in order to better understand seismic sources and volcano dynamics [e.g. van der Laat 2020]. Drones are also used by RSN, OVSICORI-UNA, and CNE to monitor topographic variations (ash deposit, ballistic impacts, landslides). OVSICORI-UNA carries out a wider application of drones for direct gas measurements in the volcanic plumes (miniDOAS and mini-MultiGAS; [de Moor et al. 2019]) and crater lake sampling.

In 2019, the monitoring was undertaken by 16 scientists (OVSICORI-UNA: 5 PhDs and 1 Master, RSN: 7 PhDs, 3 Masters), 7 laboratory assistants (OVSICORI-UNA: 3, RSN: 4), and 11 technicians (OVSICORI-UNA: 7, RSN: 4). In case of a crisis, it is possible to count on the support of the entire personnel at both institutes (around 30 people at OVSICORI-UNA and around 13 people in addition to student assistants at RSN). During the 2014–2018 Turrialba volcanic crisis, OVSICORI-UNA was able to accomplish a 24/7 survey of the volcano for a few months in 2016 by using all its ~30 employees.

Most of the information generated by those two monitoring groups is available in real time on their respective websites*, and the databases are available on-demand for collaborative research. The data is remotely accessible, which allows for 24/7 virtual surveys from any connected device.

3 Volcano hazard and its management

All the main volcanic complex summits in Costa Rica are located in national parks, which reduces the risks of human exposure to proximal volcanic hazards. However, these areas of conservation are also destinations for tourism, vital for the economy of the country. Moreover, the volcanoes' surroundings support diverse agriculture and livestock, also a significant economic sector, and hydroelectric/geothermal power plants. As a result, most of the population of the country lives within 50 km of an active volcano.

To address that vulnerability, volcanic hazard maps have evolved, since the mid-1980s, from exclusively geology-based to recent ones with multiple modeling-based and *Geographic Information Systems* (GIS) approaches. Integrated qualitative and administrative

*http://www.ovsicori.una.ac.cr/index.php; https://rsn.ucr.ac.cr/

Table 1: Distribution of the volcano-monitoring network managed by OVSICORI-UNA (normal) and RSN (UCR-ICE) (**bold**) in 2019. BB = Broadband seismometers; SP = Short-period seismometers; C = Campaign.

	Volcano								
Stations	Turrialba	Poás	Rincón de la Vieja	Irazú	Arenal	Miravalles-Tenorio	Barva	Platanar	Orosí
BB	5 + **5**	4 + 2	2 + **1**	4 + 2	1 + **1**	2 + 2	1 + 2	1 + **3**	-
SP	-	-	**5**	-	**4**	**12**	-	-	-
Infrasound	2	1	1	1	-	-	-	-	-
GPS	6+6C	4+1C	3 + **1**	6+4C	3	4	-	-	1+1C
MultiGAS	1	1	(1)*	1	C	-	-	-	-
DOAS	1	1	C	-	-	-	-	-	-
Webcam	2 + 2	3 + 2	2 + 2	-	-	-	-	-	-
Radar	1	-	-	-	-	-	-	-	-
SO_2 ExpoGAS	-	1	-	-	-	-	-	-	-
Spring	-	-	2	-	-	-	1	-	-
Meteo	1**	1**	1	1*	-	-	1	-	-

* Destroyed
** Managed by the IMN (National Meteorological Institute)

hazard maps have also been used with varying aims and in different situations.

Efficient communication is also key for the protection of national interests. OVSICORI-UNA is primarily responsible for communicating the level of activity of all volcanoes in Costa Rica. For instance, the institute developed a scale to describe the different levels of activity (Figure 3A) that goes from 0 (no degassing, no deformation, and no seismic activity; i.e. dormant volcano) to 5 (significant eruption in progress or expected, sustained high-amplitude seismic activity, fast deformation, or intense degassing). Furthermore, both entities (OVSICORI-UNA and RSN) provide technical expertise to the CNE, the governmental institution in charge of hazard management and risk prevention, hazard maps, the alert level, and decision-making. RSN and CNE have also been working on hazard maps (the first one produced in 1979 for Arenal volcano and in 1986 for the Central Volcanic Range compiled by Paniagua and Soto [1986]) and OVSICORI-UNA is developing a complementary capacity to simulate volcanic hazards related to eruptive scenarios in order to improve hazard risk assessment and mitigation. Geological maps, at a scale of 1:50,000 or larger, of most of the volcanic edifices have been produced by personnel of the ECG at UCR, and RSN, and several of them are currently under revision.

When an eruption occurs, OVSICORI-UNA primarily sends alerts to the CNE, the national parks, the *Volcanic Ash Advisory Centre* (VAAC), Juan Santamaría International airport (SJO) near San José, and private aviation and touristic companies through emails, chat forums (WhatsApp groups) and phone calls. OVSICORI-UNA and RSN also publishes information on social media websites* which are followed by the media and the population in general (e.g. Facebook, and a few communities share volcano information via WhatsApp). During a volcanic crisis, OVSICORI-UNA automatically runs models of ash dispersion and deposition twice a day, using `Ash3D` [Schwaiger et al. 2012], an eulerian tridimensional model that simulates the dispersion and deposition of volcanic ash using the NOAA global atmospheric model, based on volcanic eruption input parameters, including vent location, plume height, and eruption duration. The results are posted on the webpage of OVSICORI-UNA and used to anticipate most likely affected areas in case of an event. OVSICORI-UNA runs these models as well as the Hybrid Single Particle Lagrangian Integrated Trajectory model (`HySPLIT`) provided by NOAA [Stein et al. 2015] which tracks a single particle emitted in the atmosphere at a given place and elevation. Social media platforms are used to collect information of confirmed affected areas.

Due to the Turrialba and Poás volcanic crises since 2014, OVSICORI-UNA started assessing the quality of ambient air in an exposed urban area (automatically analysing PM1, PM2.5, and PM10 and SO_2 in the ambient air) and in the Poás Volcano National Park a warning system for SO_2 concentration called ExpoGAS was set up at the tourist lookout point. Collaboration between OVSICORI-UNA and other institutes (the *Laboratorio de Química de la Atmosfera*, LAQAT-UNA, the *Escuela de Ciencias Ambientales*, EDECA-UNA, and the *Instituto Regional de Estudios en Sustancias Tóxicas*, IRET-UNA) allows the quantification of potential impact and scope of the effects of volcanic emissions on the population, visitors of volcanic craters, and the environment [Herrera et al. 2014].

*https://www.facebook.com/OVSICORI/; https://twitter.com/OVSICORI_UNA; https://www.facebook.com/RSN.CR

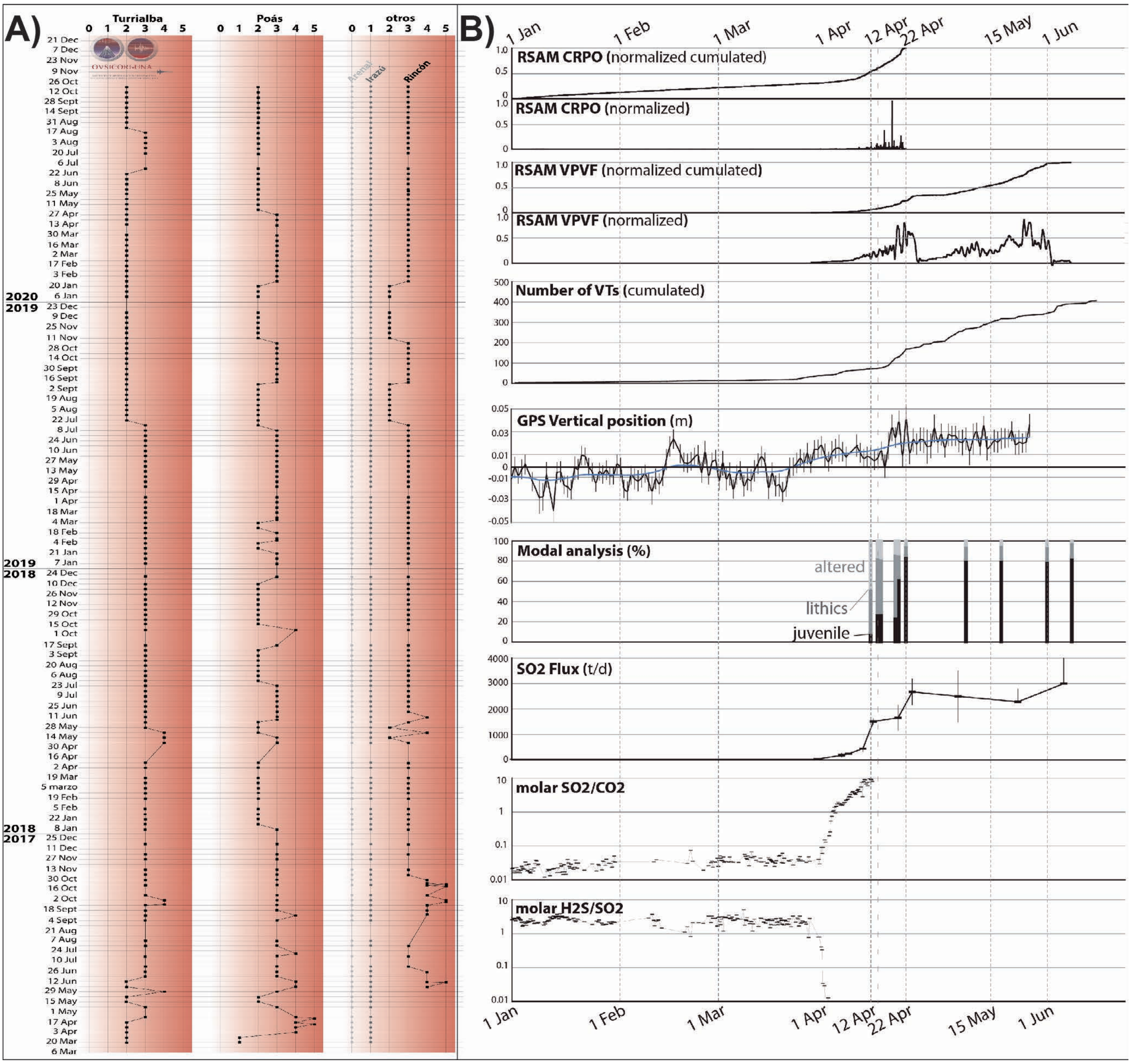

Figure 3: [A] Example of the activity level of the volcanoes over time updated weekly and as presented on the OVSICORI-UNA website. The activity level starts at 0 (dormant), goes to 3 (the volcano is considered in eruption), and to 5 as the maximum (intense ash emission, high seismicity, fast deformation and/or intense degassing). [B] Seismology, deformation, gas chemistry and petrology sequence for the 2017 eruptive crisis at Poás volcano as monitored by the OVSICORI-UNA.

4 Information dissemination and outreach

OVSICORI-UNA, RSN, and CNE are strongly involved in communication at the national level. The OVISCORI-UNA group in charge of volcano surveillance meets weekly or every time the volcanic activity requires, to update its interpretation and communication (Figure 3A*). OVSICORI-UNA publishes a daily, weekly, and annual bulletin. RSN also publishes a separate weekly bulletin and a special bulletin when activity changes. Both institutes use emails, and social media: Facebook (about 13 % and 8 % of the Costa Rican population follows the OVSICORI-UNA and RSN Facebook pages, respectively), Twitter, Instagram and

*http://www.ovsicori.una.ac.cr/index.php/vulcanologia/nivel-de-actividad-volcanica

WhatsApp. RSN has a YouTube channel[*] to display live webcams and volcanological explanations. Both institutes provide updates, explanations, and educational material directly to the population through mass media (TV, newspaper, and radio) and direct interventions in communities and classes.

Since 2015, RSN successfully scheduled activities at schools in the vicinity of Turrialba and Poás volcanoes[†]. Also, training courses have been held by CNE and OVSICORI-UNA for tour guides to national parks and by RSN-UCR and the *Laboratorio Nacional de Materiales y Modelos Estructurales* (LANAMME-UCR) for teachers of the Turrialba volcano schools in conjunction with the *Japan International Cooperation Agency* (JICA). In 2017, twelve teachers from the *Ministerio de Educación Pública* (MEP) graduated from the program called Masters of the Volcano[‡].

Frequently, RSN and OVSICORI-UNA receive visits from teachers and children from primary school. Due to the COVID-19 pandemic in 2020, these forms of communication switched to virtual as well as the classes provided by these two university institutes.

Moreover, both monitoring groups are technical advisors to the CNE, and are also in frequent communication with the national park authorities, as all large volcanoes in Costa Rica are part of different national parks. The groups also contribute to training tour guides, requests from politicians, and to fulfilling any public or personal expectation related to volcanic and seismic hazards and risk, and their impact on the people living nearby [van Manen et al. 2015; Ortiz-Apuy 2020; Sáenz-Vargas 2020].

Thanks to the long-term database obtained from over four decades of monitoring, diverse and numerous research topics on volcano geophysics and geochemistry have been investigated in joint monitoring-research collaboration with national and international scientists. Examples of such collaboration include: (i) the successful emplacement and maintenance of a NOVAC system and MultiGAS+DOAS to monitor volcanic degassing in Costa Rica by OVSICORI-UNA, currently ongoing [Galle et al. 2010; de Moor and Kern 2015; de Moor et al. 2016a], (ii) the monitoring and study of the systematics of volcanic gas chemistry along the Costa Rica-Nicaragua volcanic segment [Aiuppa et al. 2014; de Moor et al. 2017], (iii) studies of the Earth's volatile cycles and stable isotopes in volcanic fluids [Fischer et al. 2015; Ramírez-Leiva et al. 2017; Barry et al. 2019], (iv) volcano seismology experiments and research (VOLUME Project, Bean et al. [2009]), and (v) international workshops on monitoring techniques (PASI: Volcanic Hazards and Remote Sensing in Pacific Latin America in 2011[§]; Rose et al. [2013]; Soto et al. [2015]; NOVAC workshop in 2015[¶]; GPS workshop for Latin America observatories in 2019).

In early 2020, the CNE, together with other state institutions, initiated an intensive program for the placement of informative warning signs as well as large educational panels with information about volcanic structure, history, and examples of past volcanic hazards.

Another example is the multi-edition and reprinting of educational and informative books about Costa Rican volcanoes since 1989. Among these is the national best-selling geoscientific book that contains complete information about all volcanoes [Alvarado 2021].

5 Needs, challenges, and future perspectives

In 2020, OVSICORI-UNA, RSN, and CNE carried out a Gap Analysis together to evaluate the weaknesses and coordinate future efforts to better monitor the volcanoes in Costa Rica. It followed the method described by Ewert [2007], which consists of associating a number depending on the past and current activity, the past affectation, and the present human activity and vulnerability near each volcano to classify the volcanoes by the risk they represent. The monitoring network was evaluated by giving 10 points per permanent equipment (Table 1), not including short-period seismometers, so it reflects the level of monitoring attention in early 2020. This analysis pointed out the high level of volcanic risk due to the small size of the country and the resulting concentration of human activity around a few frequently active volcanoes, particularly Irazú. Indeed, using this method, the USA considered high risk volcanoes above 120 points, which would include 9 volcanoes out of 14 for Costa Rica; hence, we defined 3 levels adapted to our situation as seen Figure 2A. It also emphasized the deficiencies in the monitoring network, particularly around Arenal and Rincón de la Vieja. However, the main weakness of this analysis and therefore conclusions is the lack of knowledge of past activity of each volcano, in terms of volcanic history, past affected areas, and dating. Prior to the 18^{th} century there is a general gap in volcano stratigraphy and historical knowledge (Figure 2A), in large part due to tropical forests that cover the deposits. An exception to this is Arenal volcano that has a detailed history uncovered [Soto and Alvarado 2006].

OVSICORI-UNA and RSN operate with compound budget coming from host universities (salaries and related expenses) and the Costa Rica National Law for Emergencies and Risk Prevention No. 8488 Transitory I, a national investment expiring in 2023 (equipment

[*] https://www.youtube.com/user/RSNCostaRica

[†] https://www.ucr.ac.cr/noticias/2016/11/28/proyecto-capacitara-a-turrialbenos-para-entender-y-actuar-en-caso-de-actividad-volcanica.html; https://www.elpais.cr/2016/05/28/ucr-comparte-informacion-del-volcan-con-comunidad-turrialbena/

[‡] https://www.nacion.com/ciencia/aplicaciones-cientificas/turrialba-gradua-a-sus-primeros-maestros-del-volcan/M64EWHBOTJDHXPFMARUPUJOJMI/story/; https://www.youtube.com/watch?v=gwKEv0H0MVw

[§] https://vhub.org/resources/303

[¶] https://deepcarbon.net/feature/report-5th-novac-meeting-turrialba-volcano-costa-rica and material expenses). OVSICORI-UNA has an average annual budget around 3 million USD (~33 % is dedicated to salaries and related expenses of the ~30 employees and ~67 % in material expenses). RSN has an average budget of about 1 million USD (~40 % in salaries and related expenses and 60 % in material expenses). Today, all institutes are limited by their human resources, and threatened by the expiration of the law. While better collaboration between RSN and OVSICORI-UNA has been implemented to coordinate efforts, more organization, unification, and synchronization between institutes is necessary to ensure the sustainability of funding and monitoring networks. Likewise, the groups are working on automating the processing of large volumes of geophysical and geochemical data through machine learning.

Much success has been achieved in terms of accident occurrences at volcanoes (only 2 fatalities this century so far compared to 101 in the previous one), even though Arenal, Poás Turrialba, and Rincón de la Vieja have been very active and eruptive during the last two decades. This has mostly been due to mandatory restrictions to visitors and partly because no eruptions of VEI >2 have occurred since 1968. In order not to rely on luck, the institutes are deeply involved in educating the population and the decision makers, as well as decreasing the vulnerability on-site (i.e. signs, protocols, simulation exercises, shelters, and gas concentration measurements). The need for standardized and modern hazard mapping (with topography, volcanic history, and geologic maps of the ten volcanic complexes, model-based and resulting administrative hazard maps), taking into account previous efforts from heterogeneous sources, is vital for keeping the volcanic national parks safe. Various volcanoes need greater attention in monitoring, such as Rincón de la Vieja, where the terrain, climate, volcanic activity, and vandalism make it extremely challenging to install and maintain monitoring equipment. Similarly, dormant volcanoes in calderas like Miravalles and Barva have episodic seismic swarms and large deformation that requires further attention. Despite frequent volcanic activity near the capital, funding for monitoring is not ensured. However, the Gap Analysis exercise as well as the contribution from this paper are among the promising results for future progress in the effort to improve volcano surveillance in Costa Rica.

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Author contributions

Geoffroy Avard wrote the manuscript, made the figures, and provided petrological monitoring data. Mauricio Mora provided data and information about RSN. Henriette Bakkar provided information about OSIVAM. Guillermo Alvarado provided historical information about the history of volcano monitoring networks, volcanic hazards, and risk management. Mario Angarita provided figures and computing monitoring tools. Maarten de Moor provided gas monitoring data and constructive comments. María Martínez provided geochemical monitoring data. Cyril Muller provided geodetic monitoring data. Javier Pacheco provided seismic monitoring data. Paulo Ruiz provided information about communication and education. Gerardo J. Soto provided historical and volcanic hazards information, and hazard maps. All authors reviewed the manuscript.

Data availability

Each institute involved in this report is proposing a large set of live monitoring data in consultation through its own webpage. The database as well as not-in-real-time processed data are available on demand through personal or institutional collaboration only (contact by email the institute or directly the corresponding investigator). Hazard maps are available on the CNE website (https://www.cne.go.cr/reduccion_riesgo/tipo_amenazas/vulcanismo.aspx), and RSN website or its researchers sites (i.e. https://rsn.ucr.ac.cr/documentos/informativos/informes-de-volcanes;https://www.researchgate.net/profile/Gerardo-Soto-4).

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