

# Volcanic event management in the Galápagos Islands, Ecuador

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## ABSTRACT

The volcanoes of Galápagos, Ecuador, are among the most active in the world, with an average of five eruptions per decade. Monitoring and communication of their activity are essential for timely management of events. In this context, the Instituto Geofísico de la Escuela Politécnica Nacional carries out constant surveillance of Galápagos volcanoes using geophysical monitoring, remote sensing and field campaigns with the support of the Dirección del Parque Nacional Galápagos. Collaborations with national emergency agencies and international scientists have also been key to ensuring the protection of the population, economic activities, and endemic fauna of Galápagos. Since 2010, there have been numerous changes in the way volcanic unrest and eruption are detected and communicated to decision-makers and the public in general. This paper summarizes six eruptions and one period of unrest from different Galápagos volcanoes that occurred in the last decade to illustrate and discuss the evolution of surveillance and hazard communication.

## RESUMEN

Los volcanes de Galápagos, Ecuador, se encuentran entre los más activos del mundo, con un promedio de cinco erupciones por década. El monitoreo y la comunicación de su actividad son esenciales para el manejo oportuno de los eventos. En este contexto, el Instituto Geofísico de la Escuela Politécnica Nacional realiza una vigilancia constante de los volcanes de Galápagos usando monitoreo geofísico, teledetección y campañas de campo con el apoyo de la Dirección del Parque Nacional Galápagos. Las colaboraciones con organismos nacionales de emergencia y científicos internacionales también han sido clave para garantizar la protección de la población, de las actividades económicas y de la fauna endémica de Galápagos. Desde 2010, se han producido numerosos cambios en la forma de detectar y comunicar las agitaciones y erupciones volcánicas a las autoridades y al público en general. Este manuscrito resume seis erupciones y un periodo de agitación de diferentes volcanes en Galápagos ocurridos durante la última década para ilustrar y analizar la evolución de la vigilancia volcánica y la comunicación sobre sus peligros.

Keywords: Galápagos; Volcano; Eruption; Unrest; Monitoring; Communication

## 1 INTRODUCTION

### 1.1 Volcanic activity in Galápagos

The Galápagos Archipelago is located in the eastern equatorial Pacific about 1000 km west of Ecuador and is the current subaerial expression of the Galápagos Hotspot [Simkin 1984]. The islands sit on top of the Carnegie Ridge, also produced by the Galápagos Hotspot. This ridge is moving along with the Nazca plate toward the east and subducts below South America at a velocity of 5.6 cm yr<sup>-1</sup> [Alvarado et al. 2016]. The Galápagos Archipelago is constructed on a relatively young (<10 My) and thin (6–12 km) lithosphere produced by the Nazca-Cocos Spreading Center, north of the Archipelago. The Nazca-Cocos Spreading Center is spreading at a rate of 6–7 cm yr<sup>-1</sup> [Simkin 1984; Feighner and Richards 1994; Gutscher et al. 1999]. Along with Hawai'i, Iceland, and La Réunion, the Galá-

pagos Archipelago is one of the most active hotspots of the planet with a crustal volume flux estimated around 0.13–0.3 km<sup>3</sup> yr<sup>-1</sup> [Sallarès and Charvis 2003; Mittelstaedt et al. 2008] and an average eruption frequency of once every 2 years [Bernard et al. 2019, and references therein]. Galápagos volcanoes are known for the diversity of their morphologies, eruptive dynamics, and magmatic compositions, which still constitute a challenge for their understanding [Poland 2014; Harpp and Geist 2018]. The western volcanoes, which are also the most active because they are closer to the Galápagos Hotspot, have an inverted soup bowl shape with a large caldera at the top, while the eastern volcanoes do not have steep slopes or calderas, most likely due to the lack of large shallow magma reservoirs [Harpp and Geist 2018]. Typical subaerial eruptions in the Galápagos are basaltic in composition and Hawaiian to Strombolian in style, but explosive eruptions can also occur, such as the hydromagmatic eruption of Fernandina in 1968 [Howard et al. 2019] and the >100 ka rhyolitic

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Plinian eruption of Alcedo [Geist et al. 1994]. The Galápagos Archipelago has 21 main subaerial volcanoes, 12 of which erupted during the Holocene, and 8 in historical times (i.e. since 1797; [Global Volcanism Program 2013], Figure 1). It also has dozens of islets and hundreds of seamounts.

## 1.2 The stakes in the Galápagos Islands

The giant tortoises, which gave their name to the archipelago due to the shape of their carapace resembling a saddleback (Galápagos is an old Spanish word for saddleback), are of course the most famous representatives of the islands. Some individuals have even been made world famous for being the last survivors of their species, like Lonesome George (*Chelonoidis abingdonii*) and Diego (*C. hoodensis*). Recently, a tortoise named Fernanda, descendant from a species previously considered extinct from Fernandina Island (*C. phantasticus*), was found on the island thanks to a national and international research effort\*. The Galápagos tortoises are known to be the largest tortoises and the longest-lived reptiles in the planet [MacFarland et al. 1974; Berkel and Cacan 2021]. Their history is closely linked to the geological development of archipelago, with distinct species present on the different islands and even on the different volcanoes of the Isabela Island [Poulakakis et al. 2020]. Unfortunately, severe harvesting by human since the discovery of the Galápagos Archipelago in 1535 by Tomás de Berlanga, followed by predation and competition for food with introduced fauna, has decimated their population [MacFarland et al. 1974]. Recent eruptions, such as that of Cerro Azul in 1998 [Global Volcanism Program 1998] and Wolf in 2015 [Bernard et al. 2019], have threatened their already highly endangered populations.

In addition to the 15 species of giant tortoises (2–3 of which are considered extinct), the Galápagos Archipelago is home to more than 7,000 species of fauna and flora, nearly 30 % of which are endemic†. As a result, in 1959 the unsettled areas were transformed into the Galápagos National Park, which encompasses 97.5 % of the land area, and in 1978, the archipelago was declared a World Heritage Site by UNESCO. Since the beginning of the human settlement in the late 19th century, the local population has grown exponentially, reaching over 25,000 inhabitants in 2010‡. Before 1969, the main economic activity on the islands was fishing and agriculture, but since then, the increase of tourist visitation by airplane and boat, land-based hotels and the convenience of two national airports (Seymour Airport on Baltra island and San Cristóbal Airport on San Cristóbal island) have made the island an international destination with >270,000 tourists per year before the

2020 pandemic§.

## 1.3 The history of monitoring Galápagos volcanoes

Although the Galápagos volcanoes have attracted geologists since their discovery, systematic study did not begin until the late 1960s [McBirney and Williams 1969; Simkin 1984]. Due to its remote location and rough terrain, the Galápagos archipelago is mostly isolated. Until the end of the 20th century, most transportation was by boat, access to electricity was limited to the town centers and communications were by shortwave radio. An analog seismic station (GIE) was first installed on Santa Cruz Island from 1964 to 1985 as part of the World-Wide Standardized Seismograph Network (WWSSN). The single station recorded some events that occurred during this period such as the large-scale collapse of the Fernandina (also known as La Cumbre) caldera in 1968 [Filson et al. 1973]. The development and application of satellite remote sensing to volcanoes in the 1990s made it possible to monitor and study some eruptions and periods of unrest in Galápagos, including the eruptions of Fernandina in 1995 and Cerro Azul in 1998 [Wooster and Rothery 1997; Jónsson et al. 1999; Rowland et al. 2003]. In 1996, the Instituto Geofísico from the Escuela Politécnica Nacional (IG-EPN) installed a network of four analog seismic stations in order to monitor seismicity and the state of active volcanoes of the Archipelago; these stations were located at Punta Espinoza (FER1) on Fernandina Island; at Volcán Chico (VCH1) and Punta Alfaro (ALCE) on Isabela Island; and at Bartolomé on Santiago Island (Figure 1). All the stations sent their signals by radio to the Volcán Chico repeater, from where they were retransmitted to the Cerro Crocket repeater on Santa Cruz Island and finally sent to the Charles Darwin Research Station in Puerto Ayora (Santa Cruz) where the signals were received and stored in a server to be later processed by the IG-EPN. This network also integrated a three-component digital seismic station (PAYG) installed in 1998 on Santa Cruz as part of the Global Seismograph Network operated by IRIS/USGS¶ with the recording system installed at the Charles Darwin Research Station. Temporary or campaign seismic networks for scientific purposes were installed from 1999 to 2003 (the entire archipelago, Villagómez et al., 2007) and from 2009 to 2011 (only Cerro Azul and Sierra Negra [Tepp et al. 2014]). Periodic Global Positioning System (GPS) and gravity campaigns began on Sierra Negra and Fernandina in 2000 [Geist et al. 2006], shortly followed by the installation of a cGPS (continuous GPS) network in 2002, 2006, and 2009 [Chadwick et al. 2006; Geist et al. 2006].

In 2010, an agreement was signed between the Dirección del Parque Nacional Galápagos (DPNG) and the

\*<https://www.bbc.com/mundo/noticias-57258965>

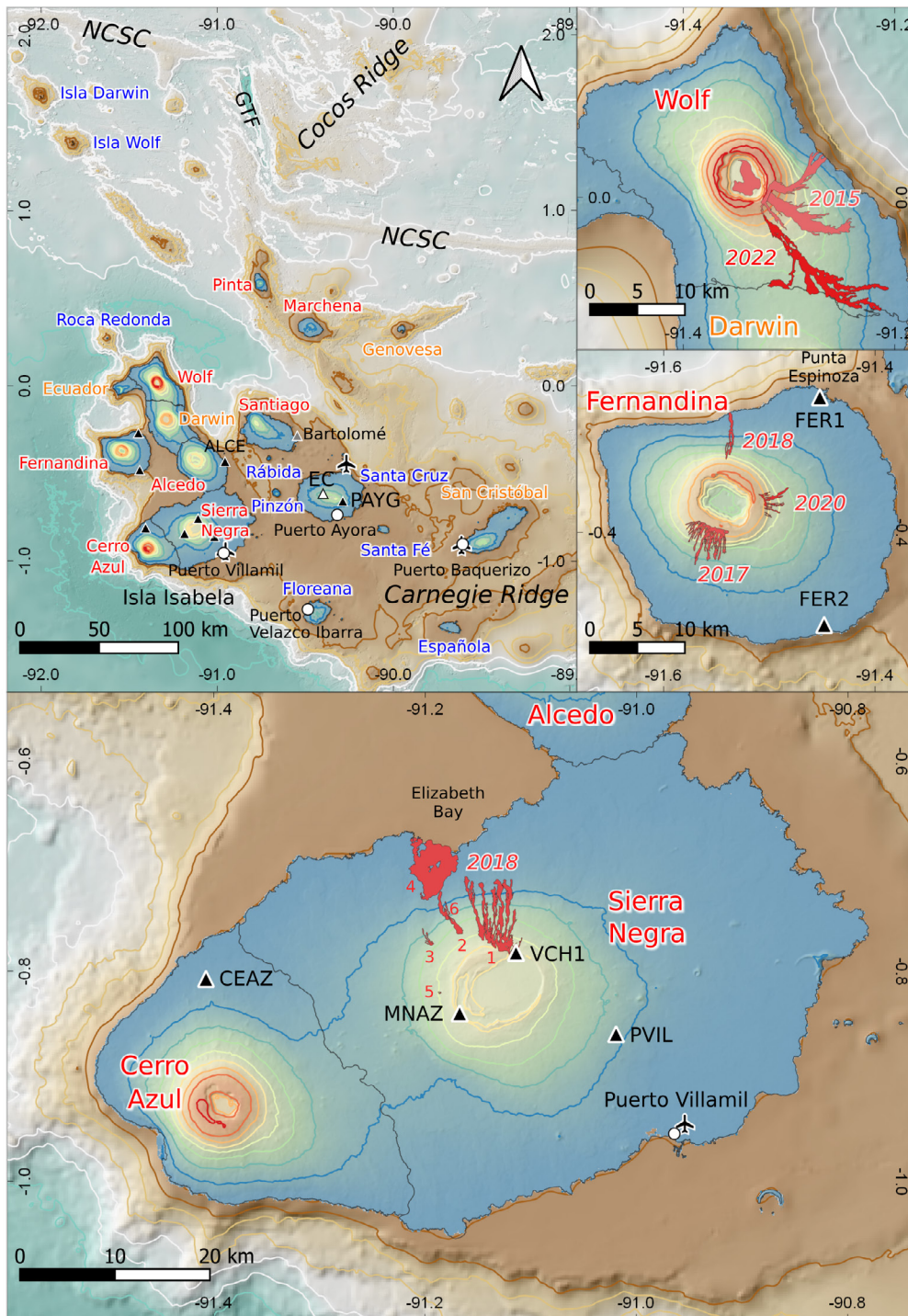
†<https://www.darwinfoundation.org/en/datazone>

‡<https://www.ecuadorencifras.gob.ec/>

base-de-datos-censo-de-poblacion-y-vivienda/

§<https://www.observatoriolagalapagos.gob.ec/arribos-anales>

¶<https://www.iris.edu/hq/programs/gsn>



**Figure 1:** Map of Galápagos archipelago and close-ups of Galápagos volcanoes with eruptions since 2010. The names of the main subaerial volcanoes are in blue (no evidence of Holocene eruptions), orange (evidence of Holocene eruptions) and red (evidence of historical eruptions). Darwin and Ecuador volcanoes are in orange because they lack confirmed historic (since 1797) eruptions but are suspected to have been active in the last 500 years based on their unvegetated lava fields. White dots are for main populations and airplane symbols for airports. New lava fields since 2010 are shown in shades of red on the close-up maps. Numbers in red for the Sierra Negra lava fields correspond to the eruptive fissures. Subaerial contours: 200 m, submarine contours: 500 m. NCSC: Nazca-Cocos Spreading Center; GTF: Galápagos Transform Fault. Black triangles with white outlines show the location of the IG-EPN monitoring stations. PVIL: Puerto Villamil; VCH1: Volcán Chico; MNAZ: Minas de Azufre; CEAZ: Cerro Azul; FER1 and FER2: Fernandina; PAYG: Santa Cruz seismic station; EC: El Chato, Santa Cruz repeater. Coordinate System: WGS 84.

IG-EPN to update and install additional permanent, real-time monitoring instrumentation on the most active volcanoes in Galápagos (stations shown on [Figure 1](#)). In 2012, a seismic network of six stations was installed on Sierra Negra (2), Fernandina (2), Cerro Azul (1) and Alcedo (1). The monitoring station VCH1 (Volcán Chico) located on Sierra Negra also includes an infrasound sensor to detect superficial activity. A DOAS (Differential Optical Absorption Spectrometry) station was also installed in 2013 on Sierra Negra, near Minas de Azufre, to monitor SO<sub>2</sub> emissions (MNAZ). Finally, a visual NETCAM web camera was installed at the VCH1 station in 2018. These stations send their signal by radio to Volcán Chico repeater, which transfer it to El Chato (EC) on Santa Cruz where it is sent directly to the IG-EPN by satellite. Field campaigns for gravity, GPS, and tephra collection complete the surveillance program run by the IG-EPN. Ground-based instrumental monitoring is complemented by satellite remote sensing including ground deformation (Interferometric Synthetic Aperture Radar [InSAR]: Sentinel-1), outgassing (SO<sub>2</sub>: AURA, Suomi NPP, NOAA-20, Sentinel-5P), ash emissions (GOES-16), thermal anomalies (Sentinel-2, TERRA, AQUA, Suomi NPP, NOAA-20), and surface changes (Landsat 8, Sentinel 2, PlanetScope). This multi-parametric monitoring system has been used to track and investigate the most recent eruptions of Wolf (2015 and 2022 [[Bernard et al. 2019](#)]), Fernandina (2017, 2018, and 2020 [[Vasconez et al. 2018](#)]), and Sierra Negra (2018 [[Vasconez et al. 2018](#); [Bell et al. 2021a](#); [b](#)]). It has also captured recent periods of volcanic unrest such as the 2017 sill intrusion at Cerro Azul [[Guo et al. 2019](#)].

#### 1.4 Coordination during volcanic event in Galápagos

When an adverse event is detected, the Galápagos Comité de Operaciones de Emergencia (COE), including all concerned authorities (Consejo de Gobierno de Régimen Especial de Galápagos, mayors, Servicio Nacional de Gestión de Riesgos y Emergencias SNGRE, national government, DPNG, Dirección General de Aviación Civil), and emergency responders (ECU911, Ecuadorian Red Cross, firefighters, police, army), meets to assess the situation. The COE can also invite members from different partner institutions (Galapagos Conservancy, Charles Darwin Research Station, universities and NGOs) to present their results and coordinate field actions. Since 1983, the IG-EPN has conducted monitoring of the Ecuadorian volcanoes (both Mainland and Galápagos archipelago) and, through a government mandate signed in 2003, it is responsible for providing hazard assessment and issuing warnings about volcanic activity [[Alvarado et al. 2018](#); [Ramon et al. 2021](#)]. The IG-EPN communicates with the authorities through e-mails, direct phone calls or instant messaging during emergency. All IG-EPN reports are

available on its webpage\* and shared on its social network accounts (Facebook and Twitter since 2010, Telegram since 2019). Examples of those reports are available in the [Supplementary Material](#). Although the IG-EPN is responsible for volcanic hazard monitoring, it is the SNGRE that is in charge of changing the colour of the volcanic alert during an event and coordinating emergency response†. The DPNG, as administrator of the Galápagos National Park, requires up-to-date information on the activity of the volcanoes and important changes through time, in order to implement safety measures for the residents and tourists, as well as to consider response activities pertaining to fauna that may be threatened. Therefore, thanks to the formal agreement and ongoing close collaboration with the IG-EPN, the DPNG is positioned to inform the authorities, the local population, and the tourists in a timely manner regarding hazards and required actions. The participation of the rangers in fieldwork and in providing of information from sites close to the volcanoes are of great importance for the monitoring of the volcanic activity during or after eruptions. In addition, the DPNG approves and supports research projects that, under the agreement with the IG-EPN, allow monitoring of volcanoes for the purposes of early warning.

This manuscript describes the evolution of volcanic event management in the Galápagos through the experience gained over the last decade. In particular, it focuses on two main questions:

1. How are volcanic unrest and eruptions detected and monitored by the IG-EPN?, and
2. How does the IG-EPN communicate critical hazard information to authorities—in particular the DGNP—and the public during those events?

Finally, we discuss the results of the monitoring effort and propose a communication plan that links the state of activity with specific communication products. Throughout the manuscript, time is given in Galápagos Local Time (UTC – 6 hours). The information for the different volcanic events is based on the IG-EPN reports‡ and scientific publications, along with some additional unpublished seismic data.

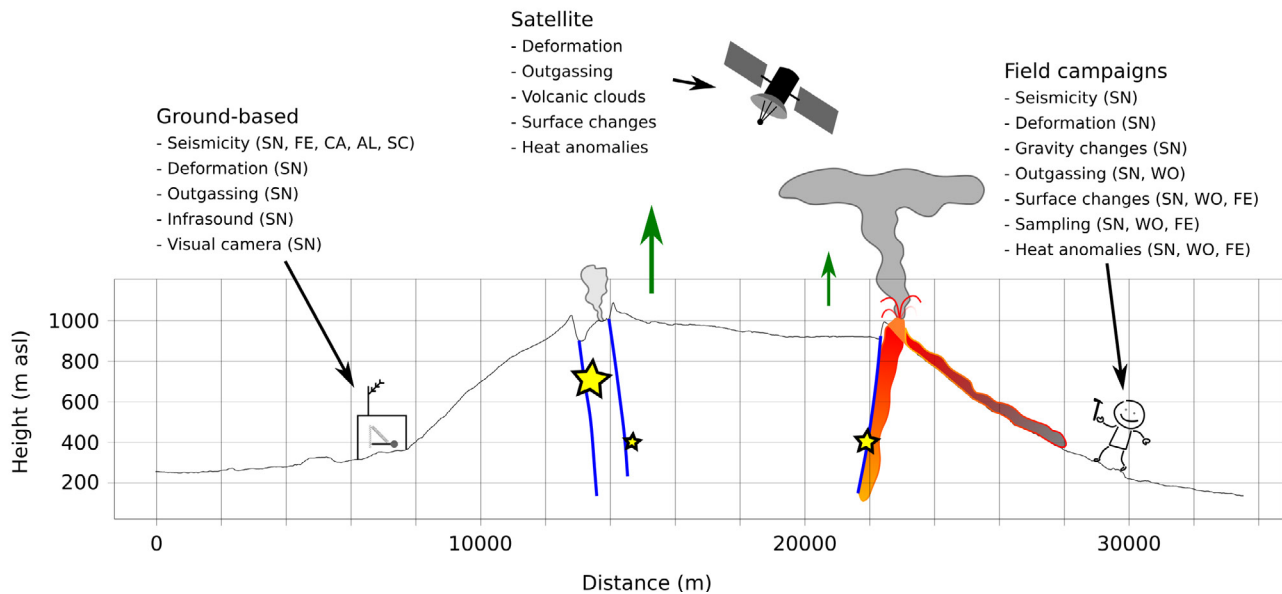
## 2 WOLF RECENT ERUPTIONS

Wolf shield volcano (Latitude: 0.042°N, Longitude: 91.335°W, Altitude: 1705 m above sea level a.s.l.) is situated at the northern tip of Isabela Island. Since 1797, 13 eruptions have been reported at Wolf [[Geist et al. 2005](#); [Global Volcanism Program 2013](#); [Bernard et al. 2019](#)]. Wolf is considered one of the most active volcanoes of the Galápagos Archipelago. Nonetheless,

\*<https://www.igeptn.edu.ec/>

†<https://manualcoe.gestionderiesgos.gob.ec/portfolio-item/estados-de-alerta-por-eventos-peligrosos/>

‡<https://www.igeptn.edu.ec/servicios/busqueda-informes>



**Figure 2:** Idealized diagram of the IG-EPN multi-parametric monitoring system at Galápagos volcanoes. SN: Sierra Negra; FE: Fernandina; CA: Cerro Azul; AL: Alcedo; SC: Santa Cruz; WO: Wolf. Stars are representative earthquake hypocenters; blue lines are caldera bounding faults; green arrows show typical pre-eruptive ground deformation.

due to its remote location and difficult access, this low-threat volcano [Santamaría and Bernard 2018] does not possess a dedicated ground-based geophysical monitoring network as of 2022. The closest seismic station is located on Fernandina Island ~33 km SW (FER1, Figure 1). Before the 2015 eruption, Wolf underwent a ~0.6-m intracaldera inflation, observed by InSAR, from 1992 to 2009 that stabilized by 2010 [Bagnardi 2014; Stock et al. 2018]. Unfortunately, the satellite radar data acquisition was discontinued from 2010 to 2015, preventing the possibility of tracking ground deformation in the lead-up to the eruption.

## 2.1 Wolf 2015 eruption

After 33 years of quiescence, the 2015 eruption of Wolf was the first to occur since the installation of permanent, real-time geophysical monitoring on Isabela and Fernandina islands. Although noticeable seismic unrest occurred on Sunday 24 May at 23:10 (Figure 3), retrospective analysis of the seismic record revealed low-level seismicity started about 14 hours earlier [Bernard et al. 2019]. The eruption itself may have started around 00:33 on 25 May, coincident with a M3.3 earthquake. The eruption was filmed by a member of the Charles Darwin Foundation at 00:50\*. At 01:00, the seismicity switched from discrete events to tremor. The eruption was detected by remote sensing at 01:28 by the Hawai'i Institute of Geophysics and Planetology (HIGP). The first institution to emit a public warning about the eruption was the Washington Volcanic Ash Advisory Center (W-VAAC) at 02:00 due to the presence of a 15 km-high eruptive column on GOES-16 im-

agery. Due to the remote location of the volcano, the images of the eruption taken from a cruise ship were shared with IG-EPN only several hours later (Figure 4). Scientists from the University of Idaho (USA) were also rapid to spot the eruption on satellite imagery and contacted the IG-EPN. A VONA (Volcanic Observatory Notice for Aviation) was issued by the IG-EPN at 08:38 due to the persistent eruptive column (mostly gas) and a special report was addressed to the authorities and general public through the IG-EPN webpage and social network accounts at 08:52. This report was sent by e-mail to the DPNG, the director of the Giant Tortoise Restoration Initiative (GTRI), and the University of Idaho. During the eruption, international colleagues helped IG-EPN monitor via satellite SO<sub>2</sub> emission (Oxford University, UK, since 26 May; Chalmers University, Sweden, since 29 May), thermal anomalies (Middle InfraRed Observation of Volcanic Activity MIROVA platform since 27 May) and ground deformation (University of Miami, FL, USA, since 9 June). The eruption lasted in total 36 days with two main phases of activity. The first involved eruption of lava from a circumferential fissure on the SE and E rim of the caldera, active from 25 May until 16 June. The second included lava flows from an intracaldera vent, active from 13 June until 30 June. The intracaldera activity was also preceded by a seismic swarm and was rapidly detected by satellite, in particular thermal anomalies that changed location from the SE flank to the caldera area [Bernard et al. 2019]. The IG-EPN participated in two field missions during the eruption (29 May and 12 June) to assess the eruptive activity and help the DPNG ensure that the endemic species, in particular Wolf unique pink iguana (*Conolophus marthae*), were not threatened by it. During the eruption, the IG-EPN was in regu-

\*[https://www.youtube.com/watch?v=m9Wi\\_K70A7Y](https://www.youtube.com/watch?v=m9Wi_K70A7Y)

lar contact by e-mail with the DPNG (Santa Cruz Environmental Management Office and Isabela Technical Office) and published two additional reports for the authorities and general public describing the evolution of the activity.

## 2.2 Wolf 2022 eruption

Between the 2015 eruption and 2022, Wolf volcano exhibited relatively slow ( $\sim 8 \text{ cm yr}^{-1}$ ) ground deformation that accelerated to  $\sim 30 \text{ cm yr}^{-1}$  around 12 December, 2021 pointing to the migration of magma from the sill-shaped reservoir 2 km below the caldera to an area identified as the southeast diffuse rift according to Geist et al. [2005] and located on the southeastern flank. After only three hours of seismic unrest characterized by discrete volcano-tectonic events detected by FER1 seismic station (Figure 1), the eruption started at 23:15 on 6 January 2022 coincident with the onset of tremor (Figure 3). Compared to the 2015 event, the seismic unrest in 2022 was about one order of magnitude smaller in amplitude. In addition, the onset of the 2022 eruption was less explosive. The eruption was rapidly noted in GOES-16 satellite imagery by the W-VAAC who issued a Volcanic Ash Advisory (VAA) at 00:20 on 7 January describing two ash-poor volcanic clouds at 5.5 and 3.7 km a.s.l. directed northeast and west respectively. Communications between the W-VAAC and the IG-EPN were carried out using the NWSchat, an instant messaging program utilized by the W-VAAC host agency in the US Government, the National Weather Service (National Oceanic and Atmospheric Administration). The eruption was visually confirmed by DPNG Rangers that were on a boat east of the volcano (Figure 4). A VONA was emitted by the IG-EPN at 02:29 to inform the civil aviation of the volcanic cloud. Instant messaging between the IG-EPN and the DPNG started at 02:39 on 7 January 2022. A short report (format called IGalinstante) announcing the beginning of the eruption was issued at 03:30 to the authorities, the public and international scientists. The IG-EPN issued a more detailed special report at 07:42, which was also shared widely with the public. Pictures taken during a helicopter flight to evacuate scientists and DPNG rangers from the Pink Iguana area (north of Wolf caldera) confirmed a radial fissure on the southeast flank and the advance of lava flows up to 9 km before 09:54. A videoconference meeting of the Galápagos Comité Operativo de Emergencia (COE) including all concerned authorities and emergency responders was held at 11:00 on 7 January to analyze the threat posed by the eruption to the local population and endemic wildlife. To help coordinate actions between the IG-EPN and the DPNG, a dedicated instant messaging chat was created. The IG-EPN started issuing daily reports to inform the authorities and public of the status of the eruption. The Servicio Nacional de Gestión de Riesgos y Emergencias (SNGRE) coordinated activa-

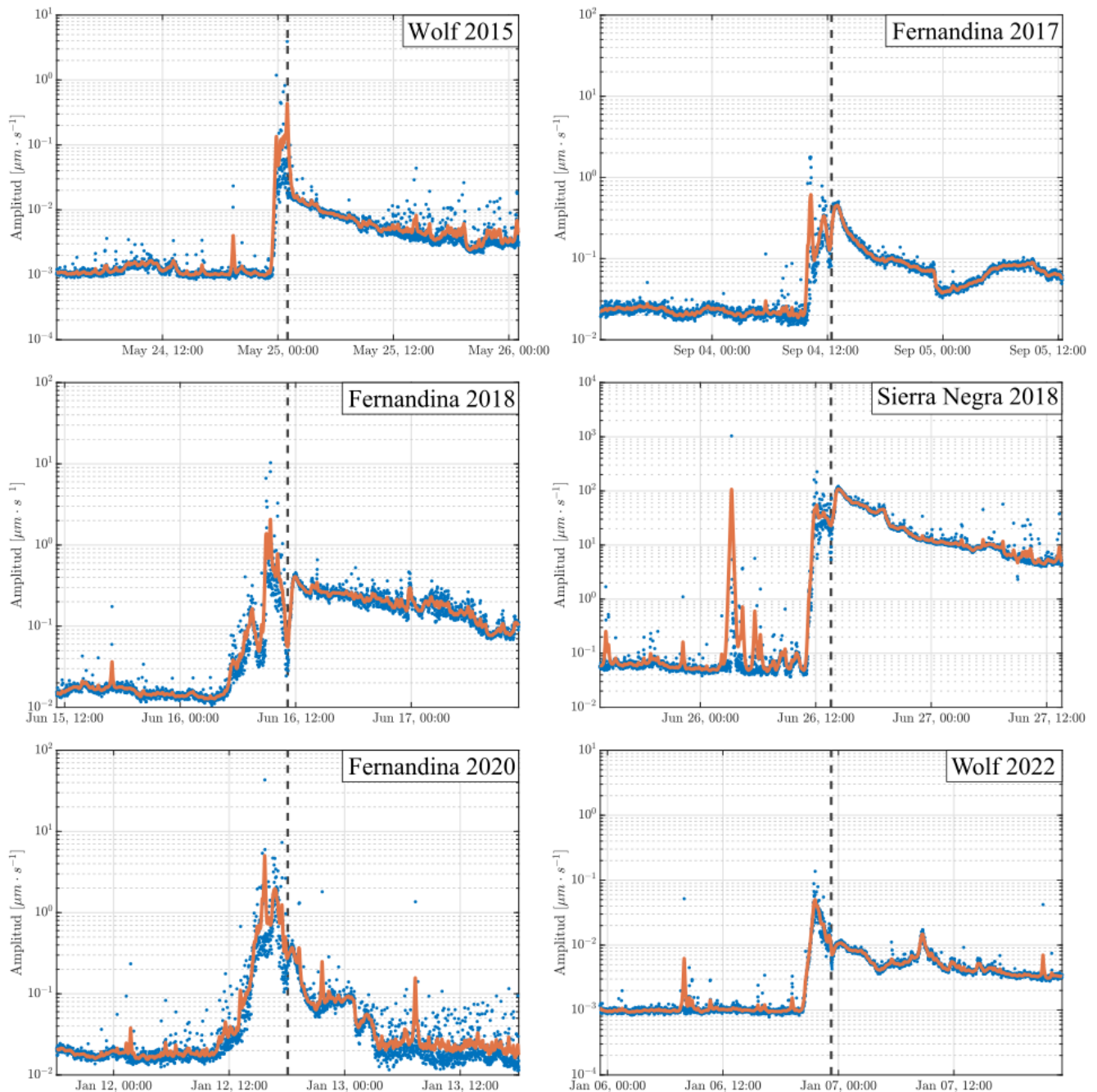
tion of the International Charter Space and Major Disasters\* in order to have access to additional satellite imagery to support monitoring and study of the eruption. Colleagues from the Universidad Nacional Autónoma de México (Mexico) added Wolf in the MOUNTS (Monitoring Unrest from Space) platform and surveyed the gas emissions ( $\text{SO}_2$ ) throughout the eruption. Thermal anomalies were analyzed by MIROVA platforms with the help of the Università degli Studi di Torino (Italy) for the estimation of the Time-Averaged Discharge Rate (TADR) and the cumulative volume of the eruption, while the FIRMS (Fire Information for Resource Management System) platform allowed to track the progression of the lava fields over time. The W-VAAC and the IG-EPN continued to emit VAA and VONA respectively until 8 January when the gas emission significantly decreased along with thermal anomalies. The first map of the eruptive fissures and associated lava field reaching a length of 16.5 km was included in the special report published on 13 January. Increased activity associated with the migration of the activity to a lower vent was communicated on 14–15 January in short reports. This activity implied the widening of the lava field without reaching the sea. At the time of writing in February 2022, the eruption was still ongoing and the lava field had already covered about  $20 \text{ km}^2$ .

## 3 CERRO AZUL 2017 UNREST

Cerro Azul (Latitude:  $0.942^\circ\text{S}$ , Longitude:  $91.404^\circ\text{W}$ , Altitude: 1647 m a.s.l.), is located on the southwestern tip of Isabela Island (Figure 1). According to the Global Volcanism Program [2013], it has had at least ten eruptions since 1932, making it one of the most active volcanoes in the Galápagos Archipelago. Its recent eruptions in 1998 and 2008 were observed in near-real time by satellite [Mouginis-Mark et al. 2000; Rowland et al. 2003; Teasdale et al. 2005; Galetto et al. 2020]. Results of these studies have significantly improved the understanding of the magmatic system and eruptive activity of Cerro Azul. For the 2008 eruption, the PAYG seismic station (Figure 1) helped pinpoint the onset of activity at 21:43 on 29 May. However, due to the distance from the volcano ( $\sim 120 \text{ km}$ ), the station did not record any pre-eruptive activity.

The 2017 unrest was the first activity detected on this volcano since the start of continuous ground-based geophysical monitoring in Galápagos. Unfortunately, the seismic sensor on the north flank of the volcano (CEAZ) was not functioning at the time of the unrest, so earthquakes were detected using the Sierra Negra network (VCH1 and PVIL in Figure 1). Seismic activity began in February with two swarms of small volcano-tectonic earthquakes on 15 and 16 March. Then, seismicity decreased before a rapid increase at 05:30 on 18 March, reaching a peak on 20 March with a M3.7 earthquake

\*<https://disasterscharter.org/>



**Figure 3:** Selected seismic records of recent eruptions of Galápagos volcanoes. Blue dots correspond to the mean of absolute amplitude for a 60 seconds window length and orange line to a 30 minute average. Filtering of the seismic signal to avoid seismic noise mostly depends on the distance between the eruption site and the seismic station. Wolf 2015 and 2022 were recorded at FER1 seismic station (~33 km) and filtered between 5 and 7 Hz. Fernandina 2017 was recorded at FER2 (~15 km) seismic station and filtered between 2 and 8 Hz. Fernandina 2018 and 2020 were recorded at FER1 seismic station (~13 km) and filtered between 2 and 8 Hz. Sierra Negra 2018 was recorded at VCH1 (<1 km) seismic station and filtered between 0.5 and 16 Hz. The vertical dotted lines indicate the onset of the eruption.

at 06:35. This activity led of the IG-EPN to issue a special report that concluded a future eruption as the most likely outcome of the seismic unrest. The report also mentioned a lateral intrusion (i.e. magma moving from the main reservoir to the flank of the volcano) as a less likely scenario. This report was transmitted

to the DPNG by e-mail. A further increase in seismic activity and the appearance of a spasmodic tremor on 21 March at 18:15 triggered release of a short report (IGalinstante) at 20:47 indicating that this signal could be the precursor of eruptive activity. Scientists from the University of Leeds (UK) calculated a Sentinel-1 in-



Figure 4: [Caption on next page.]

**Figure 4:** [Previous page.] Pictures of the recent eruptions of Galápagos volcanoes. Wolf 25/05/2015: circumferential fissure feeding a 150 m-high lava curtain. Fernandina 04/09/2017: 3.5 km a.s.l. gas emission associated to the circumferential eruption close to the caldera. Fernandina 16/06/2018: radial fissures and lava flows coming down the north flank of the volcano. Sierra Negra 26/06/2018: circumferential fissure and lava flows entering the caldera. Fernandina 12/01/2020: lava flows coming down the eastern flank of the volcano. Wolf 07/01/2022: radial fissure and lava flows coming down the southeastern flank of the volcano.

terferogram from 8 to 20 March immediately after being informed of the seismic unrest by IG-EPN (COMET, 2017). Based on their results, the seismic activity was associated with 11 cm of deflation centered on the caldera and 14 cm of inflation located on the southeast flank near the sea. This information was communicated in a second special public report. Preliminary deformation analysis supported the model of a lateral sill-type intrusion draining the magma reservoir beneath the caldera (COMET, 2017). Seismicity and ground deformation yielded the same location between 3.5 and 6.3 km beneath the southeast flank. During a visit by DPNG rangers to the area, no surface changes were noticed. After 26 March, seismicity decreased and the last special report on this event mentions that the most likely scenario was no longer an eruption but rather a decrease in activity to background levels. This report was transmitted by e-mail to the DPNG and shared with the public through the IG-EPN webpage and social network accounts. Ground deformation in April was minimal and seismicity returned to baseline by the end of May. Subsequently, the event was classified as a non-eruptive unrest (i.e. intrusion). Guo et al. [2019] further calculated the sources of the deformation and estimated the volume of the intrusion at 60 million m<sup>3</sup>.

## 4 FERNANDINA RECENT ERUPTIONS

Fernandina/La Cumbre volcano (Latitude: 0.353°S, Longitude: 91.525°W, Altitude: 1481 m a.s.l.) is the lone shield volcano on Fernandina Island. It experienced between 27 and 29 eruptions since 1813 [Global Volcanism Program 2013; Vasconez et al. 2018] from which 18 occurred since 1944. Accordingly, Fernandina has the highest historical eruptive frequency of the Galápagos volcanoes. Three eruptions occurred in the last ten years, after the installation of two permanent seismometers on the volcano, allowing—for the first time—details to be recorded about the eruptive processes and associated phenomena [Vasconez et al. 2018].

### 4.1 Fernandina 2017 eruption

After eight years of quiescence, Fernandina erupted on 4 September, 2017. Precursors included 17 cm of uplift of the caldera floor from March 2015 to September 2017, of which 5 cm occurred in the last two months prior to the eruption. The period of recorded seismic unrest was extremely short, with a swarm of hybrid

earthquake noted at 09:55 on 4 September and peaking at 10:20 (Figure 3). Retrospective analyses of the seismic records show that the swarm probably started around 5:34 with small events [Vasconez et al. 2018]. At 11:25 the seismicity switched from hybrid to low-frequency events and at 12:25 volcanic tremor associated with the onset of the eruption was recorded. The eruption was confirmed by GOES-16 satellite at 12:30 and, due to mainly the gas emission (Figure 4), a VONA was also issued at 14:54. The first special report on the eruption was sent to DPNG at 15:34 and then published more broadly at 15:58. A second VONA was issued at 16:25 and included information about the eruptive column height and volcanic cloud dispersion from the W-VAAC. The eruption occurred on the southwestern upper flank through a circumferential fissure and lasted only three days. During this period, instant messaging between the DPNG and the IG-EPN was used frequently to answer questions about false news reports and to inform the DPNG about the decrease of the eruption intensity. A second special report informing about the decrease of the eruption was sent to the DPNG on 6 September at 17:45 before being published on the IG-EPN website and social network accounts. Maps of the lava fields and wildfires were sent to the DPNG by e-mail on 19 September and 12 October.

### 4.2 Fernandina 2018 eruption

Only nine months after the 2017 eruption, Fernandina reawoke in June 2018. No significant deformation occurred during the inter-eruptive period [Vasconez et al. 2018]. The seismic unrest prior to the June eruption started around 08:37 on 16 June and was detected early enough to issue a warning to the authorities and general public before the onset of the eruption (Figure 3). The largest earthquake (M4.1) during the seismic unrest occurred at 09:22 and was located to the northeast of the volcano. The DPNG was directly informed about the ongoing seismic swarm and possibility of renewed eruption on 09:26. Two large earthquakes (M2.9 and M3.4) were communicated to the public through the publication of earthquake reports at 09:52 and 10:43, respectively. The eruption started around 11:15 while the IG-EPN staff was preparing a special report on the unrest. A second special report was published immediately after (12:43) to announce the eruption onset. Back and forth communication with the DPNG who had rangers in the field helped to characterize the development of the eruption that occurred on the north

flank through a radial fissure (Figure 4). Lava entering the sea triggered the publication of a third special report at 14:26 to inform about hazards associated with this phenomenon. Instant messaging with the DPNG and public communications (two additional special reports) continued throughout the two day-long eruption to describe the eruptive activity and eventually its termination on 18 June. Additionally, a GOES-16 satellite imagery animation was published on social network accounts for scientific outreach purposes.

### 4.3 Fernandina 2020 eruption

During the 19 months of quiescence following the 2018 eruption, 30 cm of inflation of the caldera floor was observed using InSAR. Minor seismic unrest was discussed with colleagues from the University of Edinburgh (UK) as early as 10 December. The peak of seismicity occurred on 28 December, characterized by a series of six earthquakes up to M4.3. This observation was shared with the DPNG and the public through a short report. On 12 January 2020, more intense seismic unrest started around 09:00 and peaked at 16:42 with a M4.7 earthquake (Figure 3). At 17:27 a second short report was sent to the DPNG as well as the public to describe the possibility of an upcoming eruption. The eruption started less than an hour later between 18:00 and 18:10 on a circumferential fissure located on the upper eastern flank. Eruption onset was detected using satellite imagery (GOES-16) and described in a special report published at 20:19. Back and forth communication with the DPNG helped confirm the exact eruption site (Figure 4). On 13 January, instant messaging was used to inform the DPNG of the decrease of activity and a special report was published to officially announce the end of the eruption that lasted only 9 hours. Although the surface activity (lava and gas emission) ended on 13 January, internal unrest, including strong ground deformation and seismicity, continued for weeks afterward. The possibility of resumed eruption was discussed in a special report published on 23 January. Further communication with the DPNG included numerous informal messages regarding ongoing seismicity through March. Although seismicity decreased thereafter, continued ground deformation and low seismicity prompted the publication of a special report on 12 November, 2021 suggesting the possibility of renewed eruption in the medium to long term (weeks to years).

## 5 SIERRA NEGRA 2018 ERUPTION

The Sierra Negra (Latitude: 0.782°S, Longitude: 91.139°W, Altitude: 1139 m a.s.l.) eruption in 2018 was the most anticipated in Galápagos for various reasons. Sierra Negra is the only active volcano in Galápagos with frequent historical eruptions (11–13 eruptions

since 1813 [Global Volcanism Program 2013]) that has a town, Puerto Villamil (~3000 inhabitants), and agricultural areas on its southern flank. Sierra Negra is also one of the most visited volcanoes of the Archipelago. Although recent eruptions mostly affected the uninhabited northern flank and caldera floor (Figure 1), an eruption on the southern flank could potentially significantly disrupt the economic activity on Isabela Island and even destroy many homes such as the recent Kīlauea 2018 [Neal et al. 2019] and La Palma 2021 [Rodríguez-Hernández et al. 2022] eruptions.

### 5.1 Long-lasting unrest

From its last eruption in 2005 [Geist et al. 2008] until 2018, Sierra Negra experienced greater than 6.5 m of uplift of its caldera floor [Vasconez et al. 2018; Bell et al. 2021a; b]). It also experienced two years of increasing seismicity including numerous felt earthquakes. The first major earthquake swarm prior to the 2018 eruption was detected on 19 October 2017, the swarm included a 16 km-deep M3.8 earthquake that was immediately reported to the authorities and the general public. Colleagues at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami (USA) helped characterize  $>70 \text{ cm yr}^{-1}$  of uplift of the caldera floor in 2017 using InSAR. The occurrence and location of each  $M>3$  earthquake was communicated directly to the DPNG. In January 2018, the IG-EPN installed ashmeters on Sierra Negra volcano and participated in a field campaign to improve the GPS and seismometer telecommunication links. Due to the unrest, the SNGRE declared a yellow alert for the area of influence of Sierra Negra on 16 January, 2018. Following IG-EPN recommendations and the change of color of the alert by the SNGRE, as a safety measure, the DPNG restricted visits to the volcano to the southeast rim of the caldera beginning on 17 January, 2018. A gravity survey was completed in February 2018. In April 2018, a 14-station seismic network was installed as part of the IGUANA project [Bell et al. 2021a]. In total, eight special reports were published from October 2017 to June 2018 to describe the unrest. These reports were primarily intended for the DPNG, but were also shared with the public through the IG-EPN webpage and social network accounts. In the special report of 19 March, 2018, the IG-EPN described the state of the volcano along with possible eruptive scenarios ordered by decreasing probability. In this report, the most likely scenario at medium term (weeks to months) was a moderate-size eruption occurring inside the caldera and/or on the northeast and northwest flanks.

### 5.2 Expected and unexpected events

Although all eyes were focused on Sierra Negra for several months, the lead-up to eruption was abrupt. On

26 June, 2018 at 03:15, a M5.3 earthquake located in the caldera probably initiated the eruptive sequence (Figure 3). The earthquake magnitude and location were published on social networks at 03:22 and transmitted to the DPNG via instant messaging. A special report was issued at 05:59 indicating that the earthquake and further seismic tremor could be precursor of eruptive activity. A seismic swarm started at 10:17 and, according to satellite imagery, the eruption began around 12:45 (Figure 3). Thanks to the constant communication between the IG-EPN and the DPNG who had rangers in the area, the site of the eruption (northeast flank close to Volcán Chico) was confirmed (Figure 4). Several special reports were published in the hours after the beginning of the eruption to inform about its evolution. Several fissures opened on the northern flank and a VONA was issued at 16:03 to inform civil aviation about a 10 km a.s.l. gas plume directed toward the southwest. At 16:45, the SNGRE changed the volcanic alert color to orange. Thanks to the inter-institutional coordination of the crisis between the SNGRE, the DPNG and the IG-EPN, a field mission was carried out on 27 and 28 June to evaluate the situation and participate in the meeting organized by the COE. The site of the eruption was made off-limits to the public along with other touristic sites that were partially re-opened on 3 July. After the first day of eruption, which occurred through a wide area spreading from the Volcán Chico touristic site located on the northeast side of the caldera to fissure 5 located on the western flank of the caldera, the eruption focused on the north-northwestern lower flank of the volcano (fissure 4) and continued from there until 23 August (Figure 1). Daily reports issued by the IG-EPN ensured continuous information about the status of the eruption. Throughout the eruption, instant messaging was used to communicate with the DPNG and special reports were published to inform about major pulses of activity. On 31 August the last special report confirmed the end of the eruptive activity.

### 5.3 In-depth post-eruption field studies

Thanks to the well-documented unrest and eruptive processes, the 2018 eruption of Sierra Negra was the target of numerous field missions in order to complement the abundant geophysical results [Gaddes et al. 2019; Hedelt et al. 2019; Bell et al. 2021a; b; Davis et al. 2021; Sandanbata et al. 2021]. Gravity surveys were also carried out in August 2018, January and November 2019, and February 2022. Thermal and visual imaging of the fissure and lava fields using Unoccupied Aerial Vehicles (UAV) were realized as early as 28 June and completed by different groups in October 2018 [Carr et al. 2021] and March 2020. Numerous lava and tephra samples from the eruptive were also obtained from the different fissures to support studies of the magmatic storage system, eruptive discharge rate and lava rhe-

ology. Those field missions were coordinated with the DPNG within the framework of the inter-agency agreement and research projects with *ad hoc* research permits.

## 6 VOLCANIC EVENT MANAGEMENT

### 6.1 Monitoring successes and challenges

Over the past decade, the IG-EPN, in collaboration with DPNG, has installed and maintained a distributed, multi-parametric monitoring network in the Galápagos Archipelago that has tracked the unrest and eruptions at four active volcanoes (Wolf, Cerro Azul, Fernandina, and Sierra Negra): a challenging task in these remote locations (Table 1). During this period, the IG-EPN also increased its capacity in using satellite remote sensing to complement the ground-based geophysical monitoring data.

Long-term unrest, typically lasting from months to years, have mainly manifested in inflationary ground deformation (Wolf 2015 and 2022, Sierra Negra 2018, Fernandina 2017 and 2020), and sometimes by elevated seismicity (Sierra Negra 2018, Fernandina 2020). The rate of ground deformation would sometimes accelerate in the weeks or months before the eruptions (Sierra Negra 2018 and Wolf 2022); use of these datasets are challenged by limits on frequency of image acquisition and computational power to conduct image processing. Such issues could be partially resolved by strengthening international cooperation and through further training [Ramon et al. 2021]. Currently, a project between the IG-EPN and UNAVCO\* is attempting to implement the telemetry for the GPS network that will allow for near-real-time assessment of the ground deformation.

Short-term unrest, which typically lasted from a few hours to weeks, were all characterized by seismic swarms, sometimes preceded by or including large ( $M > 4$ ) earthquakes (Wolf 2015, Fernandina 2018 and 2020, Sierra Negra 2018). Although the threat level of active volcanoes in Galápagos is low due to small nearby population and the absence of critical infrastructure [Santamaría and Bernard 2018], with the exception of Sierra Negra; as potentially active and dangerous volcanoes, they should all have an elementary seismic monitoring with real-time data transmission [Lowenstern et al. 2022]. Historic eruptions from Santiago, Marchena, and Pinta volcanoes along with recent lava fields on Darwin, Ecuador, and San Cristóbal volcanoes should motivate urgent reinvestment into improving real-time geophysical monitoring infrastructure. This would allow for more timely short-term early warning of seismic unrest. Installing and maintaining a larger ground-based monitoring network would be a human and financial challenge for the IG-EPN and its

\*<https://www.unavco.org/>

allies [Ramon et al. 2021]. The 2015 and 2022 Wolf eruptions helped the IG-EPN to push the monitoring capabilities to their limits, using distal seismic sensors to obtain meaningful information about the timing of the eruption in combination with different satellite information. Nevertheless, both eruptions were reported several hours after the beginning of the seismic unrest due to the difficulty in interpreting the noisy seismic records. Figure 3 shows that, with adequate filtering, short-term seismic unrest occurred up to a few hours before all eruptions. An additional challenge is to implement automatic alarms based on artificial intelligence to alert the IG-EPN staff when the seismic activity exceeds a threshold defined for every seismic station. The recent eruptions of Wolf, Fernandina, and Sierra Negra should make it possible to parameterize the automatic alarms, but this could be much more difficult for other volcanoes such as Cerro Azul and Alcedo where no eruptions have occurred since the installation of the permanent monitoring network. An additional challenge for the IG-EPN, which is an academic department and not a governmental agency, is when eruptions occur at night (Wolf 2015 and 2022) or over the weekend (Wolf 2015, Fernandina 2018 and 2020), highlighting the need for strengthened 24/7 surveillance and development of alarms.

During this period, the increased use of satellite data complemented the information provided by ground stations, allowing confirmation and follow-up of the eruption (volcanic clouds, gas emission, thermal anomalies, and lava field). For this aspect, international collaborations (W-VAAC and universities) have been essential to monitor the Galápagos volcanoes with the most advanced remote sensing platforms. The close relationship between the IG-EPN and the DPNG also allowed a continuous stream of information on the eruptions that greatly improved their monitoring and hazard assessment. Inter-institutional coordination and the agreement with the DPNG allowed the IG-EPN staff to travel to the eruption site on several occasions for additional data collection, including sampling. A key to the success of monitoring volcanic events at Galápagos is to maintain and strengthen these collaborations over the long term.

An important product of the volcanic monitoring is the interpretation of the precursory signals and its translation to potential eruptive scenarios. Comparing the characteristics of the Sierra Negra 2018 eruption from Vasconez et al. [2018] to the most likely scenario published on 19 March (three months before the eruption), we found that the initial location of the eruption was accurate (Volcán Chico) as well as the area reached by the lava flows (mostly on the north and northwestern flanks, up to Elizabeth Bay and within the caldera) but the volume ( $189 \pm 89$  million  $m^3$  compared to 40–150 million  $m^3$ ) and area (30.6 million  $m^2$  compared to 10–20 million  $m^2$ ) of the lava fields were slightly underestimated. The duration of the eruption (eight

weeks) was also underestimated, and the most unexpected part was a small fissure opening on the western flank close to the Minas de Azufre site very far from the main fissures (Figure 1). The experience gained in every volcanic event is likely to improve the forecasting skills of the staff in charge as long as such experience is shared and discussed among peers. Recent publications co-authored by the IG-EPN on the Galápagos eruptions prove that it is possible to combine continuous surveillance and hazard communication with scientific research [Stock et al. 2018; Vasconez et al. 2018; Bernard et al. 2019; Stock et al. 2020; Bell et al. 2021a; Carr et al. 2021]. In terms of eruptive scenarios, although the prospect of explosive eruptions—such as Fernandina in 1968 [Howard et al. 2019]—is considered in the IG-EPN special reports, their communication and preparation with the authorities is insufficient, likely due to their low probability. An effort should be made to improve collective awareness about these hazardous phenomena and to prepare the response in case an explosive event occurs.

## 6.2 Communication strategy

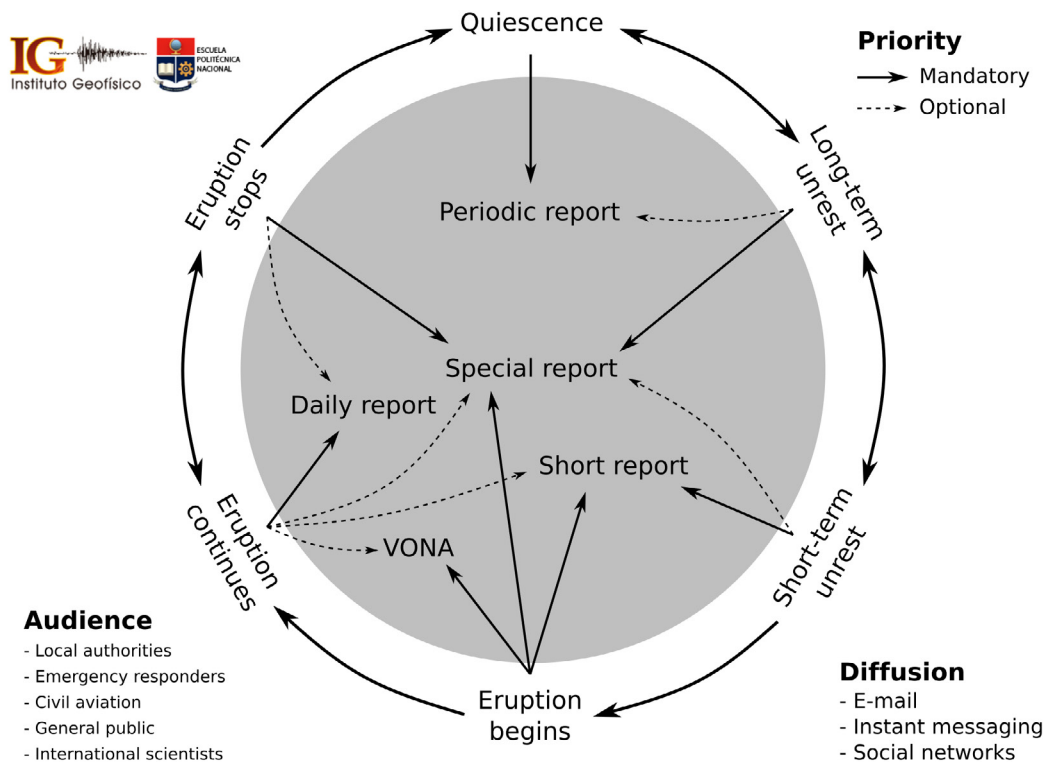
The recent periods of volcanic unrest and eruption at Galápagos volcanoes tested Ecuador's inter-institutional coordination and public communication protocols, highlighting the need for continuous and relevant information streams. Evidence of improving communication protocols and methods includes moving from a post-eruption notice (Wolf 2015 and Fernandina 2017) to pre-eruption, early warnings (Sierra Negra 2018 and Fernandina 2020). Communication during unrest at Cerro Azul 2017, Sierra Negra 2018, and Fernandina 2020, and immediately after the start of the eruptions at Fernandina 2018 and Wolf 2022 helped increase the trust of the authorities and the public in IG-EPN. Communication products have evolved to include short, easy-to-share messages that are quickly disseminated on social media. Feedback from the authorities and the general public through the social network accounts helped improve the format quality, relevance, and timeliness of the IG-EPN reports. The need for continuous information has been satisfied by the use of daily reports (Informe Diario) for erupting volcanoes (Sierra Negra 2018, Wolf 2022). These semi-automated daily reports include information from the geophysical monitoring network, satellite remote sensing, and direct observations of the eruption (e.g. DPNG reports). The use of short factual reports (IGalinstante) has shortened the time between the event and its publication (Table 1). Both daily reports and IGalinstante are written by monitoring staff according to templates prepared in advance and reviewed by the volcanologist in charge before publication. Special volcanic reports (Informe Volcánico Especial) are prepared by the volcanologist in charge with help of different specialists for the different monitoring techniques used. They present a

**Table 1:** Summary of recent volcanic events in the Galápagos Islands and communication products. M = Magnitude. Ground deformation is mostly detected by InSAR, except for Sierra Negra where GPS networks are also used.

Volcano (eruption)	Long-term unrest	Short-term unrest	Eruption duration	Lava field (km <sup>2</sup> )	Special Reports	VONA	Short report	Daily Reports
Wolf (25/05/2015)	Ground deformation	Seismic swarm (~1:50) up to M4.4	36 days	24.0	3	1		
Cerro Azul (03/2017)*		Ground deformation and Seismic swarms			3		1	
Fernandina (04/09/2017)	Small ground deformation	Seismic swarm (~2:55)	3 days	6.5	2	2		
Fernandina (16/06/2018)		Seismic swarm (~6:40) up to M4.1	3 days	1.6	5			
Sierra Negra (26/06/2018)	Large ground deformation and sustained seismicity	Ground deformation, seismic swarm (~2:50) preceded by M5.3	58 days	30.6	22	9	2	71
Fernandina (12/01/2020)	Small ground deformation and seismicity	Seismic swarm (~7:25) up to M4.3	1 day	1.6	3		5	
Wolf** (06/01/2022)	Small ground deformation	Ground deformation, seismic swarm (~3:05)	>36 days	19.9	2	7	3	>36

\* Cerro Azul 2017 is classified as a non-eruptive unrest.

\*\* Wolf 2022 eruption is ongoing at time of writing in February 2022.



**Figure 5:** IG-EPN communication plan for Galápagos and Mainland Ecuador based on volcanic status. The arrows connecting the volcanic status can go in both directions for non-eruptive unrest and when eruption stops and resumes. Optional reports depend on the size and evolution of the volcanic events.

broader and more detailed descriptions of the eruptive process. Sometimes they also include hazard scenarios and recommendations for the authorities and the general public. The current IG-EPN communication plan for Galápagos and Mainland Ecuador (Figure 5) has been designed to improve public trust in official sources and counter the problem of fake news. This communication plan includes:

1. periodic (monthly or annual) reports for quiescent volcanoes (pending);
2. special reports for unrests and eruptions, which include a detailed factual description and interpretation of volcanic activity;
3. short report (IGalinstante), which inform of special events (e.g. large earthquake, seismic swarm, eruption) which necessitate immediate notification;
4. VONA for civil aviation; and
5. daily reports when the eruption lasts for several days in order to maintain a continuous flow of information.

An essential part of any communication strategy is to identify the recipients of the information and the channels of dissemination (Figure 5). The audience includes the authorities (DPNG, Consejo de Gobierno de Régimen Especial de Galápagos, mayors, national government, SNGRE, Dirección General de Aviación Civil), emergency responders (ECU911, Cruz Roja Ecuatoriana, police, firefighters, army), the W-VAAC, the general public, and international scientists. Direct communications of critical information to the authorities, in particular the DPNG, have benefited from the use of instant messaging applications. Over the past decade, IG-EPN has positioned itself at the forefront of social media in Ecuador by accumulating over 3 million followers across platforms. It also gained visibility in the traditional media (print, radio, TV) by structuring its response to them through EPN's Institutional Relations Direction and by using designated speakers, single voice messages, and press conferences. Accordingly, the IG-EPN follows most of the guidelines for volcano observatory operations during crises [Lowenstern et al. 2022]. Nevertheless, challenges remain such as the education of the public on volcanic hazards, addressing false information in social media, and maintenance of the communication channels with the authorities that can change with every election.

## ACKNOWLEDGEMENTS

The authors thank the IG-EPN staff in charge of installation and maintenance of the ground-based geophysical instruments that allowed follow-up of unrest periods and eruptions at Galápagos volcanoes. The authors also thank the IG-EPN staff in charge of monitoring and communicating the volcanic events. The

DPNG and the Ecuadorian Navy are acknowledged for the logistic support during field missions. The SNGRE is acknowledged for the inter-institutional coordination during volcanic crisis. The authors also thank Dennis Geist, Falk Amelung, Mike Stock, Andy Bell, Diego Coppola, Peter Lafemina, Marco Bagnardi, Simon Carn, Sébastien Valade, Santiago Arellano, Bo Galle, and Elisa Carboni, who helped in the monitoring of Galápagos volcanoes. Part of this work was funded by an EPN junior grant (PIJ-18-02) and by the National Planning Secretariat (SENPLADES). The authors gratefully acknowledge Tina Neal and Dennis Geist for their thoughtful reviews that improved the quality of this manuscript.

## AUTHOR CONTRIBUTIONS

All authors contributed to the preparation and drafting of various parts of the manuscript. They also participated in the elaboration of the various reports used throughout this manuscript. BB drafted the manuscript, compiled the information on the study cases and created the figures, except Figure 3. PR and GV compiled the information on the communication processes. LG provided the information concerning the DPNG actions. SH(1) provided the seismic data and Figure 3. FJV provided the maps of the recent lava fields, except for Wolf 2015. SH(2) helped design the communication protocol.

## DATA AVAILABILITY

All the reports, except VONA, published by the IG-EPN on the different volcanic events are accessible in the IG-EPN website (<https://www.igepn.edu.ec/servicios/busqueda-informes>). Seismic data for Figure 3 are available by simple request to the corresponding author. Examples of IG-EPN reports are provided as [Supplementary Material](#) alongside the online version of this article.

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