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To cite this version:

Silvana Hidalgo, Francisco J Vasconez, Jean Battaglia, Benjamin Bernard, Pedro Espín, et al.. Sangay volcano (Ecuador): the opening of two new vents, a drumbeat seismic sequence and a new lava flow in late 2021. Volcanica, 2022, 5 (2), pp.295-311. 10.30909/vol.05.02.295311 . hal-03881769

HAL Id: hal-03881769
https://uca.hal.science/hal-03881769

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Sangay volcano (Ecuador): the opening of two new vents, a drumbeat seismic sequence and a new lava flow in late 2021

Silvana Hidalgo*[α], Francisco J. Vasconez†[α], Jean Battaglia[β], Benjamin Bernard[α], Pedro Espín[α], Sébastien Valade[γ], María-Fernanda Naranjo[α], Robin Campion[γ], Josué Salgado[α], Marco Córdova[α], Marco Almeida[α], Stephen Hernández[α], Gerardo Pino[α], Elizabeth Gaunt[α], Andrew Bell[δ], Patricia Mothes[α], and Mario Ruiz[α]

[α] Instituto Geofísico de la Escuela Politécnica Nacional, Quito, Ecuador.
[β] Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, Clermont-Ferrand, France.
[γ] Instituto de Geofísica, Universidad Nacional Autónoma de México, Mexico City, Mexico.
[δ] School of GeoSciences, University of Edinburgh, Edinburgh, UK.

Abstract

On 2 December, 2021 we recorded a sequence of drumbeat seismic events at Sangay volcano. This sequence lasted several hours and resulted in two explosive emissions whose eruptive columns reached 9 km above crater. Unexpectedly, these explosions did not produce any ash fallout in the inhabited areas around the volcano. This drumbeat sequence was produced after a series of morphological changes, including the opening of two new vents (W and N) and a landslide. These occurred during an enhanced period of ground deformation and degassing. Further analysis of satellite images allowed us to determine that this sequence was associated with the widening of the recently open vent to the north of the main crater and the extrusion of a new lava flow. Timely communication of this event to the authorities and the population was ensured by the IG-EPN by following internal protocols. The corresponding short reports reached more than 300,000 people.

Resumen

El 2 de diciembre de 2021, registramos una secuencia de eventos sísmicos tipo *drumbeat* en el volcán Sangay. Esta secuencia duró varias horas y dio lugar a dos emisiones explosivas cuyas columnas eruptivas alcanzaron 9 km sobre el nivel del cráter. Inesperadamente, estas explosiones no produjeron caída de ceniza en las poblaciones aledañas al volcán. Esta secuencia de *drumbeat* se produjo después de una serie de cambios morfológicos que incluyen la apertura de dos nuevos cráteres (W y N) y un deslizamiento. Éstos ocurrieron durante un período de mayor deformación y desgasificación. El posterior análisis de imágenes satelitales permitió determinar que esta secuencia estuvo asociada al ensanchamiento del cráter recientemente abierto al norte del cráter principal y a la extrusión de un nuevo flujo de lava. El IG-EPN se encargó de comunicar oportunamente este evento a las autoridades y a la población siguiendo los protocolos internos. Los correspondientes informes llegaron a más de 300.000 personas.

Keywords: Sangay; Drumbeat sequence; Lava flow; Morphological changes; Rapid public outreach; Volcano monitoring.

1 Introduction

Sangay is a 5286-m-high andesitic stratovolcano located in the southern part of the Ecuadorian Andes, about 200 km south of the capital city of Quito (Figure 1A). Historically, Sangay has been almost constantly active with variable periods of quiescence [Global Volcanism Program 1976; Monzier et al. 1999; Vasconez et al. 2022] and has had at least 9 major eruptions since 1628 [Global Volcanism Program 1996; Monzier et al. 1999]. Sangay has been instrumentally monitored by the *Instituto Geofísico* of the *Escuela Politécnica Nacional* (IG-EPN) since 2013. In May 2019, Sangay began a new eruptive period, which is still ongoing (September 2022) and has been categorized as the most intense in the last six decades [Vasconez et al. 2022, IG-reports‡]. Explosions, ash and gas emissions, lava fountaining, lava flows and associated pyroclastic currents and secondary lahars characterize this period [Vasconez et al. 2022].

Since May 2019, seven episodes of increased activity have been registered. These episodes lasted typically hours and occurred on 8–9 June and 20 September 2020, and on 5–6, 11 March, 12 April, 7 and 30 May 2021. They were characterized by long lasting tremor and ash emissions.

Despite the remote location of the volcano, its ongoing activity has had a negative impact on the surrounding populations [SNGRE 2019; Jara 2020; Sandoval 2021, IG-reports]. Ash fallout associated with the phases of increased activity have affected and continue to affect inhabited areas, mainly to the west of the volcano, which is the prevailing wind direction, reaching as far as 280 km from the vent [Bernard et al. 2022, IG-EPN reports]. Agriculture and cattle-rearing are the main economic activities impacted by ash fallout. In addition, the international airport of Guayaquil had to be closed on five separate occasions due to ash fallout, and flights had to be canceled due to the presence of volcanic ash in the atmosphere. Moreover, to the southeast of the volcano, a deep and wide ravine has been progressively excavated. This phenomenon is probably produced by the high rate of lava extrusion and

* shidalgo@igepn.edu.ec
† fjvasconez@igepn.edu.ec
‡ https://www.igepn.edu.ec/servicios/busqueda-informes

Editor: F. Wadsworth | Typesetter: J. Farquharson

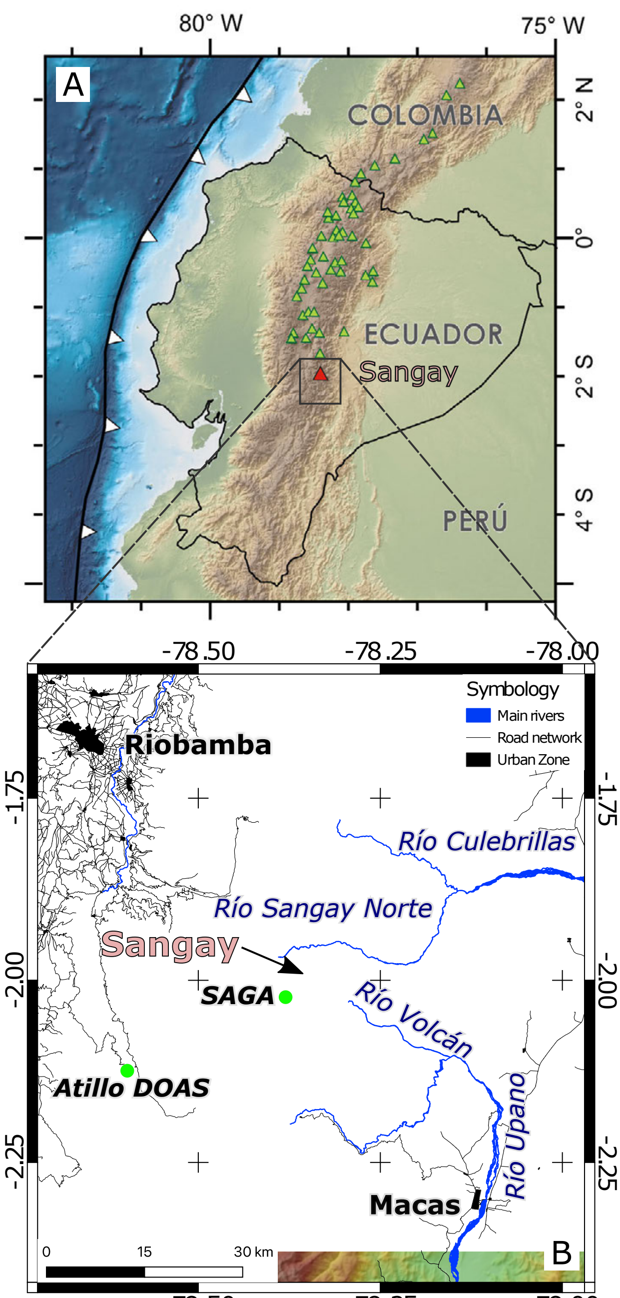

Figure 1: [A] Location of Sangay volcano in the Ecuadorian volcanic arc; [B] Monitoring instruments (green dots), main rivers (in blue) and populated areas are represented as black zones.

consequent lava front collapses, which generate multiple erosive pyroclastic currents [Vasconez et al. 2022]. Another hypothesis explaining the deepening of the ravine could be the thermo-mechanical erosive action of lava flows and pyroclastic currents, similar to that described by Gallant et al. [2020] at Momotombo volcano (Nicaragua). The loose new volcanic deposits and debris have been mobilized by rain, generating secondary lahars, which transport the blocks and ash downstream into the Upano River, forcing the closure of the Macas-Puyo road bridge (45 km downstream, Figure 1B) on at least eight occasions.

Ground-based monitoring at Sangay is limited due to the remoteness of the volcano; in particular, limited access makes the installation of instruments extremely difficult. Additionally, real-time transmission of data is only possible by satellite link. Given these conditions, the volcano is monitored by a very modest local instrumental network, but it is complemented by data provided via satellite remote sensing instruments.

Since the last regional ash-fallout produced during the eruptive phase of March–May 2021, the activity of Sangay volcano has been predominantly characterized by almost continuous Strombolian-type activity and the intermittent effusion of lava flows down the southeastern flank. Since July 2021, the monitoring data showed a clear increase in the number of small explosions, which were confirmed by visual observations through the cameras of the ECU-911 surveillance system. From 25 July to 9 August 2021 a thick lava flow was emitted through the central vent and emplaced in the southeastern ravine. The lava covered an area of 125,000 m^2 and its maximum runout distance was 0.8 km according to an estimation performed using the Planet Explorer image [Planet Team 2017] from 4 August, 2021. The flow was observed and reported on various occasions by the inhabitants of Macas, the closest city to the volcano at 45 km to the southeast (Figure 1B). During this period and until the end of November 2021, most of the eruptive activity at Sangay was generally low and gradually the lava flows and pyroclastic material began to fill the southeastern ravine.

On 1 December, from around 19:20 UTC, the seismic recordings of SAGA station began to show transient events occurring regularly. These events persisted for the next 13 hours with an irregularly accelerating rate of occurrence and increasing amplitude before merging into tremor at around 08:20 (UTC) on 2 December. This is the first sequence of drumbeat seismic events observed at Sangay volcano since the volcano has been instrumentally monitored. This sequence was rapidly followed by two explosive emissions, which were observed by the GOES-16 satellite, the first one at 09:02 (UTC) and the second at 09:13 (UTC). The emissions produced a 14.5 km-high gas-rich, ash-depleted eruptive column without any associated regional fallout reported. Additionally, satellite images from Sentinel-2 (SWIR bands) on 2 December show a strong thermal anomaly related to the presence of a new lava flow on the northern flank of the volcano. In this article, we describe in detail a time series of the most notable volcanic events during the days before and after the recorded drumbeat sequence at Sangay and the surface phenomena and morphological changes related to the opening of the new vents occurring during an ongoing active period. In order to put the changes observed at each monitored parameter into context, we plot time series since January 2021 and highlight the main preceding phenomena. We also include the most notable events that occurred between 12 November and 12 December, 2021.

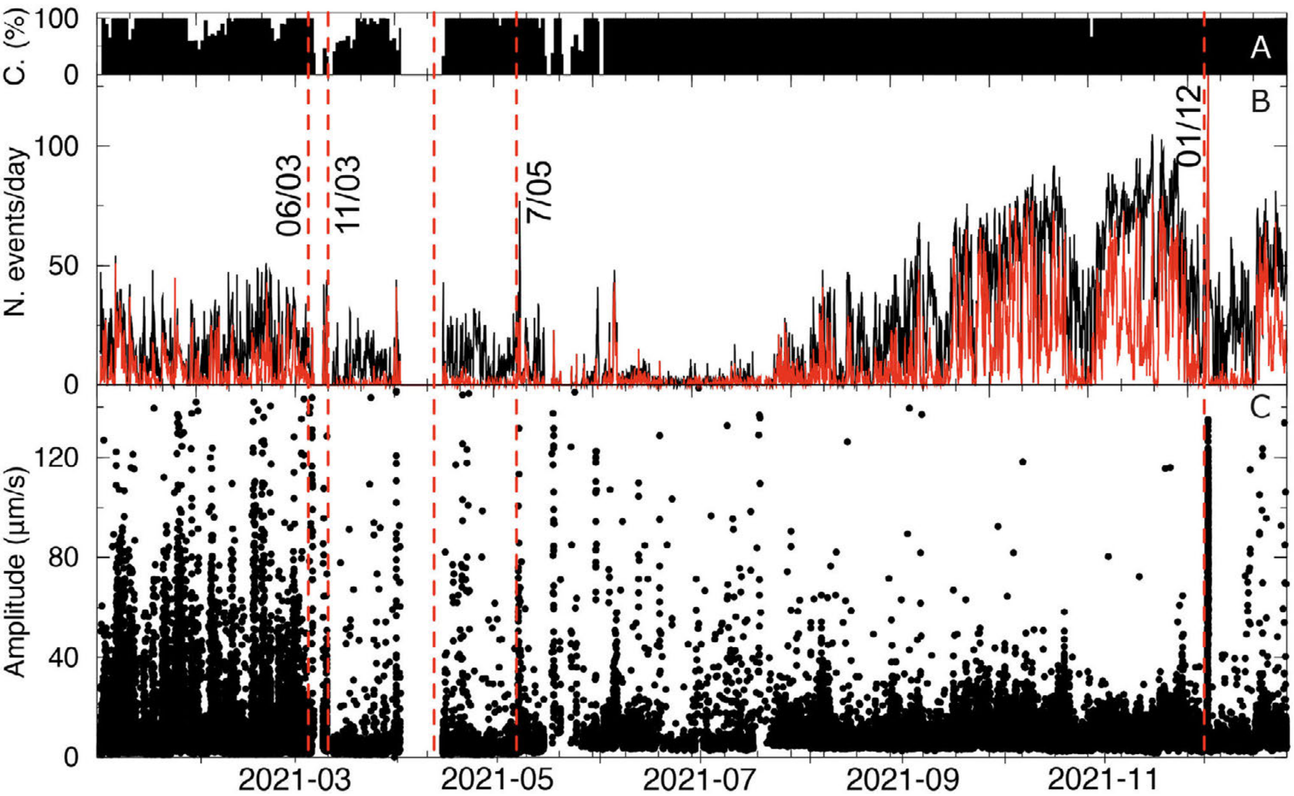

Figure 2: Seismic parameters at SAGA station: [A] Percentage of daily data-completeness (C. %). [B] Number of events detected per day with an STA/LTA (short-term average amplitude/long-term average amplitude) higher than 2.5 (black) and with a peak-to-peak amplitude higher than 8.0 µm s^{-1} (red). [C] Peak-to-peak amplitude, calculated between 0.5 and 15 Hz, of the individual seismic events with an STA/LTA higher than 2.5. Events in this chart correspond mainly to explosion quakes.

2 Ground based and satellite-derived monitoring network

The monitoring of Sangay volcano by the IG-EPN is done through the analysis of real-time data from a local seismic and acoustic station (SAGA) located 6 km to the SW of the summit (Figure 1B), and from two regional stations (PUYO and TAIS) located further afield (50 km from the volcano). Thanks to specific data processing techniques that identify the waveforms typical of events from Sangay, described in Vasconez et al. [2022], these stations make it possible to recognize the seismic signals associated with the most significant events of this volcano. A constant record at these far-field stations allows for the determination of long-term seismicity rates, regardless of whether the local station SAGA is operating or not [Vasconez et al. 2022]. For the monitoring and analysis of ground deformation on the volcano, Interferometric Synthetic Aperture Radar (InSAR) image processing is performed on images acquired by the Sentinel-1 satellite of the European Space Agency (ESA) using the ISCE and MintPy software with the SBAS (Small Baseline) method [Yunjun et al. 2019].

SO_2 degassing is monitored by a permanent DOAS station located at Atillo, 30 km to the SW of the vent (Figure 1B). Satellite derived information from the TROPOMI sensor on board of Sentinel-5SP is processed by the MOUNTS platform [Valade et al. 2019]. In addition, thermal anomalies and morphological changes are also evaluated using satellite-derived imagery available through online platforms such as MOUNTS, FIRMS [Davies et al. 2009], and Planet Explorer [Planet Team 2017]. Finally, ash emissions are detected and tracked using the Volcanic Cloud Monitoring platform [Pavolonis et al. 2018], which utilizes the GOES-16 satellite*, and complemented by Washington Volcanic Ash Advisory Center (W-VAAC) alerts†.

Continuous and open communication with the National Risk and Emergency Management Service (*Servicio Nacional de Gestión de Riesgos y Emergencias*: SNGRE) is performed through hand-held radio, telephone, and instant messaging. The IG-EPN also communicates with the W-VAAC and the Civil Aviation Authority (*Dirección de Aviación Civil*: DAC) through e-mail and recently through the NWSChat operated by the National Oceanic and Atmospheric Administration (NOAA). The IG-EPN also supervises a network of volcanic observers (*Red de Observadores Volcánicos del Ecuador*: ROVE) which includes volunteers from different institutions (e.g. Ecuadorian Red Cross, SNGRE, DAC) and the public. These observers are located in the different cities around the country and provide information about the presence of volcanic ash in their location via instant messaging or *Observadores Volcánicos* mobile application.

*https://volcano.ssec.wisc.edu/
†https://www.ssd.noaa.gov/VAAC/

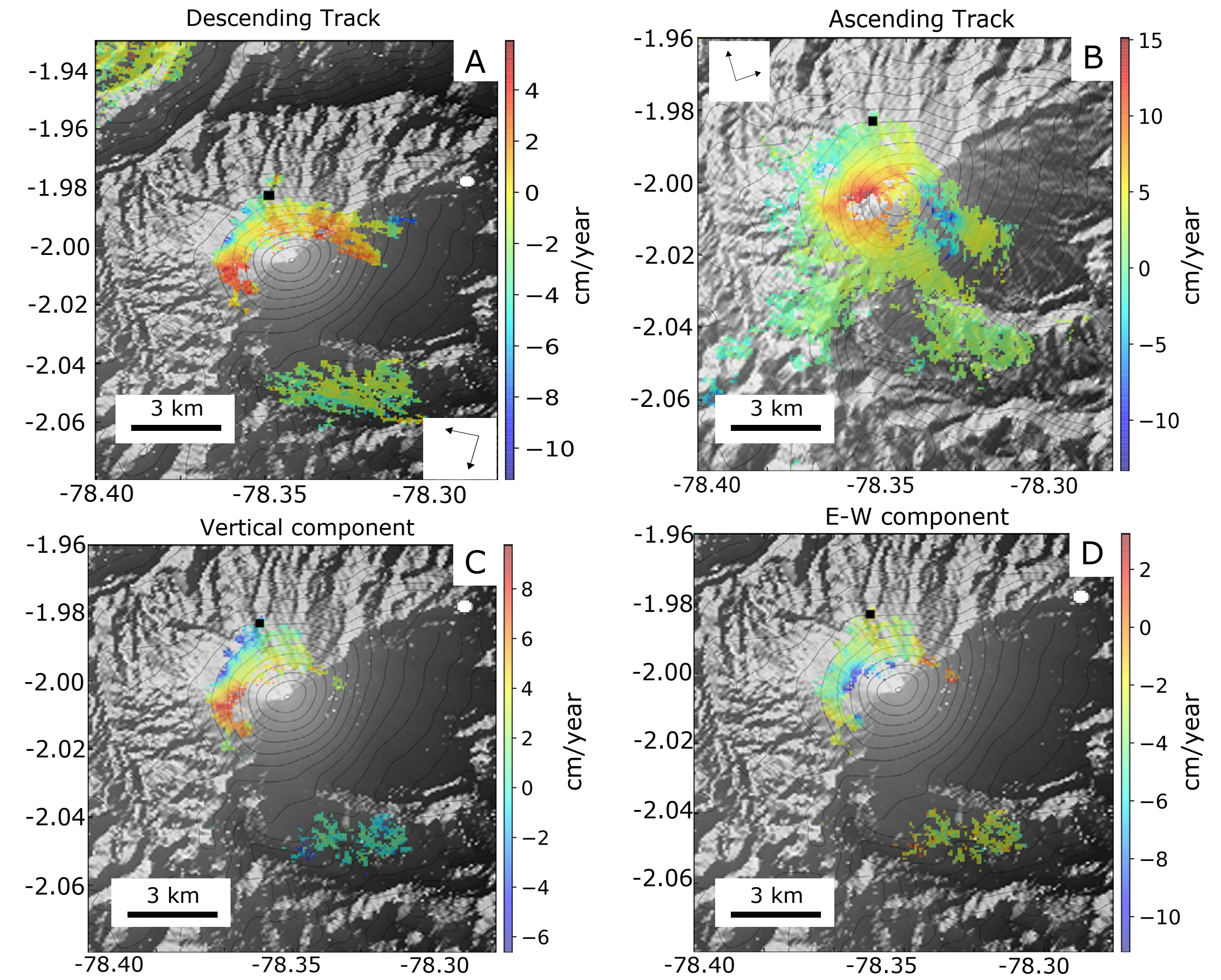

Figure 3: Results of deformation monitoring analysis obtained using InSAR, for the two years preceding the new northern lava flow onset. [A] Deformation along the LOS direction, Descending track between 05/01/2020 and 07/12/2021, [B] Deformation along the LOS direction, ascending track between 02/01/2020 and 04/12/2021. Components of motion: [C] Vertical component and [D] Horizontal component at Sangay volcano. The black square represents the reference point.

2.1 Seismicity

To quantify the seismicity throughout 2021 we used an STA/LTA (Short Term Average Amplitude/Long Term Average Amplitude) algorithm to count the number of seismic events and estimate their peak-to-peak amplitude at the seismic station SAGA (Figure 1B). The seismic events associated with Sangay are mainly explosions, with very few volcano-tectonic (VT) and long-period (LP) earthquakes. The completeness of the data is shown in Figure 2A. The STA/LTA algorithm was applied after filtering the data in the 0.5–15 Hz frequency band and amplitudes were calculated in the same band. Results are shown in Figure 2B, presented as a daily count of all transient events with an STA/LTA higher than 2.5 and larger amplitude events with a peak-to-peak amplitude higher than 8.0 $\mu m\,s^{-1}$. These results reveal that since July 2021 there has been a progressive increase in the number of explosions detected at SAGA station. These explosions are, however, mostly smaller than previously recorded and are not seen by the stations of the regional network due to their low amplitudes. Interestingly, as their number increased, their amplitude decreased (Figure 2C). This change in seismic activity is correlated with a change in the surface activity from Strombolian and Vulcanian discrete explosions to more sustained Strombolian activity with periods of lava fountaining. This activity intensified during the last weeks of November, 2021.

2.2 Deformation

The results of deformation analysis (velocity maps) as calculated using InSAR are shown in Figure 3 overlain on a hill-shade model (grey colors). The velocity maps highlight the fact that from September 2020 to December 2021 the volcano experienced positive deformation of approximately 6 $cm\,yr^{-1}$ on the descending track and 15 $cm\,yr^{-1}$ on the ascending track in the satellite line of sight (LOS) (Figure 3A and 3B) repre-

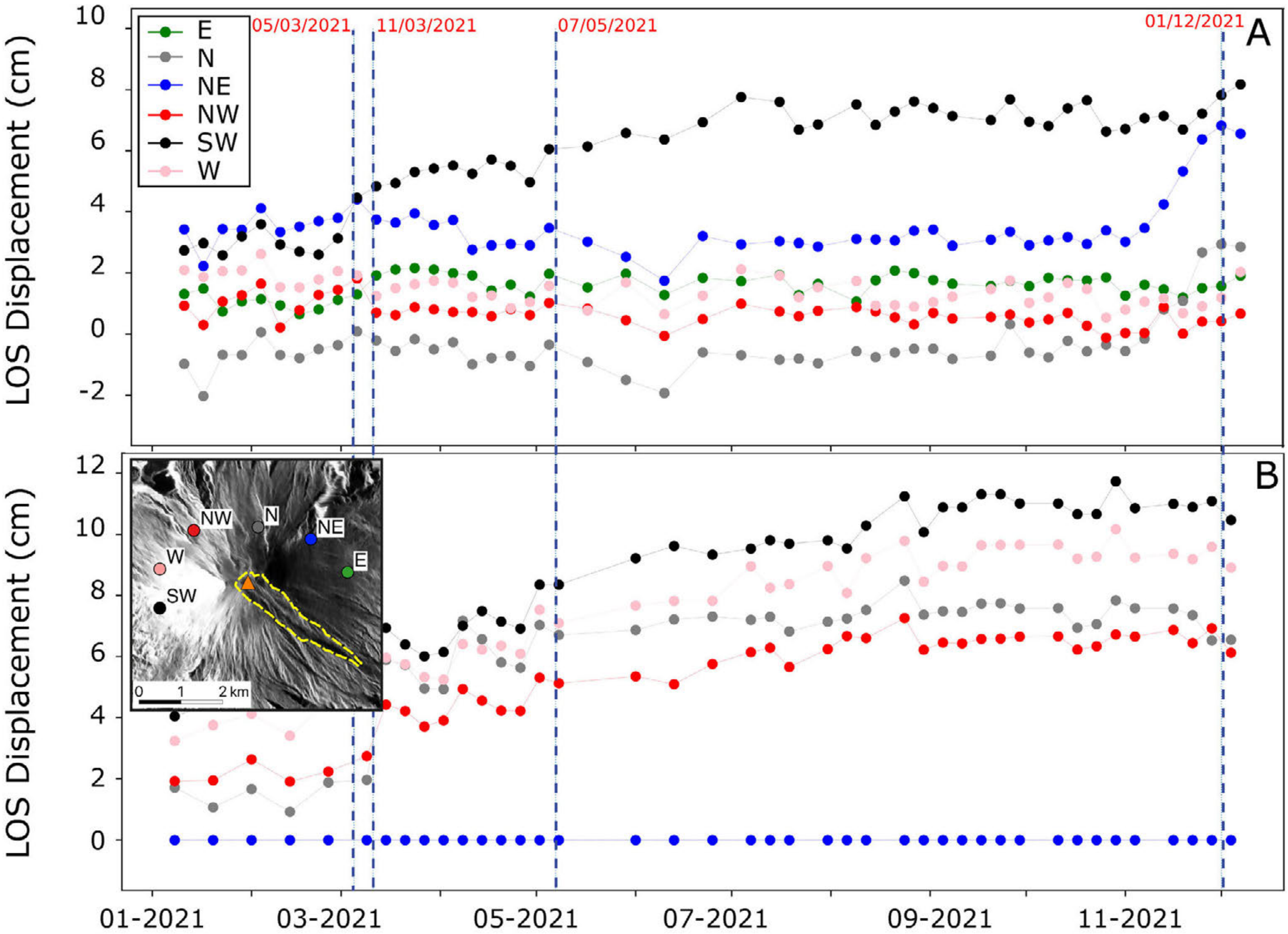

Figure 4: Satellite line-of-sight (LOS) displacement time series obtained from the two flight directions, descending [A] and ascending [B] orbit images of the volcanic edifice. Each marker color refers to the measure points. The vertical blue dashed lines represent the major eruptive events in 2021.

sented by the yellow to red colors in the velocity maps (Figure 3). This deformation is located around the flanks, close to the summit. Meanwhile, the light- to dark-blue areas represent negative deformation and are located in the lower parts of the volcano, and also the SE flank zone (Figure 3B). In the central and southeastern part of the crater, the coherence (quality of measurement data) is low due to recently deposited volcanic material, from phenomena such as pyroclastic currents, extruded lava flows, and through the formation of the ravine. This prevents deformation measurements from being carried out in these areas. It has been possible to combine the two tracks and extract the vertical and horizontal components in order to know the true uplift and subsidence movements as well as the horizontal movements in the east-west direction (Figure 3C and 3D). Figure 3C shows that the volcano experienced uplift on the mid-western flank ranging from 5 to 10 cm. Also, the volcano shows lateral movements in negative colors (blue-green) towards the west and positive colors (yellow-red) towards the east (Figure 3D).

The deformation time series generally exhibits a positive trend at least since July 2020 (not shown in Figure 4). For the descending track (Figure 4A), between 1 November and 1 December, 2021, the north and NE flanks (gray and blue markers, respectively) have shown a very marked positive trend. After this last date, deformation became negative on both flanks. The NW flank (red marker) has shown a positive trend between 19 November and 25 November, which then leveled out and remained almost stable until 1 December, when the deformation once again became positive. For the ascending track (Figure 4B), updated until 4 December, the E and NE flanks (green and blue markers, respectively) show no deformation due to the lack of coherence in these areas. While the other markers are stable until 1 December, and afterwards they show a slightly decreasing trend (Figure 3A).

2.3 SO_2 degassing

The SO_2 emissions detected by satellite (TROPOMI sensor processed by MOUNTS) show an increasing trend from the beginning of November 2021 (Figure 5A, red dots) until the effusive onset on 2 December, and on the following days (Figure 5A show the increasing trend until 7 December). The 7-day moving average (red curve) shows that the SO_2 masses increase from 500 t early November to 1000 t mid-December. The higher SO_2 value as observed by TROPOMI is on 1

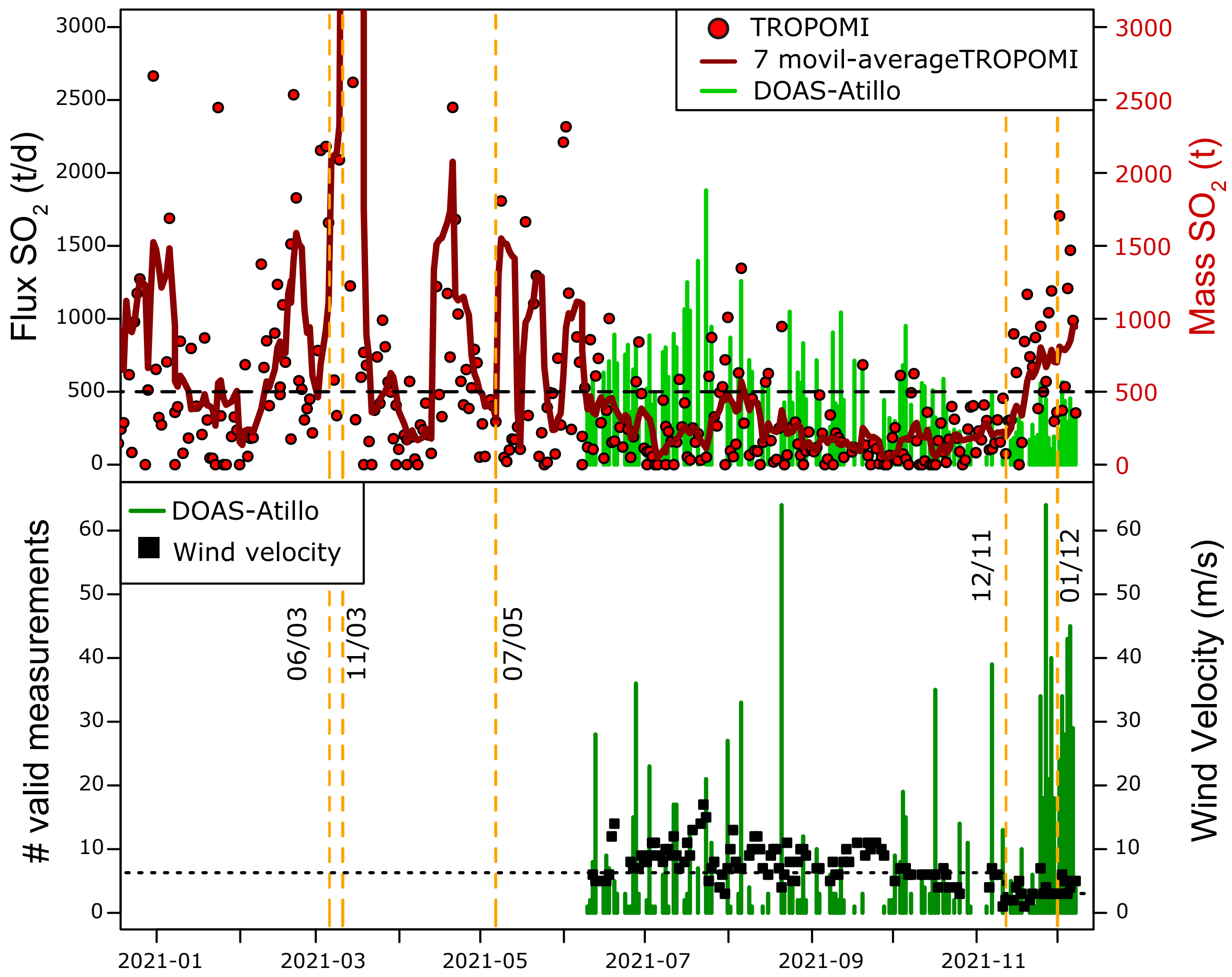

Figure 5: [A] TROPOMI daily SO_2 masses provided by MOUNTS platform (red dots) including a 7 day-moving average (red line). SO_2 fluxes calculated from data recorded at Atillo DOAS station are shown as green bars. The black dashed line depicts the average of the SO_2 mass since 2019. [B] Number of valid measurements obtained at Atillo DOAS station as dark green bars and wind direction inside the detection quadrant as black squares. Orange dashed lines highlight the most notable events in 2021 including the increasing SO_2 trend recorded by TROPOMI (MOUNTS) on 12 November, prior the drumbeat sequences. The dotted black line depicts the mean wind velocity, which is directly proportional to the flux.

December, reaching 1705 t (Figure 5A). SO_2 values decrease during the following days to increase again on 4 and 5 December (1208 and 1470 t, respectively). In contrast, data from the DOAS-station (green bars) did not record changes in the daily SO_2 flux during this time, displaying an average flux of 300 t d^{-1} (Figure 5A). There is however a significant increase in the number of valid measurements (SO_2 detections were constrained by the geometry of the gas plume), from 10 to 40 valid measurements per day since 24 November (Figure 5B), indicating a more constant presence of SO_2 in the atmosphere. Additionally, we have included in Figure 5B the wind directions to estimate its effect on the number of SO_2 measurements, where black squares depict days when the wind direction was between 180 and 270 degrees, which covers the location of the Atillo DOAS detection-quadrant (Figure 1). Overall, it appears that the increase in the number of valid measurements is not related to changes in wind direction nor is it due to high wind velocities (Figure 5B, black dotted line).

2.4 Thermal anomalies

Data provided by FIRMS platform, which uses satellite-derived information from SUOMI-NPP and NOAA-20, registers thermal anomalies at the surface. For the location of the thermal anomaly alerts, we applied a filter of <0.5 km on the track GSD (ground sample distances) to avoid anomalous locations due to high scanning angles [Wang et al. 2017]. Since May 2019, most of the anomalies were located on the south-eastern flank and close to the central crater, within a 12 km radius (gray squares in Figure 6A), displaying the lava flows and pyroclastic currents deposited to the southeast from the activity of the central crater and Ñuñurcu vent which existed at that time (see Vasconez et al. [2022] for a view of the pre-

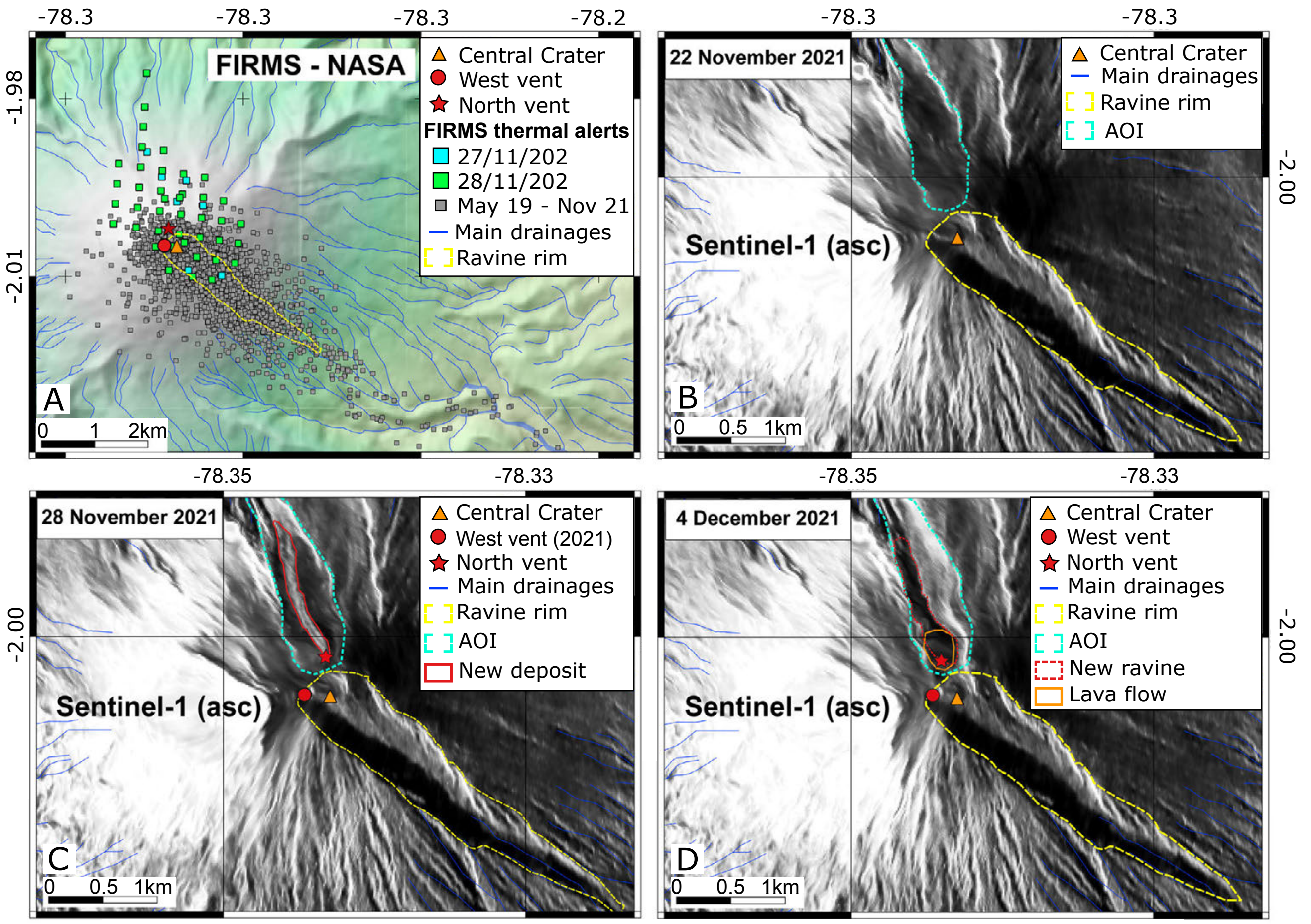

Figure 6: [A] Location of thermal anomalies (FIRMS) around the summit of Sangay since May 2019. The thermal anomalies are clearly seen to the north beginning on 27 November, 2021; [B] Sentinel-1 image (MOUNTS) for 22 November, 2021 showing no morphological changes; [C] Hot deposits on the northern flank of the volcano; [D] trace of a landslide visible in black to the north (red dotted line). The hot deposits have been completely removed and the advance of a lava flow is marked following the trace on the Sentinel-2 image of 2 December, 2021 (orange line).

vious summit morphology). On 23 November, 2021 through the cameras of ECU 911 (located at Macas), a new, small vent displaying Strombolian activity was observed to the west of the central crater on the western ridge of the summit. Since 27 November, thermal anomalies have appeared on the northern flank for the first time throughout the current eruptive period, up to 3.5 km from the summit (Figure 6A). On 3 December, the thermal anomalies were still visible, reaching up to 2 km from the summit area.

2.5 Morphological changes

Based on Sentinel-1 amplitude images (filtered, geocoded, and made available on the MOUNTS platform), we have observed morphological changes on the northern flank of the volcano, which we summarize in Figure 6B–D. On 22 November, 2021 there are no visible changes on the northern flank, i.e. area of interest (AOI) in Figure 6B. However, on the image from 28 November, there is a new deposit, probably a pyroclastic current (Figure 6C), which has associated thermal anomalies reported in the same direction and location since 27 November (Figure 6A). By 4 December, a scar—probably from a landslide—is visible on the Sentinel-1 image (Figure 6D). Additionally, by using Sentinel-2 and Planet images, we observed a lava flow advancing towards the north, on 2 December. This lava flow is longer in the image corresponding to 10 December (not shown), reaching 2.5 km from the vent.

For comparison purposes, we show a picture from the northern flank of Sangay before the landslide (Figure 7A) and after its occurrence (Figure 7B). This landslide was confirmed by visual inspection during a helicopter overflight on 27 December, 2021. Morphological changes are visible in the upper part of the edifice (yellow squares) where the scar is visible on the second image, taken on 27 December. The zone impacted by the landslide is also evident in areas where vegetation was lost and a fine layer of ash covers the downslope. The new lava flow is also present in the picture (red dashed line). In Figure 7C, we show a composition of two color infrared images from Planet from 23 and 27 December, 2021 respectively, which allows us to identify the changes in vegetation due to the late 2021 volcanic activity. The impacted zone from the landslide is marked with orange dashed lines. The limits of the lava flow as seen on 2 December, and the pyroclastic cur-

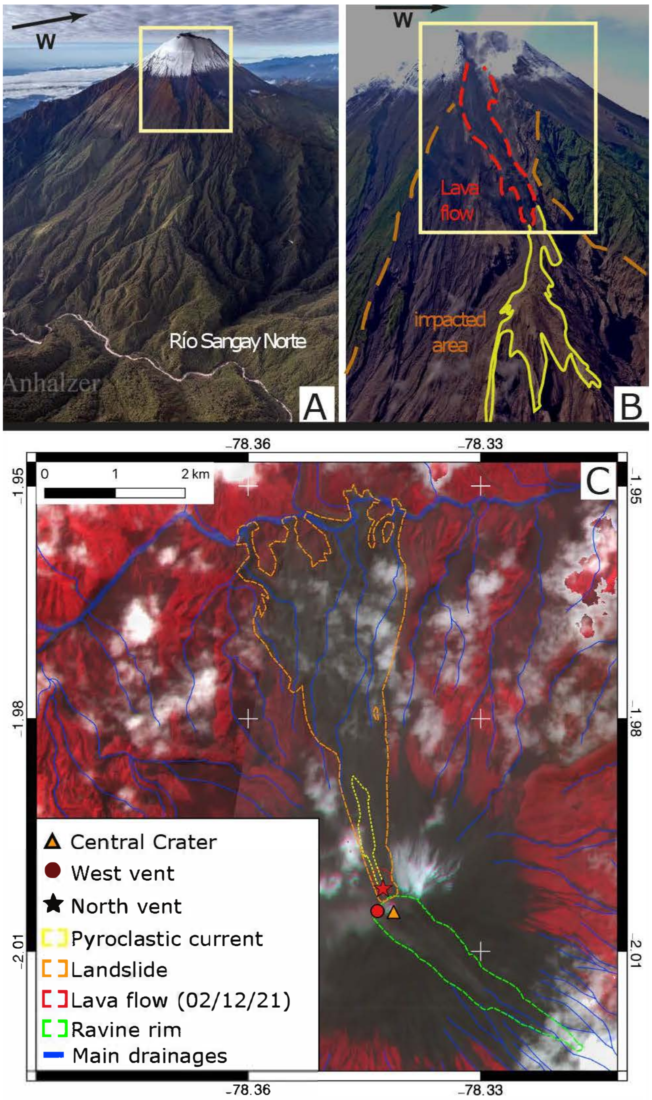

Figure 7: [A] Aerial photo of the northern flank of Sangay taken before November 2021. Photography courtesy of Jorge Anhalzer; [B] Aerial photo of the northern flank of Sangay taken during an overflight on 27 December, 2021 (i.e., after the drumbeat sequence) by Benjamin Bernard; [C] Planet infrared image composition showing the new deposits and morphological features in the northern flank of Sangay volcano, including the two new vents.

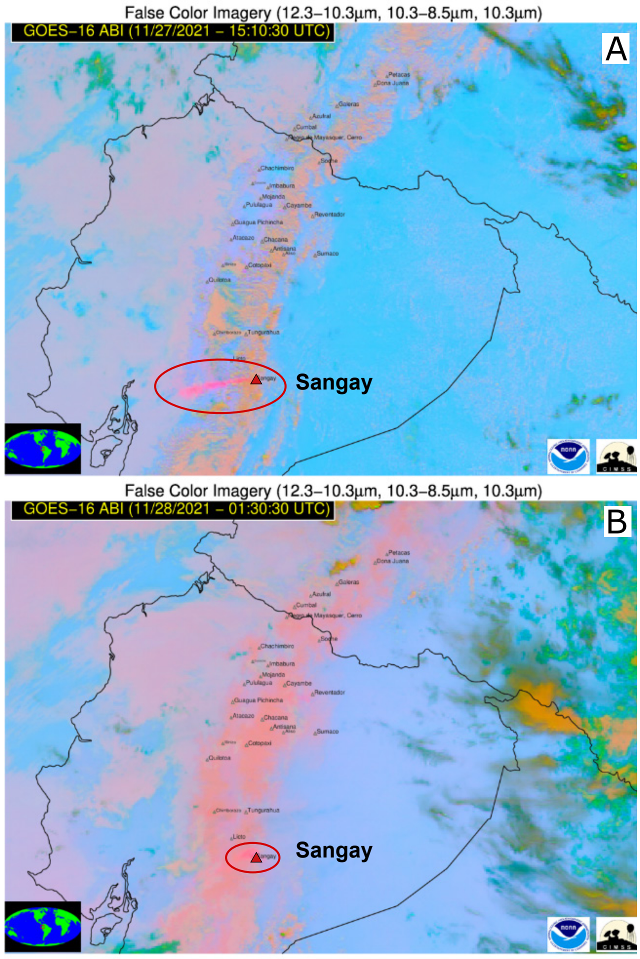

Figure 8: Volcanic clouds from Sangay volcano (bright pink color) on 27 November [A] and 28 November [B] by using the False Color Imagery (Source: NOAA/CIMSS).

rent observed on 28 November, both from Sentinel-1 images, are plotted for reference. In this image, we also show the central vent, and the two new vents appearing on 23 and 27 November. The lava flow overlying the landslide scar is visible on 2 December, indicating that the landslide must have taken place between 29 November and 2 December. The landslide affected a surface area of 6.6 km^2, with a maximum runout distance of 5.7 km reaching the Sangay Norte river (Figure 7C).

2.6 Volcanic plumes

Before the 1 and 2 December drumbeat sequence and lava emission, there was a continuous increase in the frequency of alerts emitted by the W-VAAC. In August, there were 33 alerts, 78 in October, and 86 in November. However, the height of the plumes did not vary much at this time (<2.5 km above the crater). Volcanic plumes are typically directed to the west as can be seen on the GOES-16 image of 27 November (Figure 8A). On 28 November at 01:30 (Figure 8B) a volcanic plume appeared to the north of the volcano, maybe related to the vent opened on that flank around this date.

3 Sequence of events from 1 December to 2 December, 2021

3.1 Seismicity and infrasound

The most striking feature of the 1–2 December sequence is the appearance of a series of "drumbeat" seismic events with similar, repeating waveforms, characterized by regular, progressively evolving inter-earthquake times. Beginning at around 19:20 UTC on 1 December, a gradual increase in the number of small seismic events was observed at SAGA (Figure 9). These events progressively and irregularly increased their rate of occurrence and amplitude. Eventually, they merged into an almost continuous tremor whose amplitude peaked about

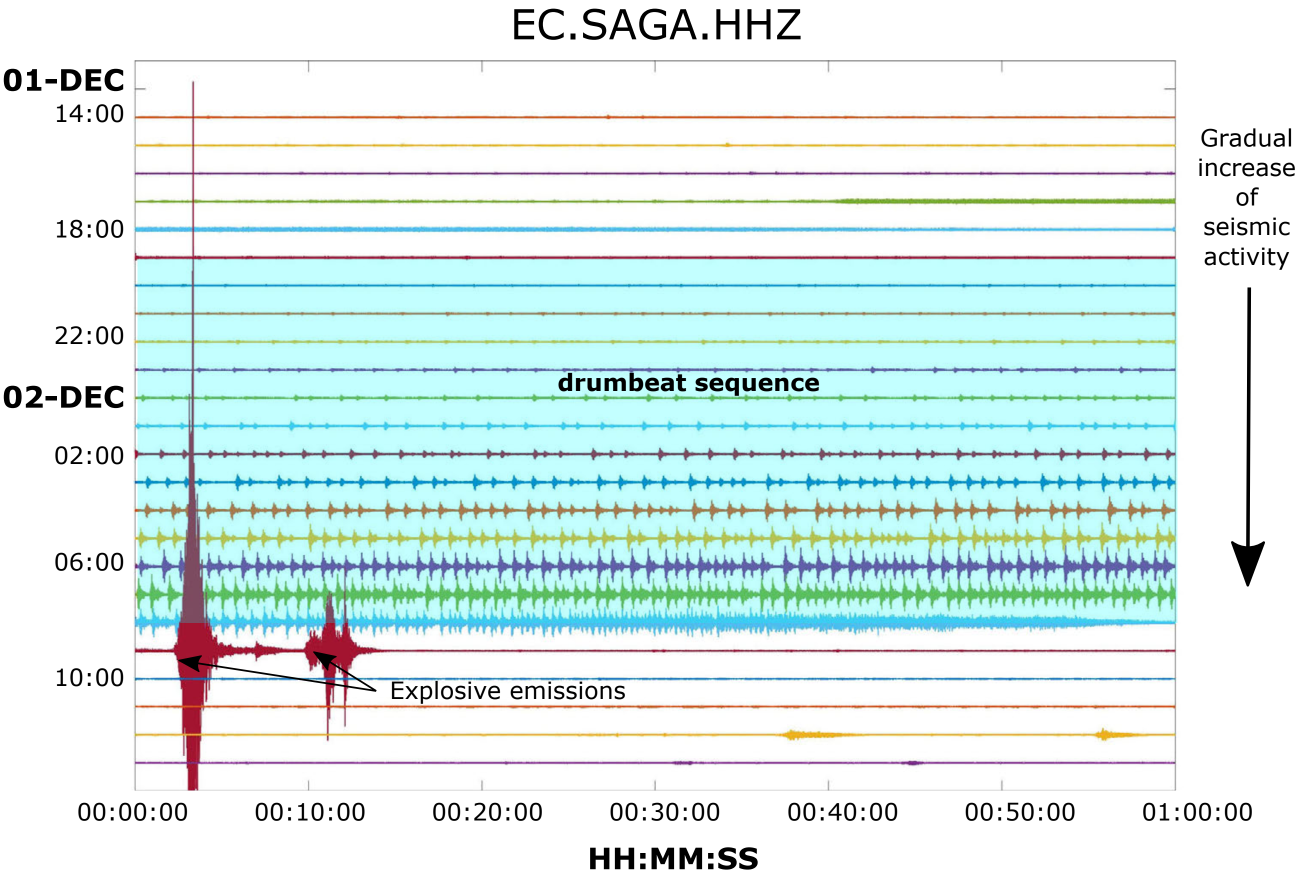

Figure 9: Helicorder of SAGA seismic station showing the drumbeat sequence, the merging of events into continuous tremor and the termination of these events in two energetic, explosive emissions. The traces are filtered between 0.25 and 16 Hz.

08:30 UTC on 2 December before decreasing. During the decrease of this tremor, a gliding of the dominant spectral peak is observed (Figure S1: Supplementary Material 1) possibly related to the continuing acceleration of the drumbeats as observed for example at Redoubt volcano [Hotovec et al. 2013]. This shortly preceded two significant explosive emission events at 09:02 and 09:13 UTC, accompanied by clear acoustic phases.

The drumbeat events are significantly different from the events observed during seismic campaigns performed on 1995 and 1998 [Lees and Ruiz 2008], and since the installation of SAGA station in 2013. A comparison among common recorded events during previous months and those comprising the drumbeat sequence is shown in Figure 10. Unlike common events, the drumbeats do not display clear acoustic phases, suggesting a deeper source. They display dominant frequencies at 1–2 Hz including, however, weak higher frequency onsets. They can be classified as LP or hybrid events [Chouet and Matoza 2013].

To further examine this sequence, we used matched filtering to detect a maximum number of events. For this purpose, we choose four templates for the vertical component of SAGA station selected during the swarm and cross-correlated these events with the continuous data after filtering between 0.5 and 15 Hz. The procedure identified 1114 events with a correlation value higher than 0.5. While this threshold is quite low, we note that no event could be detected during the weeks before and after the sequence emphasizing the uniqueness of the drumbeat events. The peak-to-peak amplitude of the detected events displays a strikingly regular exponential increase along with the swarm with the maximum amplitude reached at about 07:00 UTC on 2 December (Figure 11A). Later, these amplitudes diminished progressively while the events merged into spasmodic and almost continuous tremor around 08:45 UTC. Interestingly, we note at 02:16 UTC the reappearance of small amplitude events which initiate a second set of events with a separate increasing amplitude trend. Events from this second set are interspersed among the first set of events but waveforms keep a high degree of similarity. The degree of similarity evolves during the swarm, however, due to a progressive slow change of waveforms with time. Figure 11B displays the time between two successive detected events. It shows that the rate of occurrence of the drumbeats rapidly increases at the beginning of the sequence and also significantly towards the end of the episode when merging into tremor. In the middle, the occurrence rate of drumbeats displays fluctuations with a significant drop-in inter-event time associated with the appearance of the second set of low-amplitude events. A failure forecast approach was applied in real time prior to the explosion, using a Bayesian point process methodology

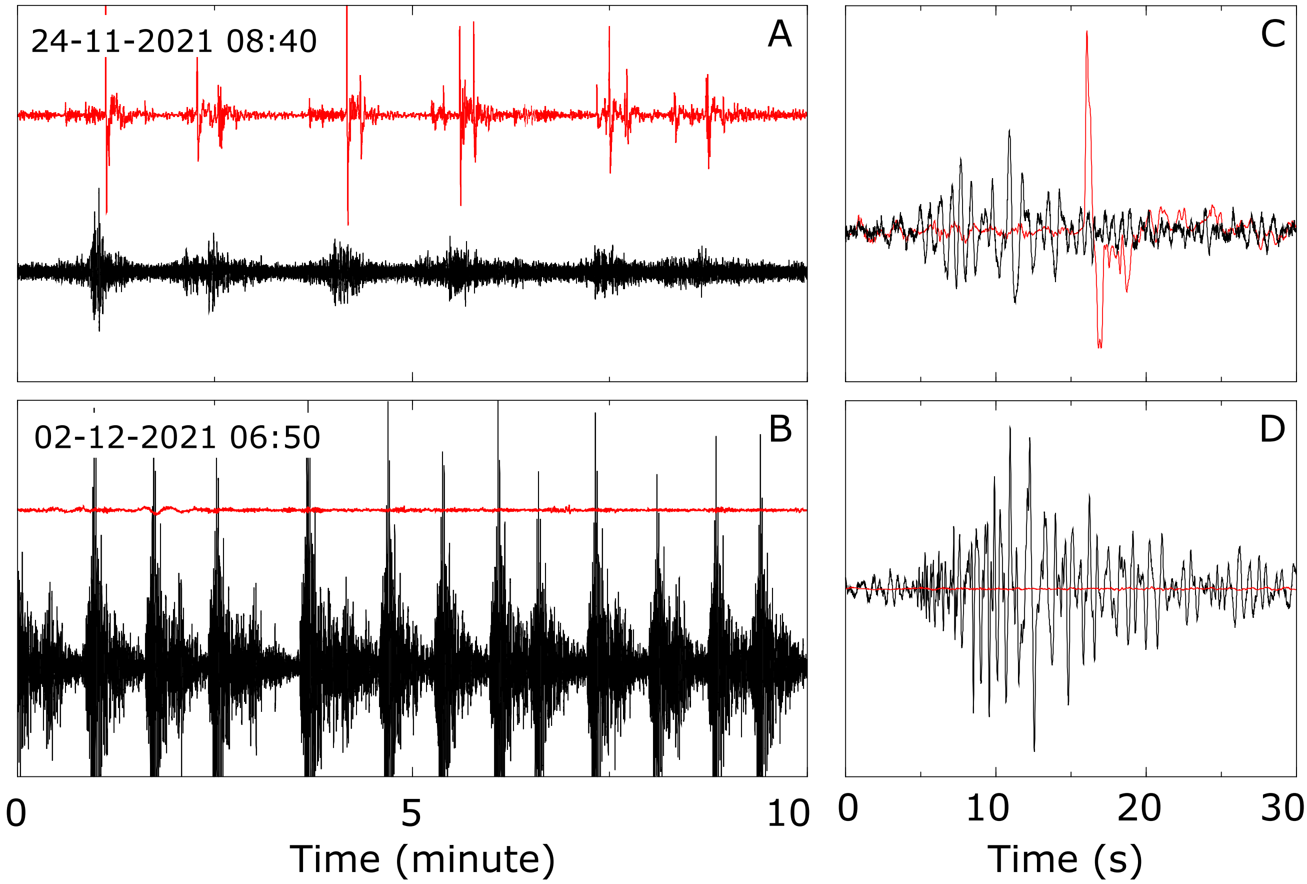

Figure 10: Waveforms registered at SAGA station. [A] and [B] 10-minute sequences for vertical seismic (black) and acoustic (red) components recorded respectively during standard low-amplitude explosive activity observed since July 2021 and during the drumbeat sequence. [C] and [D] Example of events recorded respectively during the two sequences: an explosion quake with clear acoustic phase and a drumbeat event.

to model the time-series of drumbeat earthquakes [Bell et al. 2018]. The irregular increase in earthquake rates through the sequence meant that the simple inverse-power law and exponential rate models did not fit the data well and resulting probabilistic forecasts of the failure time were correspondingly inaccurate.

Comparable sequences of repeating and/or accelerating rates of events have been observed at various volcanoes with dacitic or andesitic lavas. At Mount St Helens (USA), drumbeats were associated to the extrusion of lava spines in 2004–2005 and their size and spacing were assumed to be a function of the mechanics of extrusion rather than the extrusion rate [Moran et al. 2008]. At Tungurahua (Ecuador) accelerating rate of drumbeats preceded a large Vulcanian explosion in July 2013 [Bell et al. 2018] and were assumed to be the result of the repeated activation of a single characteristic source driven by accelerating loading. Drumbeat sequences have often been interpreted as being caused by repetitive stick-slip processes caused by extrusion of material under specific conditions [e.g. Moran et al. 2008]. In our case the drumbeat sequence could be interpreted as being caused by the forced extrusion of the lava flow through the new northern vent which was observed later on. In the present case, no surface phenomena could be observed directly related to this sequence as the volcano was covered by clouds and no camera points towards the northern flank.

3.2 Characteristics of the volcanic plume

The height of the volcanic plume was estimated using: 1) the direction and velocity of the volcanic cloud measured on the GOES-16 False Color Imagery (Figure 12A, 12C, and 12E); and 2) the minimum brightness temperature measured on the GOES-16 Color Enhanced Infrared Imagery (Figure 12B, 12D, and 12F). Both results were compared to a sounding of the GDAS1 model by the NOAA at the time of the eruption. This process closely follows Holasek et al. [1996]. A faint volcanic cloud about 1 km above the crater level (6.2 km a.s.l.) directed toward the west was detected at 08:50 UTC on 2 December, which was associated with the seismic tremor at the end of the drumbeat sequence. The main explosive event was detected at 09:10 UTC as a gas-rich and ash-poor volcanic plume (Figure 12A and 12B) that divided in two, the highest (14.2 km a.s.l.) moving slowly (8–10 m s^{-1}) to the east and south, and the lowest (10.9 km a.s.l.) moving rapidly (20 m s^{-1}) to the west-southwest (Figure 12C and 12D). Both clouds rapidly separated from the volcano indicating an ab-

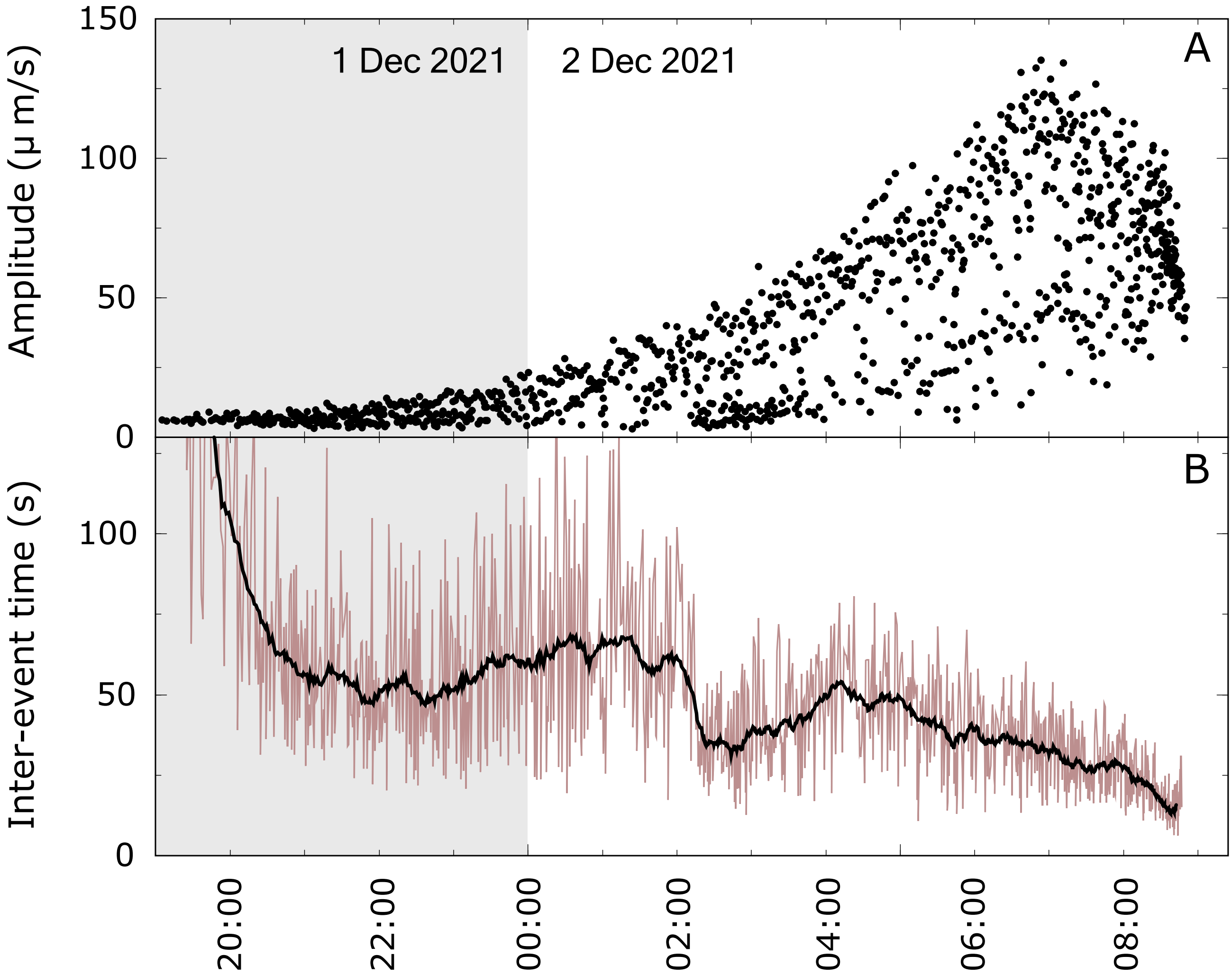

Figure 11: Seismic characteristics of the drumbeat sequence, [A] Peak to peak amplitude of the events detected by matched filtering. [B] Inter-event time for events recorded during the sequence before merging into tremor. Individual measurements are shown in the background (brown) with the black curve in foreground presenting an averaging over 30-point moving windows.

sence of sustained emission (Figure 12E and 12F). The lowest cloud disappeared around 10:50 UTC reaching 55 km from the volcano, while the highest cloud was still visible several hours later reaching 85 km form the vent. In both cases, no ashfall was reported at national scale, supporting the interpretation of a short-lived intense gas emission. Our results compare well with the VOLCAT (VOLcanic Cloud Analysis Toolkit) solution and the W-VAAC alerts. The poor ash content of the plume is also confirmed by the very low probability of ash and dust detection estimated by VOLCAT algorithm for this event.

4 Interpretation

In the short term, seismicity and deformation started to show increasing trends from early- to mid-November 2021 (about a month before the drumbeat sequence) which could be associated to an injection of new magma into the current open system (Figures 2 and 4). Strombolian activity on the central vent had been observed since July 2021 together with an increase in the number of explosions per day and the extrusion of lava flows. This activity intensified during the last weeks of November. The opening of the new vents to the west and to the north is not well depicted in the seismic record, but using satellite images and visual observations, we propose a detailed sequence of events which is described in Table 1.

The sequence of events can be summarized as follows:

1. Early–mid November—New magma intrusion and ascent into the already open volcanic system shown by: a progressive increase in seismic activity since July, heightened even further beginning in early November, 2021; a continuous inflation pattern which increased between 1 November and 1 December; and an increase in the number of VAAC alerts and an increase in SO_2 emissions since 12 November. This has been observed in other volcanoes, for instance at Cotopaxi in 2015 the rate of seismicity increased rapidly before the onset of the explosive activity [Hidalgo et al. 2018].

2. Ascent of magma generating overpressure in the upper part of the volcanic edifice, leading to the opening of the western vent on 23 November, as observed in the ECU-911 camera.

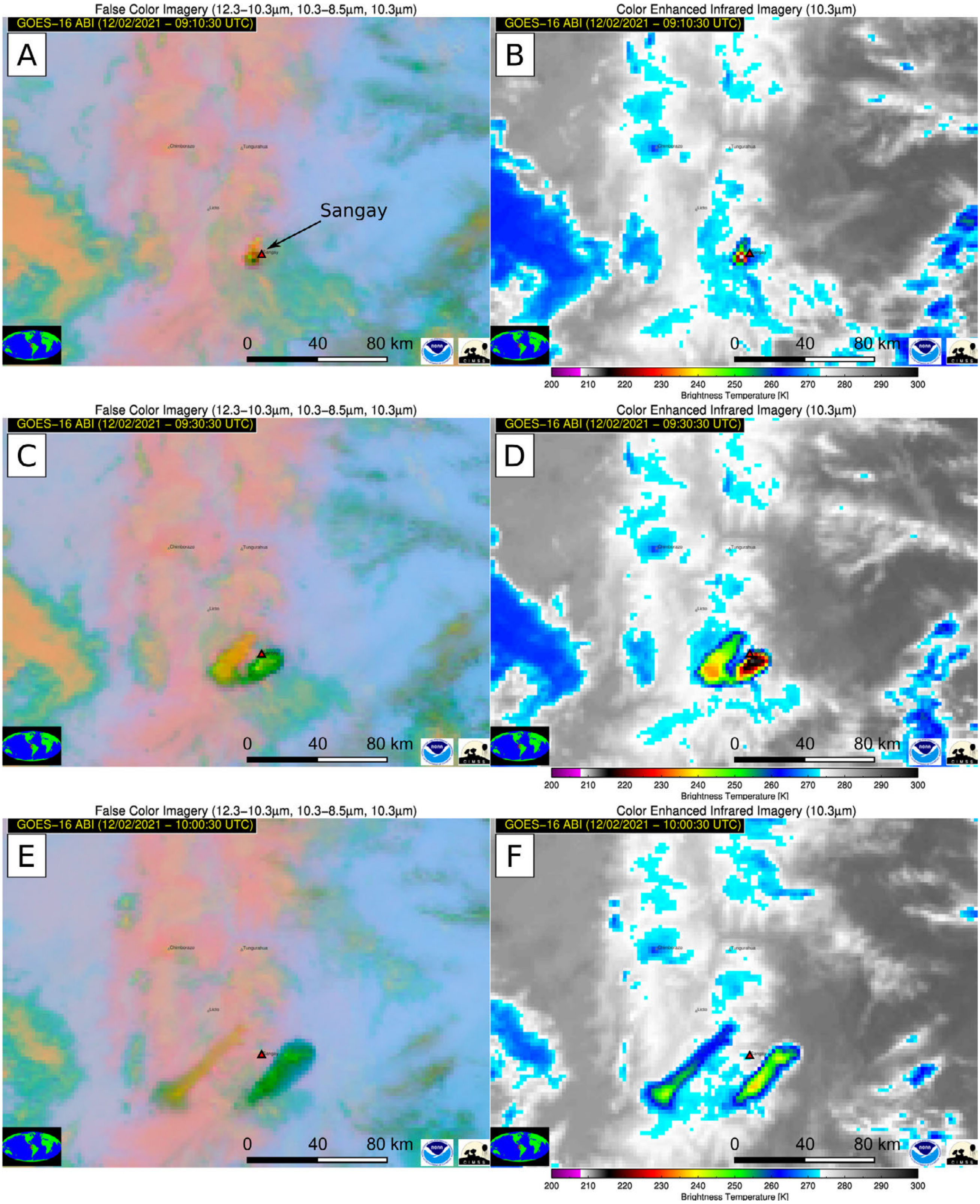

Figure 12: GOES-16 False Color and Color Enhanced Infrared Imagery of the volcanic clouds (Source: Volcanic Cloud Monitoring). [A] and [B] 09:10 UTC: initial explosion. [C] and [D] 09:30 UTC: division between a high cloud directed toward the east and a lower cloud directed toward the west-southwest. [E] and [F] 10:00 UTC: no further alimentation of the volcanic clouds is observed.

Table 1: Sequence of parameters measured and observed during the analyzed period including the corresponding source and interpretation.

Date	Phenomena	Source	Interpretation
Mid July	Decrease in the amplitude of explosions coupled to an increase in their number	Seismic and infrasound record at SAGA	Progressive but slow arrival of gas rich magma to an already open system. On 25 July a lava flow was extruded through the central crater and was active until 9 August.
October–November	Higher number of VAAC alerts	Washington VAAC alerts	Progressive increase in outgassing.
Early November to 1 December	Enhanced inflation pattern	InSAR processing	New magma input or increase in magma volume.
12 November	Increase in SO_2 emissions	TROPOMI data processed by MOUNTS platform	Progressive arrival of gas rich magma closer to the surface.
23 November	First sight of the western vent	ECU 911 visible camera located at Macas (45 km from Sangay's summit)	Magma find fragile zones in the upper edifice to cope the increase in volume/magma ascent rate.
24 November	Increase in the number of SO_2 valid measurement measured by distal DOAS	NOVAC station located at Atillo, 30 km to the SSW of the volcano.	Permanent outgassing/gas rich magma near the surface.
27 November	First thermal anomalies to the north of the volcano	SUOMI-NPP and NOAA-20 data available on FIRMS platform	Opening of a vent to the north of the volcano. Magma overpressure is higher and requires more escape valves.
28 November	Pyroclastic current identified to the north of the volcano	Sentinel-1 and Planet images	Evidence of the opening of the northern vent.
29 November–2 December	Landslide	Planet and Sentinel-2 images	On the 2 December Planet image shows the deposit of the landslide is already visible. Lava flow also visible on 2 December and overlies the landslide deposit. Therefore, the landslide occurred between these dates.
1–2 December	Drumbeat sequence and tremor	Seismic and infrasound record at SAGA	Magma is potentially being forced through the passage to the northern vent, potentially widening it.
2 December (09:02 and 9:13)	Emissions/explosions	14 km a.s.l. volcanic cloud detected by the W-VAAC.	Magma with high amount of exsolved gases reaches the surface through the northern vent. No ash fallout reported in association to these emissions.
2 December	Lava flow appears to the north of the volcano	Sentinel-2 image	The magma with low volatile content reaches the north producing a lava flow.
1–7 December	Slight changes in the deformation pattern to deflation especially to the NE	InSAR processing	Response of the edifice to the magma outflow.
4 December	Sinking/landslide scar	Sentinel-1 image	Evidence of the occurrence of further landslides.
12 December	Lava flow is 1.5 km long	Sentinel-2 image	The lava flow was still fed until this date.

3. Another new vent opened on the northern flank and produced pyroclastic current deposits, between 25 and 28 November, probably on 27 November given the appearance of thermal anomalies on that date. The opening of new vents in the crater or summit area has been observed and documented for instance for Stromboli volcano during the 2003 activity [Ripepe et al. 2005; Di Traglia et al. 2014]. Interestingly for Sangay the transition is the opposite, it changes from the small explosions to the lava effusion. In both cases overpressure is the factor controlling the dynamics.

4. A landslide occurred between 29 November and 2 December. The precise timing of this event is not possible to determine by seismic signals given that no specific distinguishable signal is found in the seismic record. For Stromboli it has been concluded that large magma overpressure could expand the conduit, but also generate conditions of instability leading

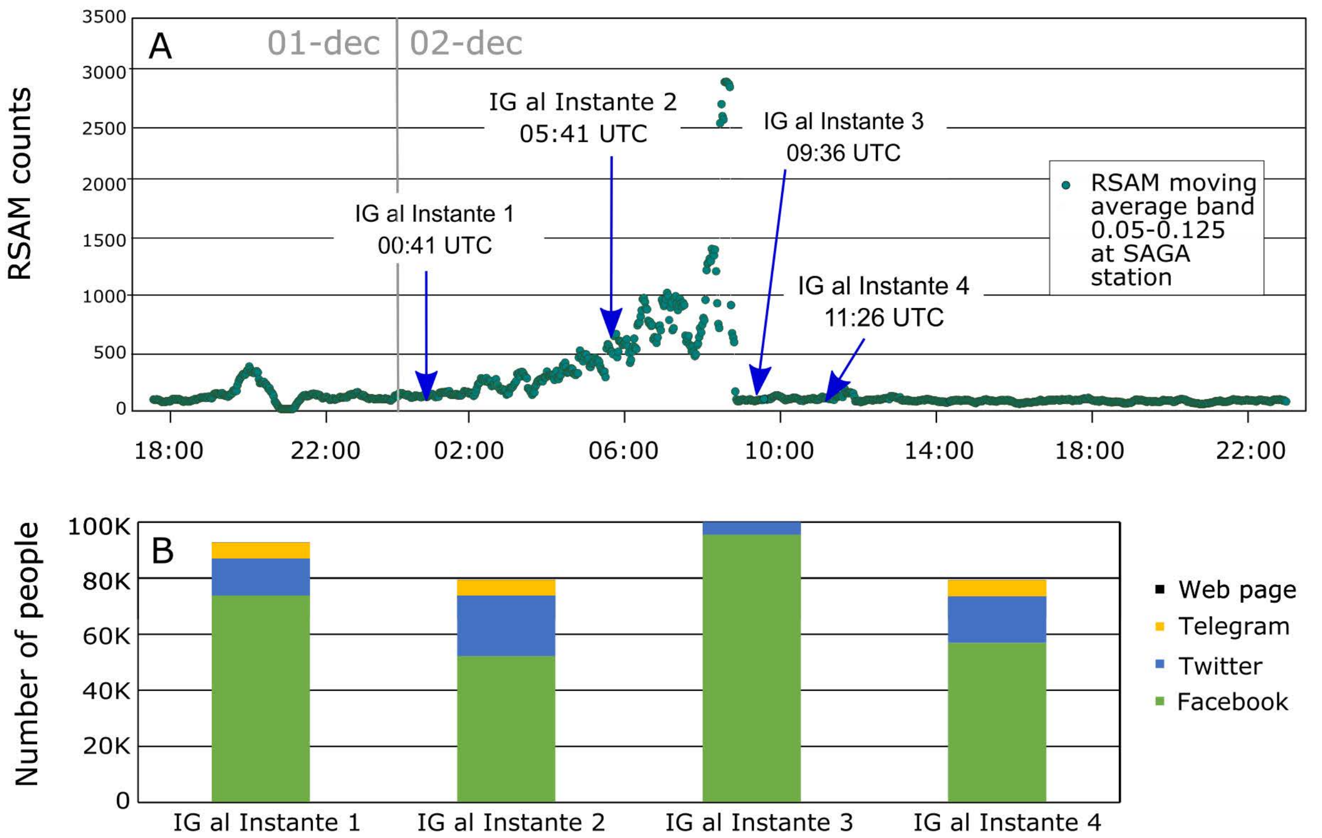

Figure 13: [A] RSAM moving average combined with the communication of eruptive process showing the time of publication for *IGalInstante* reports and their reach out in our social media channels, [B] Bar chart of the number of people reached by the *IGalInstante* publications.

to potential flank collapses [Di Traglia et al. 2014]. This might have happened at Sangay but given that this is a very isolated volcano no danger was posed to the population and the landslide was confirmed only by satellite images and during the overflight, a few weeks later.

5. We suggest that the drumbeat sequence which began on 1 December and merged into a tremor signal to finally produce two gas rich explosive emissions at 09:02 and 09:13 UTC on 2 December could be related to the magma ascent to the northern vent. The release of lithostatic pressure as consequence of the landslide may have facilitated the ascent of lava to the already open northern vent inside the scar of the landslide. This lava flow was active until early July 2022. Drumbeat sequences have been recorded for several volcanoes not leading to a unique phenomenon [Iverson et al. 2006; Hotovec et al. 2013; Bell et al. 2017, among others]. Consequently, this first recorded drumpbeat sequences at Sangay volcano deserves a closer look and we encourage other scientist to investigate it.

6. The magma batch could have been stratified and contained an important amount of exsolved gas in the upper part which rapidly escaped during the two explosive emissions. Most probably, the lava extrusion from the new vent on the northern flank began after this seismic sequence. Sentinel images from 2 and 4 December show the presence of a lava flow (Sentinel-2) and significant morphological changes on the northern flank including a landslide scar (Sentinel-1), confirming a lava effusion as the origin of the thermal anomalies observed since 2 December.

7. The volcanic system enters a new steady state phase with lava effusion and Strombolian activity on the three currently active vents.

5 Implications for hazard

The appearance of a new vent on the northern flank of Sangay's summit area has implications for hazard assessment. Even though Sangay is a remote volcano with the closest inhabited areas as far away as 25 km, the valleys that are born high on the volcanic edifice reach main rivers where there are people living on the abandoned terraces and flood plains. Depending on the volume of the newly deposited volcanic material, communities as far as 40–60 km downstream of Sangay Norte and Culebrillas rivers could be affected by secondary lahars (Figure 1B). In fact, on 3 July, 2022, a lahar descended thought these drainages reaching the road to Pablo Sexto, 45 km from the volcano. No significant damages or victims were reported due to this event. Although this hazard is considered in a previous evaluation of Sangay's volcanic hazards [Ordoñez et al. 2013], this information must be re-emphasized to the authorities and the general public to allow for timely and informed decision-making.

6 Communication of the 1–2 December event

The emergency protocol of the IG-EPN during periods of increased volcanic activity includes a rapid call to the main authorities of the SNGRE, followed by the publication of quick and short reports (*IGalInstante*) on the IG-EPN social media networks, detailing the phenomena occurring and, Volcano Observatory Notices for Aviation (VONA) whenever a volcanic cloud is observed. Finally, special reports are prepared during exceptional or changing activity, including all the geophysical parameters analyzed and providing eruptive scenarios, from the most to the least likely [Ramon et al. 2021].

The increase in seismic activity as well as the deformation inflationary trends were identified as soon as mid-November. This information was reported to the authorities and the community through a special report (*Informe Volcánico Especial* – Sangay – 2021 - N° 002), which was released on 24 November (Supplementary Material 2).

During the night of 1 to 2 December, the appearance of the drumbeat sequence triggered the emission of two direct reports to the authorities through phone calls to the Director of Adverse Phenomena from the SNGRE and to the community through *IGalInstante* reports (N° 2021-249–2021-252) (Supplementary Material 2). The first one was published at 00:40 UTC and described the seismic tremor signal, which has been on previous occasions associated with pulses of major activity. This report included a warning of the possibility of ashfall in the surrounding areas. A second report was issued at 05:47 UTC, describing the appearance of a swarm of drumbeat earthquakes, emphasizing the fact that it was also observed in the distal "regional" seismic stations. This report also mentioned the possibility of effusive behavior, such as the growth of a lava dome, or a lava flow like previous activity at other Ecuadorian volcanoes. A third report was published after the initiation of the explosive emissions sequence at 09:35 UTC, warning of the event and indicating the possibility of ash fallout in the nearby province of Chimborazo, which comprises the nearest inhabited locations to the west of the volcano. Finally, the fourth report at 11:25 UTC confirmed the altitude of the emissions columns and the extent of the gas and ash plume and again warned about the possibility of ash fallout in the nearest towns. Although the emission was significant, the SNGRE and other IG-EPN collaborators (e.g. ROVE network) reported that there was no ash fallout related to this event.

This volcanic event did not produce any impact on the population, but the internal monitoring protocols, as well as the rapid communication to authorities and population were efficiently applied (Figure 13). A proceeding log of the follow up in real time of the event is presented in Supplementary Material 3.

On 3 December, a special report (N° 03) was published detailing the eruption and proposing potential scenarios for the next days to weeks. The most likely scenario at that time was continued eruptive activity with the emission of lava flows, ash plumes (mild to moderate) and potential lahars in the rivers coming from the volcano, in particular towards the northern drainages.

The rapid publication of information corresponding to Sangay's recent eruptive activity reached a wide audience; however, due to the time of the event, most people were sleeping and so the uptake of information was lower than for events that have happened during daytime. The various reports reached 334,268 people on Facebook; 26,756 people on Telegram; 86,626 people on Twitter; and 229 on the webpage: a total of 447,879 people, which is significantly large for a country with 18 million inhabitants. The sequence of the reports is presented on Figure 13 with the RSAM (Real Time Seismic Amplitude Measurement) giving a timeline for the 1–2 December event.

The special reports corresponding to Sangay's eruptive activity were published via our social media platforms (Facebook, Telegram, and Twitter). The first one, "*Informe Volcánico Especial* – Sangay – 2021 - N° 002" published on 24 November, was read by 86,289 people on Facebook; 20,869 people on Twitter; and 5,200 views on our Telegram channel: a total of 112,355 views. The second, "*Informe Volcánico Especial* – Sangay – 2021 - N° 03" had fewer readers but still high interaction with 67,744 people on Facebook; 15,171 people on Twitter; 5,342 on our channel in Telegram; and 82 on our webpage: a total of 88,339 views.

7 Conclusions

The timely processing of remote sensing satellite data is extremely useful to monitor volcanoes, especially those in remote locations where instrumental networks are difficult to keep functioning. Sangay volcano has shown an increased level of volcanic activity since May 2019 and very rapid morphological changes have been observed during this period. Specifically, during the short time period considered in this manuscript: 1) two new vents opened; 2) a landslide affected the northern flank of the volcano; 3) the first drumbeat sequence was recorded at Sangay; and 4) a new lava flow is being emitted through the new northern vent. The drumbeat sequence could be interpreted as being caused by the forced extrusion of this lava flow through the new northern vent. Timely communication of volcanic events is favored by the creation and strict following of internal protocols within volcano observatories and the appropriate use of social networks allowing thousands of people to be reached in very short time period. Documenting this kind of peculiar eruptive episodes is key to better understand volcanoes, not only in Ecuador but worldwide.

Author Contributions

SH manuscript design and writing, elaboration, and edition of figures. FV compilation of satellite and DOAS information and elaboration of figures. JB analysis and interpretation of seismic data and elaboration of the corresponding figures. BB analysis and interpretation of satellite data associated with the plume dispersal and elaboration of corresponding figures. PE and PM analysis of deformation data through INSAR and elaboration of corresponding figures. SV and RC development of the algorithm aiming to calculate SO_2 masses from TROPOMI images. JS analysis of permanent DOAS data; MC, MA, and EG follow up of the activity and rapid reports preparation. SHe, MR, AB rapid assessment of seismic data. MFN and GP compilation of social networks reports. All coauthors revised the manuscript and participated in writing.

Acknowledgements

We acknowledge the use of data from NASA's Fire Information Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms), part of NASA's Earth Observing System Data and Information (EOSDIS) and the W-VAAC. We thank the European Space Agency and Alaska Satellite Facility (ASF) for providing us SENTINEL-1 data to study and monitor the volcano deformation. We also thank the continuous collaboration from ECU-911 and SNGRE (*Servicio Nacional de Gestión de Riesgos y Emergencias*), the *Ejercito Ecuatoriano* for providing aircrafts for the maintenance of SAGA station, and the ROVE (*Red de Observadores Volcánicos del Ecuador*). We deeply acknowledge VDAP – USGS – USAID for their continuous support and specifically in this case for providing seismic, infrasound and gas stations to improve Sangay's monitoring network. SV is funded by the PAPIIT project number #IA102221. This report has been conducted in the context of the *Proyecto de Generación de Capacidades para la Emisión de Alertas Tempranas de la SENPLADES* and in the frame of the *Laboratoire Mixte International: Seismes et Volcans dans les Andes du Nord* (LMI SVAN, IRD).

Data Availability

Supporting information is available alongside the online version of this manuscript. Supplementary Material 1: Spectrograms between 0 and 20 Hz for the seismic signal recorded at the vertical component of SAGA station, Supplementary Material 2: IG-reports and, Supplementary Material 3: Log of the 1–2 December 2021 major eruption, interactions and proceedings IG-EPN staff and authorities. All data used in this report is available under request.

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