



Developing hazard scenarios from monitoring data, historical chronicles, and expert elicitation: a case study of Sangay volcano, Ecuador

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Abstract

Sangay volcano is considered as one of the most active volcanoes worldwide. Nevertheless, due to its remote location and low-impact eruptions, its eruptive history and hazard scenarios are poorly constrained. In this work, we address this issue by combining an analysis of monitoring data and historical chronicles with expert elicitation. During the last 400 years, we recognize periods of quiescence, weak, and enhanced eruptive activity, lasting from several months to several years, punctuated by eruptive pulses, lasting from a few hours to a few days. Sangay volcano has been mainly active since the seventeenth century, with weak eruptive activity as the most common regime, although there have also been several periods of quiescence. During this period, eruptive pulses with VEI 1–3 occurred mainly during enhanced eruptive activity and produced far-reaching impacts due to ash fallout to the west and long-runout lahars to the south-east. Four eruptive pulse scenarios are considered in the expert elicitation: strong ash venting (SAV, VEI 1–2), violent Strombolian (VS, VEI 2–3), sub-Plinian (SPL, VEI 3–4), and Plinian (PL, VEI 4–5). SAV is identified as the most likely scenario, while PL has the smallest probability of occurrence. The elicitation results show high uncertainty about the probability of occurrence of VS and SPL. Large uncertainties are also observed for eruption duration and bulk fallout volume for all eruptive scenarios, while average column height is better characterized, particularly for SAV and VS. We interpret these results as a consequence of the lack of volcano-physical data, which could be reduced with further field studies. This study shows how historical reconstruction and expert elicitation can help to develop hazard scenarios with uncertainty assessment for poorly known volcanoes, representing a first step towards the elaboration of appropriate hazard maps and subsequent planning.

Keywords Sangay volcano · Eruptive chronicles · Expert elicitation · Hazard scenario · Uncertainty quantification

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Resumen

El volcán Sangay es considerado uno de los más activos del mundo. Sin embargo, debido a su ubicación remota y a sus erupciones de bajo impacto, su historia eruptiva y los escenarios de peligro están poco constreñidos. En este trabajo abordamos esta cuestión combinando el análisis de los datos de vigilancia y las crónicas históricas con la consulta a expertos. Durante los últimos 400 años, reconocemos periodos de inactividad, actividad eruptiva débil y elevada, que duran desde varios meses a varios años, puntuados por pulsos eruptivos, que duran desde unas pocas horas a unos pocos días. El volcán Sangay ha estado principalmente activo desde el siglo XVII, siendo la actividad eruptiva débil el régimen más común, aunque también ha habido varios periodos de inactividad. Durante este período, los pulsos eruptivos con VEI 1–3 ocurrieron principalmente durante la actividad eruptiva elevada y produjeron impactos de gran alcance debido a la caída de cenizas hacia el oeste y lahares de largo alcance hacia el sureste. En la consulta a expertos se consideran cuatro escenarios de pulsos eruptivos: fuerte ventilación de cenizas (SAV, VEI 1–2), estromboliano violento (VS, VEI 2–3), subpliniano (SPL, VEI 3–4) y pliniano (PL, VEI 4–5). SAV se identifica como el escenario más probable, mientras que PL tiene la menor probabilidad de ocurrencia. Los resultados de la elicitación muestran una gran incertidumbre sobre la probabilidad de ocurrencia de VS y SPL. También se observan grandes incertidumbres para la duración de la erupción y el volumen global de caída para todos los pulsos eruptivos, mientras que la altura media de la columna está mejor caracterizada, en particular para SAV y VS. Interpretamos estos resultados como consecuencia de la falta de datos volcánico-físicos, que podría reducirse con nuevos estudios de campo. Finalmente, este trabajo muestra cómo la reconstrucción histórica y la elicitación de expertos pueden ayudar a desarrollar escenarios de peligro con evaluación de incertidumbre para volcanes poco conocidos, representando un primer paso hacia la elaboración de mapas de peligro apropiados y la subsecuente planificación.

Introduction

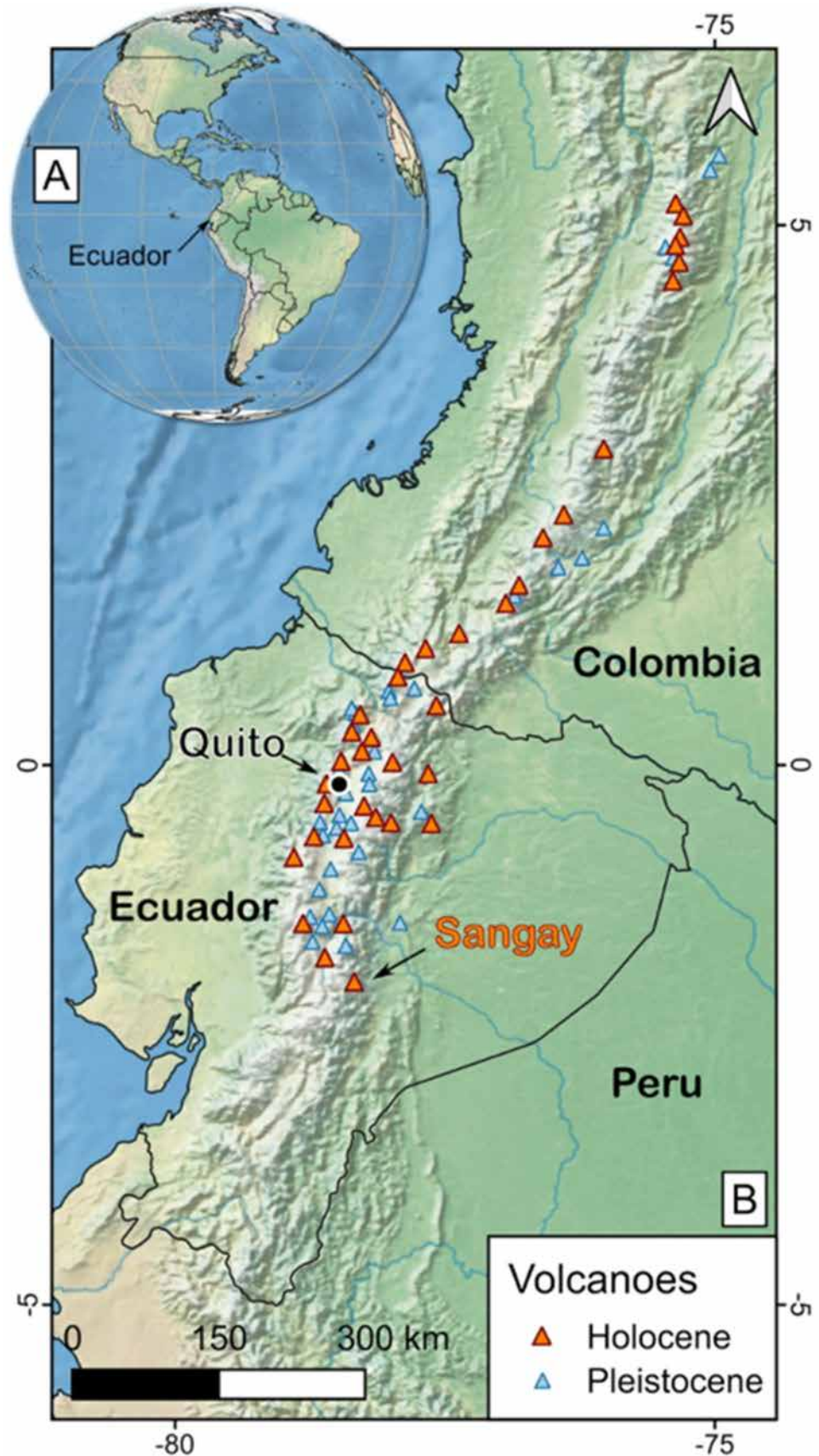
Unexpected eruptions at poorly known volcanoes are probably a volcanologist's worst nightmare because of the substantial uncertainties stemming from the limited availability of data. The sudden eruptions of Reventador (Ecuador) in 2002 (Hall et al. 2004) and Chaitén (Chile) in 2008 (Carn et al. 2009), serve as vivid examples of the potential impacts of poorly known volcanoes. In the last decades, thanks to mapping and modeling efforts and the implementation of geographic information systems, major improvements have been done in volcanic hazard and risk assessments, both from a methodological point of view and also by increasing the number of volcanoes studied (Jenkins et al. 2014; Connor et al. 2015; Ogburn et al. 2023). Nevertheless, many active volcanoes still lack geochronological and volcanophysical studies which translate into a misrepresentation of the actual volcanic threat. The study of the historical activity, when documented, is therefore a first step toward a proper and reliable hazard assessment (Hall 1977; Rosi 1996; Thouret et al. 2002; Le Pennec et al. 2008; Pistolesi et al. 2011; Drymoni et al. 2023).

Sangay volcano (latitude: 2.005 S; longitude: 78.342 W; 5307 m above sea level—ASL) is located in Ecuador, about 200 km south of the capital Quito (Fig. 1). It is positioned on the eastern flank of the Cordillera Real and is the southernmost active volcano in the Northern Volcanic Zone of the Andes, which includes Ecuadorian and Colombian volcanoes. Sangay is a large stratovolcano measuring 18 × 12 km, elongated in the E-W direction, with a relief of about 2900 m. Its summit is the site of several craters and domes

that have been active at different periods in recent history (Hidalgo et al. 2022; Vasconez et al. 2022). Its eastern flank plunges into the Amazon rainforest, while it is surrounded to the north, west, and south by high grassland or páramos. Due to its location, extreme humid weather conditions and access limited to a difficult 2-day trail, Sangay's geology and recent activity are still poorly known. Monzier et al. (1999) recognized the construction of three successive edifices in the evolution of this volcano. The constructive phases of Sangay developed over the last 500 ky and are separated by large landslides and debris avalanches that propagated eastwards, far into the Amazon basin (Valverde et al. 2021). Other studies have focused on the particular composition of its magma, which is associated with its unique location at the southern end of the Northern Volcanic Zone (Monzier et al. 1999; Narvaez et al. 2018). The Global Volcanism Program reports only 11 confirmed Holocene eruptions with volcanic explosivity indexes (VEI) estimated between 1 and 3.

In this work, we look at two complementary approaches to reconstruct the recent eruptive activity and build hazard scenarios at Sangay volcano. First, we examine the monitoring data on the last decades of Sangay's activity to create a decision matrix used to interpret historical chronicles and newspaper articles. This allows us to compile historical eruptions and attribute them to a specific type of activity and estimate the associated VEI. Second, we develop an expert elicitation process to constrain the probabilities of occurrence and the eruption source parameters of the hazard scenarios with uncertainty quantification. This study marks the initial phase of a comprehensive re-assessment of the volcanic hazard at Sangay. Such an undertaking is essential

Fig. 1 Location of Sangay volcano. **A** orthographic world-view centered on Ecuador; **B** map of the Northern Volcanic Zone of the Andes. Base map: Natural Earth 1:10 M (<https://www.naturalearthdata.com/>); Quaternary volcanoes: Global Volcanism Program (2023)



for enhancing risk assessment, given the persistent activity of Sangay volcano and the above-described practical limitations to address its eruptive history.

Data and methods

Recent activity and historical reconstruction

Over the last 20 years, the eruptive activity of Sangay volcano has been constantly monitored using a variety of methods. The first seismo-acoustic records of Sangay's activity were obtained by Johnson et al. (2003) between 1997 and 2000. Carn et al. (2008) used satellite data to assess SO₂ outgassing over the period 2004–2006. Morales Rivera et al. (2016) studied ground deformation between 2007 and 2011 using InSAR. Ortiz et al. (2021) examined data from an infrasound network installed in Riobamba between 2006 and 2013 and compared the explosion record with satellite-detected hotspots. Vasconez et al. (2022) analyzed the period 2001–2020 using a multi-parameter dataset including seismic data, satellite thermal anomalies, SO₂ outgassing, and ash cloud advisories. They also proposed a model of magma discharge based on the recharge, cooling, and viscous relaxation time relationship, which could explain the eruptive activity over the study period. Bernard et al. (2022) studied the September 20, 2020 eruptive pulse in detail using monitoring data and associated regional ash fallout. Hidalgo et al. (2022) studied a series of specific events, both internal and subaerial, that altered the morphology of the summit area in a matter of days in November to December 2021. Ash clouds and fallouts in Guayaquil from the June 2020, September 2020 to April 2021 were characterized using meteorological weather stations, weather forecasts, and satellite imagery, as well as particle size distribution and scanning electron microscopy (Moran-Zuloaga et al. 2023). These recent studies are used here to define the main types of activity at Sangay volcano. This information is complemented by field reports and newspaper chronicles to build impact scenarios and a decision matrix to classify historical eruptions.

The historical chronicles were first compiled by José Egred, former member of the Instituto Geofísico de la Escuela Politécnica Nacional (IG-EPN), and were used in part by Monzier et al. (1999). Here, we build on and complement this previous work. Original citations are extracted in their native languages (Spanish, French, German, and English) in national (<https://www.bne.gob.ec/>) and international (<https://www.bne.es/>, <https://gallica.bnf.fr/>, <https://books.google.com/>) databases. Some non-digitized references come from the Ecuadorian National Library “Eugenio Espejo.” Newspaper articles from the pre-digital era come from José Egred and Minard L. Hall personal archives at IG-EPN. The transcripts of the historical documents are

available in the Electronic Supplementary Material 1. The Global Volcanism Program (<https://volcano.si.edu/>) bulletin reports, as other scientific sources, are used for the 1972–2003 period as well. All this information is examined in the light of recent activity in order to extract meaningful qualitative and quantitative information on eruptive processes and the impact of eruptions. This enabled us to compile 63 eruptive periods and pulses since 1628, which are summarized in the Electronic Supplementary Material 2.

Expert elicitation basics

Performance-based expert elicitations rely on the external and empirical validation of expert probability assessments (Colson and Cooke 2018; Quigley et al. 2018). Experts are asked to provide their estimate of the probability distributions for quantities whose true values are known, called “seed items.” This provides calibration weights for experts. Then, the elicitation process is repeated for unknown quantities or parameters, called “target items.”

For both seed and target items, a performance-based algorithm produces group-synthesized uncertainty distributions, commonly called decision-maker (DM) solutions (Cooke 1991; Aspinall 2006, 2010), through a weighting scheme (or “pooling method”) to combine the experts' answers, i.e., individual uncertainty distributions representing the experts' opinions (Cooke 1991; Bevilacqua 2016; Quigley et al. 2018).

Seed items measure each expert's individual performance in uncertainty quantification and should comprise factual questions that are (i) designed to be as similar as possible to the target questions, (ii) with exact answers known to the analysts, and for which (iii) experts are expected to be able to provide credible intervals. For both seed and target questions, experts generally provide their credible intervals by expressing probability distributions implied by the 5th, median, and 95th percentiles. The case where all the experts are assigned the same weight is called the equal weight (EW) rule.

In the Sangay elicitation, we compared the results obtained by applying the EW rule with those obtained with the classical model (CM; Cooke 1991) and the expected relative frequency (ERF; Flandoli et al. 2011): details of the latter two weighting schemes are provided in the Electronic Supplementary Material 3. An early version of the recently released Python tool ELICIPY (de' Michieli Vitturi et al. 2024) allowed us organizing and managing performance-based expert elicitation sessions. The online tool performs all the steps of an elicitation session that are (i) the generation of webforms to collect the experts' answers (checked for errors and consistency), (ii) the analysis of the answers using different weighting schemes, and (iii) the automatic

production of outputs in different formats to create a presentation file available just after the collection of the answers.

Type of activity at Sangay volcano in recent times

Based on previous studies and geophysical and geochemical monitoring data since 2000, we classified the eruptive activity of Sangay in *quiescence*, *weak* and *enhanced eruptive activity*, and *eruptive pulses*, which are described in detail below. This subdivision is then applied in section “[Historical reconstruction](#)” to classify the eruptive activity in the period 1532–2003.

Quiescence

Quiescence is defined as a state of calm or inactivity for a prolonged period (Fig. 2). Vasconez et al (2022) identified six periods of quiescence in the interval 2001–2020. These periods last between 5 and 20 months and are characterized by minimal seismic activity (< 1 event/day), low SO_2 emissions (average 10–40 t/day), the absence of satellite-based

thermal anomalies, and no more than a few isolated ash clouds (average 1 km above the crater level, ACL; maximum 1.5 km ACL) that dissipate rapidly (< 25 km from the crater). In terms of impacts, volcanic activity during the quiescent period is dangerous only in the proximity of the crater and fumarole fields.

Weak eruptive activity

Weak eruptive activity is the most common behavior of Sangay volcano during the 2000–2023 interval (Electronic Supplementary Material 2). Two types of weak eruptive activity can be distinguished: long-lasting periods and short episodes (Vasconez et al. 2022).

The long-lasting periods last for several years and are characterized by a low rate of seismic events (average of eight explosions per day for the period 2006–2013 in Ortiz et al. 2021; average of 18 earthquakes per day for the period 2006–2013 in Vasconez et al. 2022), a low lava emission rate ($\sim 0.3 \text{ m}^3/\text{s}$; Vasconez et al. 2022), SO_2 degassing undetectable by satellite (Carn et al. 2008), and flank creep unrelated to magma chamber pressurization (Morales Rivera et al. 2016). During these periods, satellite-detected ash clouds are rare ($< 1/\text{month}$), low altitude (average 1–1.2 km ACL, maximum 3.0–3.2 km ACL), and dissipate rapidly into the atmosphere (average 40 km from the crater; Fig. 3).

In contrast, short episodes last only for a few weeks to months and are characterized by intermediate seismic event rates (average 72–88 earthquakes per day; Vasconez et al. 2022), intermediate lava emission rates ($0.8\text{--}1.5 \text{ m}^3/\text{s}$; Vasconez et al. 2022), and low SO_2 outgassing (average of 10 t/day and maximum of 224 t/day for the 2015 episode; Vasconez et al. 2022). During these episodes, ash clouds detected by satellites are more frequent ($\sim 15/\text{month}$) but remain at low altitude (average 1.0 km ACL, maximum 2.9 km ACL) and dissipate rapidly (average 44 km from the crater).

Although it can be argued that long-duration periods are much weaker than episodic phases in terms of seismic event frequency and emission rate (Vasconez et al. 2022), they both have similar eruptive column heights and limited impact scenarios. Impacts produced by weak eruptive activity are generally limited to the upper half of the volcanic cone and pose a serious threat only to climbers trying to reach the summit. Hazardous volcanic phenomena are mainly ballistic projectiles and short-distance lava flows (< 1.5 km), whose fronts are prone to small collapses. Rare ash fallouts have caused some inconvenience to local communities (< 50 km from the volcano), but are generally too small to cause damage to crops or livestock and could even be used as fertilizer (Ligot et al. 2024). Noises originating from the volcano were not heard outside its immediacy (< 10 km from the crater). Evidence of glow or incandescence during weak eruptive activity are scarce (IG-EPN

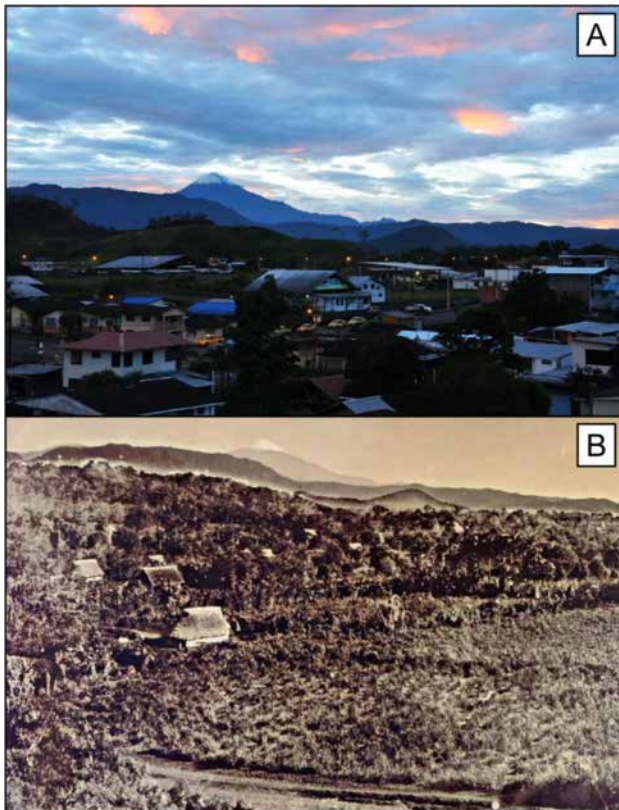


Fig. 2 Quiescence at Sangay volcano seen from Macas. **A** May 6, 2015 (credit: B. Bernard); **B** probably 1930s (downloaded from <https://rb.gy/yymj2r>, Anon)



Fig. 3 Weak eruptive activity at Sangay volcano. **A** November 17, 2009: foreground Altar volcano, background Sangay volcano with a ~500 m ACL ash cloud (credit: B. Bernard); **B** September, 1983: Sangay volcano with ash emission at crater level and directed toward the west (credit: K. and M. Krafft)

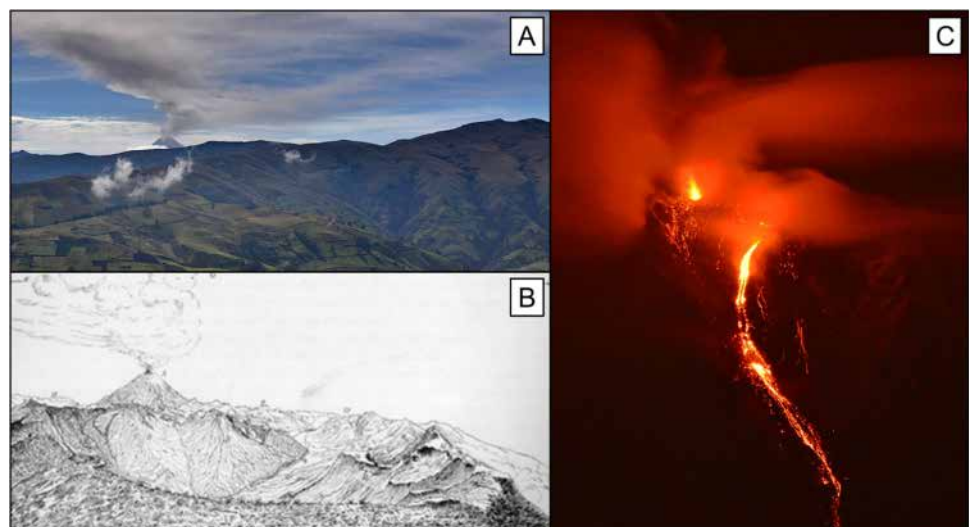
2018), partly due to atmospheric conditions in the vicinity of the volcano, but also due to the reduced luminous intensity of emissions. Based on the column height and range, individual explosions and emissions during weak eruptive activity are expected to have a VEI between 0 and 1.

Enhanced eruptive activity

Enhanced eruptive activity has been consistently observed during the current eruptive period (2019 to ongoing) and has manifested itself in two different but mostly coincident ways: (1) an increase in lava emission rate and (2) an increase in the frequency of explosions.

Since 2019, Sangay showed a clear increase in lava emission rate (average $5 \text{ m}^3/\text{s}$; Vasconez et al. (2022)), reaching three times the value for previous episodic phases and 15 times the value for long-lasting periods. This is evidently accompanied with an increase of lava flow length that commonly reaches more than 1.5 km (Fig. 4) and up to 4.5 km in length. The increase in emission rate triggers numerous lava front collapses forming pyroclastic density currents (PDCs) that erode the soft pyroclastic material from the upper southeastern flank and ultimately led to the formation of a > 500-m-wide and > 200-m-deep ravine (Bernard et al. 2022; Hidalgo et al. 2022; Vasconez et al. 2022). The PDCs reach up to 7 km and the input of volcanic material into the Volcán river is such that it accumulated a wide debris fan at the confluence between Volcán and Upano rivers, creating a temporary lagoon upstream in the Upano watershed (Vasconez et al. 2022). Periodic drainage of this lagoon and intense rainfall have repeatedly eroded this fan, increased the sediment load in the Upano river, and affected its riverside. As a consequence, a community of 30 people living on the riverside of the Upano river was forced to evacuate (El Telégrafo 2019), and the access road to the main bridge

Fig. 4 Enhanced eruptive activity at Sangay volcano. **A** September 13, 2022: ash plume from Sangay directed westward (credit: B. Bernard); **B** 1872: drawing of an ash plume from Sangay directed westward (credit: A. Stübel); **C** December 26, 2021 explosion and lava flow in the southeast drainage (credit: B. Bernard)



joining Macas and Puyo was destroyed repeatedly (El Telégrafo 2021; El Universo 2022a; Expreso 2023). A peculiar sequence occurred at the end of November to the beginning of December 2021 that led to the opening of a new vent and a new lava flow on the northern flank of the volcano (Hidalgo et al. 2022). During this activity, incandescence and eruptive sounds were reported from Palora (54 km N51° from Sangay) and El Altar (37 km N345°). This lava flow was active for about 6 months and then, in July 2022, the activity focused again on the central vent and the southeast ravine.

Enhanced eruptive activity is also evidenced by a significant increase in the frequency of seismic events. According to the IG-EPN catalog, the number of seismic events for the 2019–2023 period averages more than 200 events per day, ~80% of which being eruptive signals (i.e., explosions and emission tremors). During this period, seismic activity exceeded 1000 events per day on 40 days. Furthermore, sounds from the volcano are heard frequently in the local communities and sometimes in distant cities such as Macas (42 km N146°), Riobamba (51 km N317°), Cuenca (124 km N217°), and Guayaquil (175 km N267°) (Expreso 2022; El Universo 2022b). Such explosive activity is associated with a clear increase of ash cloud detections (average 90/month) and reach (average 66 km from the crater; Fig. 4), while the height (average 1.1 km ACL, maximum during eruptive pulse) remained similar to weak eruptive activity. Occasionally, high altitude ash clouds (> 3.5 km ACL) are observed dissipating rapidly and associated with discrete explosions, such as those observed in July 10, 2020 and April 29, 2024. As a consequence, since 2019, numerous ash fallout events have been reported from local communities (< 50 km from the volcano).

Along with the increased lava emission and explosive activity, one of the most evident changes from weak to enhanced eruptive activity is a significant increase (up to 50 times) of SO₂ degassing (average 500 t, maximum 4500 t). A consequence of the recent enhanced eruptive activity is the multiplication of photographic evidence of incandescence, both of the explosive and effusive activity, observed from viewpoints located dozens of kilometers away from the volcano (Fig. 4). Even though the volcanic activity assigned to this category is much stronger than that assigned to the weak eruptive activity category, most of the individual explosions and emissions recognized as part of enhanced eruptive activity periods have probably a VEI between 0 and 1. Interestingly, during the 2019 to ongoing period, the enhanced eruptive activity has been punctuated by eruptive pulses which are described in the following paragraphs.

Eruptive pulses

Eruptive pulses occurred at a much shorter time scale (hours to days) than the previous types of activity and two

sub-categories of eruptive pulses have been observed. The first sub-category of eruptive pulses is identified as strong ash venting (SAV). These pulses have become common since November 2019 and are frequently associated with peaks of lava emission rate and PDCs formation (Vasconez et al. 2022; Bernard et al. 2022). They are characterized by a clear increase of the seismic amplitude in the SAGA monitoring station located 6 km southwest of the crater, and much more elusive signals in the regional seismic network. SAVs generally last for hours to days with typical column height < 5 km ACL, bended eruptive plumes (Fig. 5), and sometimes higher (up to 8 km ACL) pulsatile mostly gas clouds. During a SAV event, ash clouds frequently reach more than 100 km from Sangay. On several occasions, this activity has resulted in moderate-intensity ash fallout (100–1000 g/m²) in local communities (< 50 km from Sangay) causing crop damages, and



Fig. 5 Eruptive pulses at Sangay volcano. **A** June 12, 2020: continuous bended plume seen from Macas (credit: Secretaría de Gestión de Riesgos); **B** March 11, 2021: darkness in Riobamba (credit: Red de Observadores Volcánicos del Ecuador); **C** May 7, 2021: lava flow seen from Macas (credit: ECU-911)

lesser amounts in more distant areas (Moran-Zuloaga et al. 2023), sometimes causing flight cancellations (e.g., Guayaquil on August 13, 2022; Swissinfo 2022) up to airport closures (e.g., Cuenca airport on December 11, 2019; Guayaquil airport on June 08–11, 2020; El Diario Ecuador 2019; El Universo 2020a). During the June 08–11, 2020 SAV event, PDCs traveled about 11 km in the Volcán river and their deposits were the source of lahars that reached the confluence with the Upano river on June 21, 2020 (El Universo 2020b). At least 14 SAVs occurred from 2019 to 2023 with VEI estimated between 1 and 2 (Fig. 6, Electronic Supplementary Material 2). Looking at previous eruptive periods of recent activity, only the September 18, 2018 event, which produced a small tephra fallout in Guayaquil, can be considered a SAV event.

The second sub-category of eruptive pulses is identified as violent Strombolian (VS; Bernard et al. 2022). Until writing of this manuscript (December 2023), these pulses only occurred between September 2020 and May 2021 and are easily spotted on both local and regional seismic records. They are also associated with large SO_2 emissions (typically > 7500 t and maximum > 45,000 t) as measured by TROPOMI, high lava emission rate (> 20 m^3/s ; Fig. 5), and PDCs formation. According to the monitoring data, VS events lasted between 2 and 6 h with typical high (5–10 km ACL) eruptive plumes that create wide umbrella-shaped ash clouds. These events provoked strong ash fallout (> 1000 g/m^2) in local communities and systematically affected multiple provinces of Ecuador (Bernard et al. 2022; Moran-Zuloaga et al. 2023). According to the Secretaría de Gestión de Riesgos, the March to May 2021 series of VS events affected about 500,000 people, 145,000 ha of crops, and 235,000 farming animals (<https://shorturl.at/dsX47>). Five eruptive pulses are identified as VS with VEI between 2 and 3 (Fig. 6, Electronic Supplementary Material 2).

Phenomenology and impact scenarios

Based on recent activity at Sangay volcano, a series of phenomena and associated impacts have been identified and summarized in Table 1. This table enables us to classify past events on the basis of the description of the eruption and/or its impacts. Most geophysical and geochemical monitoring signals have been omitted from this table because historical eruptions have no instrumental monitoring data.

Historical reconstruction

From 1532 to 1728: scarce information

The first written chronicle of Sangay's eruptions dates from November 3, 1628 and corresponds to the proceedings of Riobamba's city council (Electronic Supplementary Material 1), which reported strong eruptions for a month that covered the town with ash, "turning days into nights," and also covering fields and pastures, causing starvation and the death of livestock (Lewis 1950). Based on this description and comparing with the recent period, it seems that during this month several eruptive pulses occurred during an enhanced activity period. Although it is difficult, based solely on the description of the impact in the Riobamba region, to estimate precisely the size of these eruptions, we assume that they were at least as large as the eruptions of March to May 2021 (VEI 2–3). Furthermore, we did not find a distinctive layer of ash and lapilli on top of the current soil near Sangay volcano, and we therefore consider unlikely that the eruptions of 1628 reached a VEI of 4, although they may have been Suplinian (VEI 3).

Prior to 1628 and from 1628 to 1728, there are no historical chronicles of Sangay's eruptions. This may be attributed to periods of quiescence, a lack of observations or the fact

Fig. 6 Timeline of the recent activity at Sangay volcano. **A** 2000–2023 period with eruptive period distinction; **B** 2019–2023 period with eruptive pulses

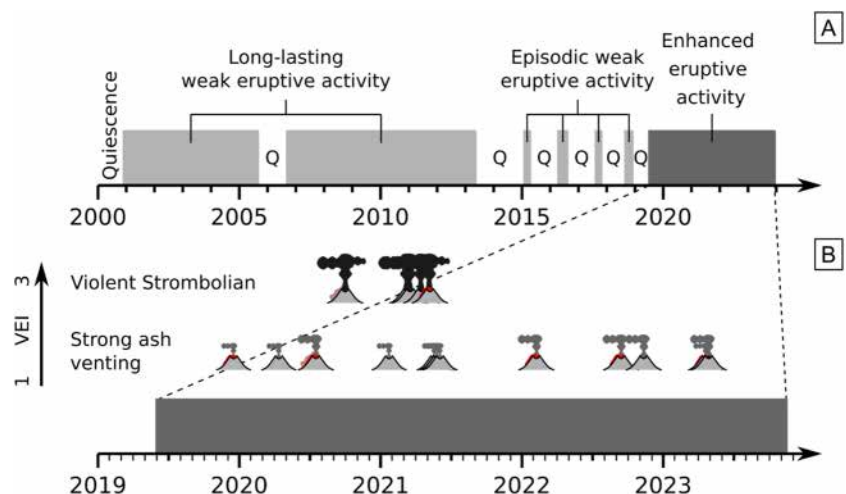


Table 1 Decision matrix based on the recent eruptions of Sangay volcano to define activity types

Eruptive activity	Duration	Lava flows	Pyroclastic density currents	Explosions	Eruptive columns	Incandescence	Sound	Local ash fallout (< 50 km)	Regional ash fallout (> 50 km)	Macas-Puyo road cut
Quiescence	Months to years	No	No	Rare (phreatic?)	Mostly gas and low altitude (< 1.5 km)	Possible glow from high temperature gas	No	No	No	No
Weak eruptive activity	Months to years	< 1.5 km in length, on top of the flank	< 3 km from the vent	Regular (hours to minutes)	Low to intermediate altitude (< 3.5 km ACL) and pulsatile	Rare glow from explosions and lava flows	Rare and local (< 50 km)	Rare and probably small < 100 g/m ² /d	Rare and probably small < 10 g/m ² /d	No
Enhanced eruptive activity	Up to years	Frequently > 1.5 km and up to 4.5 km in length, in ravines	Up to 7 km from the vent	Frequent (minutes to seconds)	Low to intermediate altitude (< 3.5 km ACL), pulsatile and continuous-plumes	Regular glow from explosions and lava flows	Regular and regional (> 50 km)	Frequent and very small to small < 100 g/m ² /d	Regular and very small < 10 g/m ² /d	Regular (months to years)
Eruptive pulse	Hours to days, recurrence interval from days to months	During periods of high emission rate	Up to 13 km from the vent	Frequent to continuous blast	Intermediate to high altitude (1.5–10 km ACL), bended plumes and umbrella clouds	Regular glow from explosions and lava flows	Regular and regional (> 50 km)	Always and intermediate to strong 0.1–10 kg/m ² /d	Frequent and small to intermediate < 1 kg/m ² /d	Frequent (after the eruptive pulse)

that chronicles are scarce and may not have been found. These last two hypotheses are most often suggested by naturalists and volcanologists at that epoch (Wolf 1892; Lewis 1950). Eruptive pulses (VEI 1–3) may have occurred and smaller eruptions (VEI 0–1) are likely to have occurred during this period, but there is no confirmation.

From 1728 to 1912: the arrival of scientists and explorers

From 1728 to 1903, Sangay was mostly constantly active (La Condamine 1751a; Wolf 1892). From November 19 to 26, 1738, La Condamine reported from Siçapongo (probably close to Sicalpa Viejo, 59 km N304°), which they could clearly see the volcano's flames (La Condamine 1751b). From late March to early April 1739, La Condamine reported even greater activity from Tioloma (46 km N225°), with incandescence all over the volcano and a lava flow on the SW flank (La Condamine 1751b). He also reported that the sound of the eruption was heard in Guayaquil. Such reports indicate that Sangay probably had enhanced eruptive activity between 1738 and 1739.

During his visit to Ecuador, von Humboldt (1855) mentioned hearing Sangay explosions from Quito (203 km N356°) in 1802. Although not confirmed with ash fallout reports, such an eruption could be considered as enhanced eruptive activity. He also mentioned eruptions from Sangay in 1842 and 1843 being heard in Guayaquil, Païta (459 km N222°) and San Buenaventura (1114 km N173°) in Peru. This activity has not been confirmed by regional ash fallout, but if confirmed, would require an eruptive scenario greater than enhanced eruptive activity and probably several eruptive pulses.

One of the most detailed descriptions of the activity of Sangay volcano belong to Sébastien Wisse that climbed Sangay volcano on December 21, 1849 (Arago et al. 1853). Wisse classified the explosions in three groups: (1) weak, with ejecta only inside the crater; (2) strong, with ejecta reaching the flank of the volcano; (3) extraordinary, with ejecta covering the flank and going down into the ravines. He also compared this activity to what La Condamine observed in 1739. Wisse described the sound of the explosions as thunder that is generally preceded by a sort of bel- low called “bramido” in Ecuador. He counted 267 explosions in 1 h, which is not surprising based on the recent seismo-acoustic records from Sangay. All this information points to an enhanced eruptive activity at the end of 1849.

Stübel (1897) reported frequent explosions during an expedition between April 23 and May 6, 1872. The whole period might be interpreted as enhanced eruptive activity while the activity during the April 30 night that produced a 2-mm tephra fall at Nagsangpungo (13 km N250°) could be classified as a SAV event. His drawing of the ash plume

resembles the activity observed in 2022 (Fig. 4). He also reported ash fallout in Alao (24 km N308°) on December 2, 1872 and in Riobamba on December 27, 1872 that can be interpreted as enhanced activity (Stübel 1873). Reiss indicated in 1874 that lava was flowing without pause for 4 years on the eastern flank of the volcano (Wolf 1892). This activity is quite similar to the 2019 to the ongoing eruptive period and might have had more eruptive pulses.

Whymper (1892) reported having heard the sound of Sangay's activity from the Chimborazo area on December 20–21, 1879. Such activity was apparently common, based on the natives' reaction, and can be characterized as enhanced eruptive activity. He observed Sangay's activity from Chimborazo volcano on January 5, 1880. He made a precise observation of the emissions occurring with a recurrence interval of 20–30 min and reaching 1.5–1.8 km ACL. He also reported frequent sounds heard from Guaranda (87 km N303°). The emission was highly pulsatile with ash clouds rapidly dissipating in the sky. Wolf (1892) stated that sounds from Sangay's activity were frequently heard in Guayaquil and that the volcanic ash sometimes fell in the Pacific. This would refer to enhanced activity with maybe some eruptive pulses, but without precise date.

The report done by Meyer (1907) of his expedition from Guayaquil to Riobamba (June 10–12, 1903) gives details on the extent of the tephra fallout, noting its presence in Bucay (95 km N258°) and abundance in Guamote (42 km N281°). On June 16, 1903, Meyer described a spectacular eruption from Sangay volcano seen from the flank of Chimborazo volcano. The eruptive column reached between 10 and 11 km ASL (4.7–5.7 km ACL) and Meyer could hear the roar of the eruption from 75 km N315° of the volcano. The eruption produced a continuous ash cloud that was directed toward the west and southwest and Meyer estimated an interval of 8–10 min between the vigorous emissions. The height of the eruptive column suggests that this was probably a VS event.

On the basis of the many testimonies of scientists and explorers reported during the period 1728–1912, Sangay volcano was active most of the time. Almost constant weak eruptive activity was observed and enhanced eruptive activity sometimes lasting for years was frequent. On at least two occasions, evidence points to eruptive pulses in the form of grouped events during enhanced eruptive activity periods (1842–1843, June 1903). No eruptions with $VEI \geq 4$ are interpreted to have occurred during this period.

From 1912 to 1972: the information age

From 1912 to 1972, most of the chronicles of Sangay's eruptions come from newspaper articles and climbers' testimonies. El Comercio (1913) reported two regional tephra fallout on October 9–10, 1912 (Alausí 60 km N249°; Guamote)

and January 25, 1913 (Riobamba in almost complete darkness). Based on their description, we associate them to eruptive pulses. El Observador (1919) reported loud noise and volcanic gas in Riobamba on March 22, 1919. This activity can be characterized as enhanced eruptive activity.

In the 1920s, several excursions to Sangay were undertaken with varying degrees of success. A failed attempt in 1925 (Dyott 1929) suggests weak eruptive activity, while the first confirmed ascent of the summit on August 4, 1929 indicates a period of quiescence with only gas emissions from the summit craters (Moore 1950).

Although Hall (1977) mentions 1934–1937 as an eruptive period, the lack of chronicle from the 1930s points to a period of quiescence or non-threatening weak eruptive activity. A photo of Macas, probably from this period, according to the city's development, shows the Sangay volcano with no surface activity (Fig. 2). Such apparent quiescence was interrupted when Sangay erupted on November 8, 1941 (El Universo 1941a). This eruption, described as violent and spectacular, provoked tephra fallout in Palmira (45 km N262°), Colta (59 km N306°), and Riobamba, where noises were heard as well. Such activity can be characterized as an eruptive pulse. Few days later, more noise was reported from Sangay volcano (El Universo 1941b). On November 21 of the same year, a tephra fall and sound of the eruption were also reported in Riobamba (El Universo 1941c). Based on the shape of the eruptive plume (elongated toward the west) and its height (0.6 km above the crater), this eruption probably corresponds to a SAV event. A note in El Comercio (1942) and the testimony of Misael Acosta Solís (El Comercio 1944) also suggested enhanced eruptive activity with tephra fallout in Carnicería Tambo (6 km N254°) and numerous explosions.

On June 22–23, 1954, El Comercio (1954) mentioned sound heard from Paccha and Combueno, near Macas. In the note, the journalist discarded Sangay being the source of the noises but recent experience has shown that particular atmospheric conditions can provoke the sound to reach Macas (El Universo 2021). In 1956, Winckell (1997) described a lava flow coming down the northern flank of the volcano. On March 23, 1959, loud noises were heard in Riobamba, explosions every 2–3 s and tephra fallout in Guayaquil (El Comercio 1959a). The April 5, 1959 eruption occurred during daytime with a clear view of the high mushroom-shaped eruptive column (El Comercio 1959b). On September 23, 1959, an eruption produced another tephra fallout that affected the provinces of Guayas, Azuay, and Cañar (El Comercio 1959c). Those three consecutive events fit the description of recent eruptive pulses. This activity is coherent with the emplacement of La Playa PDC deposits and subsequent lahars between 1956 and 1965 according to aerial photographs (Hall 1977; Monzier et al. 1999). The young “spaghetti” lava field on the northwestern flank may

also have been emplaced around this time and corresponds to a period of enhanced eruptive activity (Monzier et al. 1999).

We could not find any mention of Sangay's activity in the 1960s chronicles. An ascent report from 1967 suggest a weak eruptive activity (Bonington 1973). On June 1–2, 1971, another ascent to the summit reported numerous explosions (75 in 1 day) and described the experience of being at the top of the active volcano with scoria falling around them (El Comercio 1971). This can be also considered weak eruptive activity.

Based on these observations, it is possible to say that Sangay was active also for most of the 1912–1972 period. Complete quiescence for weeks was reported during the 1929 summit ascent (Moore 1950) but could have been common during the 1930s and 1960s. Weak eruptive activity was common throughout this period. Enhanced eruptive activity was observed in the 1910s, 1940s, and 1950s with many reports of noise from the surrounding cities and in close chronological relationship with eruptive pulses (1912–1913, 1941, 1959) that were reported by the media. No eruption $VEI \geq 4$ occurred during this period.

From 1972 to 2003: the beginning of volcanological studies

A significant shift in observational practices occurred with the arrival of Minard L. Hall to Ecuador in 1972. Thanks to the efforts of Hall and his team, Sangay's activity became a real case study with scientific reports and research. On January 11, 1974, Hall described a continuing eruptive activity with frequent explosions every 20–30 min (Global Volcanism Program 1974). A first expedition visited the volcano during the week of May 24 to June 1, 1975 and described a new lava flow on the western flank of the volcano that descended to approximately 3800 m ASL (Global Volcanism Program 1975). During this expedition, Hall also observed almost continuous gas emissions from a vent in the summit crater and infrequent ash emissions from a different vent also located in the summit area. A second expedition was carried out from July 28 to August 9, 1976, during which they observed mild explosions every 6–12 h with eruptive columns rising only 100 m above the crater and a new lava flow from the south crater that descended on the western flank several hundred meters (Global Volcanism Program 1976). On August 10, 1976, an independent British team attempted to reach the summit and an explosion that produced a 300-m-high eruptive column claimed the life of two climbers and injured three more of them due to ballistic projectiles. Based on this description, the 1974–1976 activity can be classified as weak eruptive activity.

During the 1980s, few observations were made. Krafft observed during overflights frequent explosions, every

10 min, from the western vent that formed 100–300-m-high eruptive columns and triggered small avalanches on the upper west and southwest flanks (Global Volcanism Program 1983; Fig. 3). This corresponds to weak eruptive activity. Durieux and Heiken reported only summit fumarolic activity in June 1988 and frequent explosions with small ash clouds, every 5 min, in early August 1988 (Global Volcanism Program 1988). On August 11, they observed a new lava flow from the western vent, collapses of the lava front, and larger explosions on August 13 with incandescent blocks covering the southern flank that can be characterized as enhanced eruptive activity.

A joint expedition between the IRD (former ORSTOM) and the IG-EPN between November 24 and December 12, 1995 provided further description of the activity of the volcano with the use, for the first time, of a portable seismograph (Global Volcanism Program 1996). During this expedition, the scientists observed continuous fumarolic steaming, frequent phreatic explosions (from a few hours to 26 min of interval), and rock falls from the western dome. The ash emissions reached a few hundreds of meters above the crater pointing to a weak eruptive activity. Another expedition between several US universities and the IG-EPN in April 1998 reported a relatively low-level eruptive activity, with discrete Strombolian explosions every 30 min (Johnson et al. 2003).

Therefore, during the most recent observational period, before the beginning of continuous monitoring, mostly weak eruptive activity was observed in an almost continuous fashion with at least one period that can be classified as enhanced eruptive activity (August 1988). There are no chronicles of eruptive pulses during this period, but based on unpublished field observations made during the 1995 mission, it is likely that some occurred in the 1970s.

Expert elicitation

Exercise setup

Eighteen experts took part in this exercise (listed in Table A1 of Electronic Supplementary Material 3). They were asked 15 seed questions for calibration purposes and 20 target questions. The two questionnaires were divided into thematic subsets to facilitate the experts' responses: (1) for the seed questions "Ecuadorian volcanism," "Sangay volcanism," and "eruptive source parameters"; (2) for the target questions "Sangay volcano eruptive scenarios" (subset I) and "Sangay volcano eruptive source parameters" (subset II).

In the target questions, experts were asked to give their opinion on eruptive pulses, both those belonging to categories for which there is recent evidence and available data, i.e., SAV and VS, but also those for which their occurrence is uncertain (sub-plinian, SPL and Plinian, PL). Monzier et al. (1999) mention fallout sequences, made up of 10–30-cm-thick layers of andesitic scoria and rare dacitic pumice as evidence of recent explosive activity. In particular, a 20-cm-thick layer of dacitic lapilli, located 1 m below present soil, was found near the volcano. Its geochemical composition and spatial distribution led us to consider that it originated from a recent (probably Holocene) sub-Plinian or Plinian eruption of Sangay. To facilitate the experts' task, a comparative table (Table 2) was provided to associate each pulse with, respectively, a range of VEIs, historical Sangay examples, Ecuadorian analogues, and global analogues.

For subset I of the target questions, the aim was to estimate the probability of Sangay experiencing at least one of the abovementioned scenarios in two different timeframes, namely 10 years (subset I.1) and 100 years (subset I.2) into the future. For subset II, the focus was on three eruptive source parameters, namely the average height of the column during the pulse (in km ACL), the total volume of the fallout

Table 2 Comparative table provided to the experts along with the Target Questionnaire (see also Electronic Supplementary Material 3)

Eruptive pulse	Typical VEI range	Sangay historical examples	Ecuador analogues	World analogues
Strong ash venting (SAV)	1–2	23/01/2021 28/04/2021 31/05/2021	Cotopaxi 08/2015 Tungurahua 11/2015 Reventador 07/2018	Turrialba 2010 Sabancaya 2016 San Cristobal 2020
Violent Strombolian (VS with possibly a vulcanian onset)	2–3	20/09/2020 06/03/2021 12/04/2021	Guagua Pichincha 10/1999 Tungurahua 07/2013 Tungurahua 02/2014	Telica 03/2011 Llaima 2008 Ubinas 07/2019
Sub-plinian (SPL)	3–4	1628?	Cotopaxi 1877 Tungurahua 08/2006 Reventador 11/2002	Shinmoedake 2011 Calbuco 2015 Fuego 2018
Plinian (PL)	4–5	Pre-historical?	Cotopaxi 1744 Tungurahua 1886 Guagua Pichincha 1660	Mount St Helens 1980 Chaiten 2008 Kelut 2014

deposit emitted during the pulse (in 10^6 m^3 , considered with an equivalent density of 1000 kg/m^3 to facilitate conversion from mass estimation), and the average duration of the eruption as detected by geophysical monitoring (in hours). In addition, the experts were asked to express their confidence in the answers they provided for the last three parameters, using a scale from 1 to 10 (1 being not confident and 10 being sure). Note that this estimation of confidence was mainly devised for focusing the experts on the mental exercise of comparing the uncertainties affecting the different parameters, and that the confidence results were not shown to them until they provided the estimates of the parameters.

Elicitation results

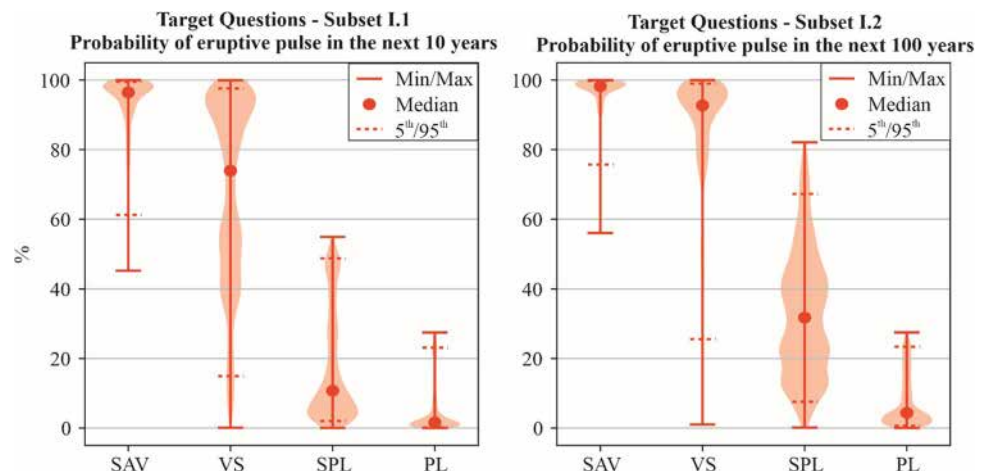
In this section, we report the results of the elicitation. The graphs in Figs. 7 and 8 show with violin plots the max/min values, the 5th/50th/95th percentile values, and the probability density functions of the decision-maker computed for the two different subsets of the target questions using the CM weighting scheme, which is here assumed as the reference one. In addition, a table summarizing the percentile values for all the target questions and the three weighting schemes (CM, EW, and ERF) is reported in Table A3 from Electronic Supplementary Material 3. Finally, confidence values about the eruptive source parameters are reported in Table 3. The full list of graphs for both the seed and target questions are available (along with all the elicitation outputs) in the powerpoint presentation given as output from ELIC-IPY (Electronic supplementary Material 3).

From the point of view of the weighting schemes, it could be observed that largest differences among CM, EW, and ERF are related to the inter-quantile ranges between the 5th and 95th percentiles, which are generally larger for the EW and smaller for the ERF, with the CM somewhere in the middle. This is a typical situation, observed in several other studies (e.g., Bevilacqua et al. 2015; Tadini et al. 2017). The

subset I results based on the CM method (probabilities for eruptive pulses; Fig. 7) show that for the next 10 years the experts identified that SAV and VS eruptions are the most probable (median value 96% and 74%, respectively), while SPL and PL are the least probable (median value 11% and 1.6%, respectively). The same trend is repeated also for the next 100 years, although with higher median values for all eruption types (98%, 93%, 32%, and 4% for SAV, VS, SPL, and PL, respectively). By comparing the 10 and 100 years of cases, we note that for SPL and PL the median percentage ratio is about 3, and not about 6 and 10, respectively, like it could be expected based on their decennial probabilities and a binomial model. In fact, this means increased annual probabilities of a SPL or PL eruption in the next 10 years with respect to the average decennial probabilities in the nine following decades of the next 100 years. While the inter-quantile range (5th–95th), which represents the degree of uncertainty, is similar for the SAV and PL eruptive pulses, it differs for the VS and SPL scenarios. For the next 10 years, the probability of VS is clearly multi-modal, highlighting different schools of thought among experts, with some might believe that VS is almost certain within this timeframe, while others point to an even chance. For the next 100 years, the probability of VS changes radically, showing a convergence of expert opinions towards almost certain VS within this timeframe, with the exception of one expert opinion which creates a wide range (Electronic Supplementary Material 3). An inverse effect is observed for the probability of SPL, with a very low median value for the next 10 years and a highly dispersed multimodal distribution for the next 100 years.

Regarding the eruption source parameters (subset II, Fig. 8), we observe that (1) inter-quantile range (5th–95th) is systematically larger for the PL eruption type with respect to the other cases and all the parameters and (2) eruption duration distributions are strongly skewed (i.e., median values are much closer to the 5th percentile rather than the 95th

Fig. 7 Violin plots showing the elicitation results for the subset I of target questions related to the CM weighting scheme. SAV, strong ash venting; VS, violent Strombolian; SPL, sub-Plinian; PL, Plinian



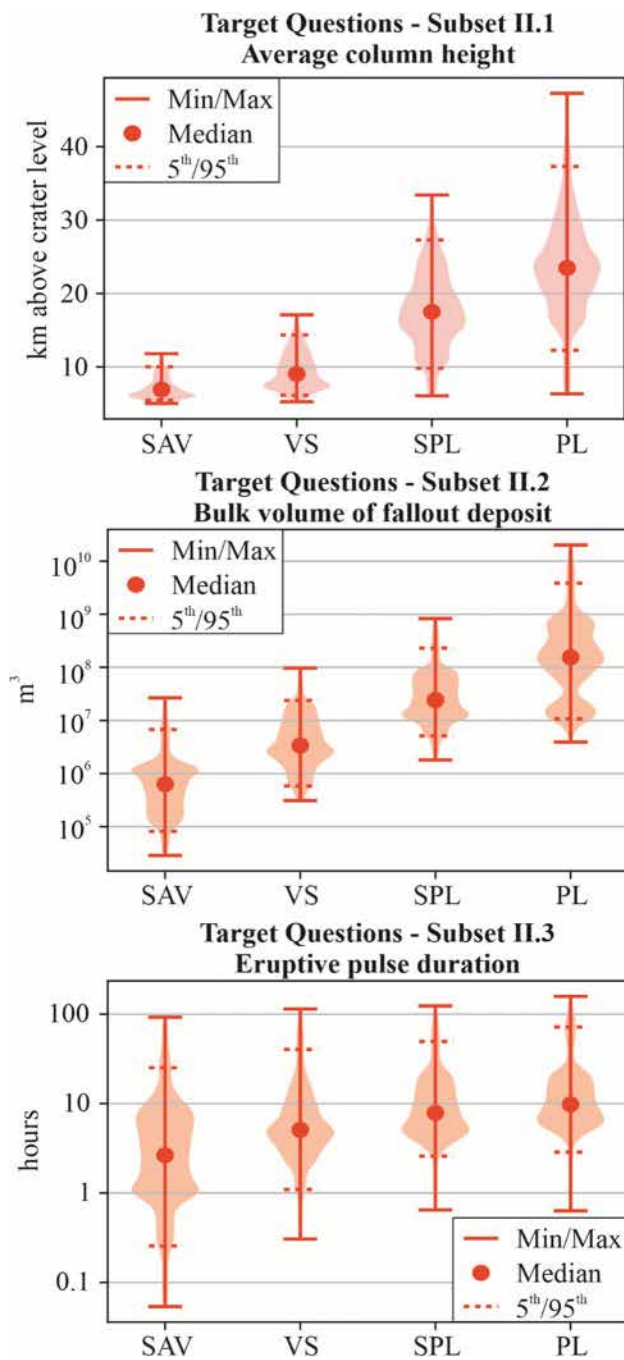


Fig. 8 Violin plots showing the elicitation results for the subset II of target questions related to the CM weighting scheme. SAV, strong ash venting; VS, violent Strombolian; SPL, sub-Plinian; PL, Plinian

one). There is some dispersion for the bulk fallout volume (especially for the SPL and PL eruption types) and the total eruption duration (especially for the SAV and PL eruption types). Multimodal distributions (bulk volume for PL and duration for SAV) highlight the most controversial parameters. These observations are linked to the confidence provided by the experts on these three parameters (Table 3),

Table 3 Confidence (1–10) on the answers provided by the experts for group II of target questions

Weighting scheme	Average column height	Bulk volume fall-out dep	Average duration
CM	6.65	4.12	4.29
ERF	7.35	5.07	5.03
EW	7.03	4.83	4.94

which is higher for the average column height (6.6–7.3/10) and lower for the other two parameters (4.1–5/10 and 4.3–5/10 for the volume and duration respectively).

Discussion

Frequency of recent Sangay eruptions

Based on the recent activity and historical reconstruction, Sangay is an almost constantly erupting volcano, as suggested by naturalists since the eighteenth century (La Condamine 1751a and b; von Humboldt 1855; Wolf 1892). More recent observations have shown that Sangay also has quiescence periods that can last months to years (Vasconez et al. 2022), which partially explains why some historical periods have no eruption chronicles.

Weak eruptive activity is most common during the period of continuous modern monitoring (13 of the last 23 years) and also appears to be very common during earlier periods (Electronic Supplementary Material 2); although, it is probably under-reported in historical chronicles due to the size of individual explosions and emissions (VEI 0–1) and the absence of regional impact. Therefore, we think that the estimate of the frequency of weak eruptive activity is probably not accurate for the observation period before 2000, and particularly before 1972.

Enhanced eruptive activity is less common (4 of the last 23 years) and shows a periodicity of 10–34 years (average 21 years) since 1903, and 6–63 years (average 32 years) from 1738 to 1903. Consequently, the enhanced eruptive activity is probably under-reported to a lesser extent in historical chronicles, particularly prior to the twentieth century. Such under-reporting has also been noted for the Ecuadorian continental arc (Santamaría et al. 2016) and for Galápagos volcanoes (Bernard et al. 2019).

During the continuous modern monitoring period, eruption pulses occurred mostly during enhanced eruptive activity (19 of the 20 pulses reported). This pattern is coherent with the historical chronicles where eruptive pulses occur in close temporal relationship with enhanced eruptive activity. It also supports the model proposed by Vasconez et al. (2022) that attribute the enhanced eruptive activity

and coincident eruptive pulses to more voluminous basic and gas-rich magma intrusions with shorter injection times, while the weak eruptive activity is triggered by buoyancy (long-lasting periods) or second boiling (short episodes). Mass injections are further supported by textural and geochemical evidence in Bernard et al. (2022) and geophysical evidence in Hidalgo et al. (2022). We observe that SAVs are scattered across the ongoing eruptive period while VSs are clustered between September 2020 and May 2021, a pattern similar to the 1959 events. SAVs are probably under-reported in the historical chronicles because of their low regional impact, but VSs are likely to be well represented at least since the end of the nineteenth century. Therefore, we propose that the frequency of eruptive pulses, in particular VS, is linked to that of enhanced eruptive activity.

Uncertainty quantification

The elicitation results allow us to make some important considerations about the hazard assessment and the uncertainty quantification. We focused on the results of the CM weighting schemes as (1) they represent the subset of the best-performing experts in the calibration questionnaire and (2) their aggregated answers (i.e., the decision-maker distributions) do not differ significantly from those of the group as a whole (given by the EW). Similar approaches have been followed by Bamber and Aspinall (2013), Bevilacqua et al. (2015), and Tadini et al. (2021).

Specifically, regarding the results about the next eruptive pulses, experts indicate that the most probable one (by considering its median value) for the next 10 and 100 years of cases is the SAV, for which however there is a large uncertainty range expressed by the group as a whole and different schools of thoughts about its duration (Fig. 7). This latter feature is linked to the general uncertainty about the definition of eruption duration and particularly about its end, as evidenced by many studies that focus on this specific aspect (Siebert et al. 2011; Witham et al. 2012; Pesicek et al. 2018). The definition of “eruptive pulse” itself that we provided to the experts is not unique (Aubry et al. 2021), and could have contributed to the uncertainty definition by the experts. To this regard, we note that eruption duration (for all the eruptive scenarios) shows consistently a skewed distribution toward the 95th percentile values (Fig. 8), which could indicate that larger uncertainty is attributed toward long-lasting eruptions and the definition of the end of an eruption. The uncertainty around the eruption duration in general is also confirmed by the relatively low reliability that the experts attributed to this parameter as compared to average column height (Table 3). Similarly, the bulk fallout deposit volume has large uncertainty bounds and several multimodalities among the distributions, expressing again a high degree of uncertainty (confirmed by the credibility value expressed

by the experts; Table 3): this is clearly linked to the difficulties in estimating especially the distal and ultra-proximal integration limit for fallout deposits, which in some cases could lead to high under or over-estimations (Bonadonna et al. 2015).

The two less likely eruption types, i.e., SPL and PL, are characterized by median probabilities of 32% and 4% in the next 100 years, with significant uncertainties. The median percentage ratio between 100 and 10 years deviate from a binomial model. This result could indicate that such large eruptive pulses are an eventuality that, according to expert consensus, has a decennial probability two and three times higher over the next 10 years, for SPL and PL respectively, than over the next 100 years on average.

Eruptive scenarios at Sangay

Eruptive scenarios have not yet been discussed for Sangay volcano in the literature. The current hazard map from Ordóñez et al. (2011) considers three scenarios for proximal phenomena (PDC, lava flows, and lahars) with VEI ranging from 2 to 4 (volume 1, 10, 100 Mm³), two scenarios for tephra dispersal and fallout with VEI 2 and 3 (1, 5 Mm³ DRE, 10, 15 km ASL respectively), and three scenarios for distal lahars (volumes 1, 10, 100 Mm³).

We compare the VEI 2 tephra dispersal and fallout scenario from Ordóñez et al. (2011) to the SAV scenario, both from the historical perspective and the expert elicitation results. We found out that considering column height, the expert elicitation yields the highest value (median of the CM = 6.67 km ACL), while the historical data point toward a more modest value (median of the last 15 events = 2.9 km ACL) and the hazard map scenario fall almost exactly between them (4.7 km ACL). The duration of the VEI 2 scenario is not presented in Ordóñez et al. (2011). Values for this parameter are quite different between the expert elicitation (median CM = 2.69 h) and the historical data (median of the last 15 events = 14 h). Finally, for bulk volume values, Ordóñez et al. (2011) propose 2.5 Mm³ (equivalent to 1 Mm³ DRE), which is four times higher than the results of the elicitation (median CM = 0.4 Mm³, equivalent to 0.26 Mm³ DRE). While no historical data are yet available for this parameter, using the median column height and the median duration, we obtain 0.75 Mm³ (equivalent to 0.3 Mm³ DRE) using Mastin et al. (2009) relationship. Therefore, we cannot exclude that some experts were possibly influenced by the eruptive pulses that occurred close to the elicitation date when estimating the column height for SAV events, even though they were VS instead of SAV. Similarly, when they estimated the duration of SAV events, some experts may have extrapolated the relationship between eruption size and duration that are not always reliable on small-sized events (Mastin et al. 2009; Aubry et al. 2021). However,

these results are affected by a wide uncertainty range that expresses a great difficulty in constraining such unknown parameters.

For further analysis, the VEI 3 tephra dispersal and fallout scenario from Ordóñez et al. (2011) was compared to the VS scenario in this study. In this case, we observe that considering the column height, the expert elicitation (median CM = 9.13 km ACL), the historical data (median for the last 5 events = 8.5 km ACL), and the hazard map scenario (9.7 km ACL) are very close. For volume values, Ordóñez et al. (2011) propose 12.5 Mm^3 (equivalent 5 Mm^3 DRE) which is also triple the value suggested by experts (median CM = 3.39 Mm^3 , equivalent 1.36 Mm^3 DRE) and the value obtained by Bernard et al. (2022) for the September 20, 2020 event ($1.5\text{--}5 \text{ Mm}^3$, equivalent $0.6\text{--}2 \text{ Mm}^3$ DRE). In this case, as well, the duration of VEI 3 scenario is not presented in Ordóñez et al. (2011). Values for this parameter are more similar between the expert elicitation (median CM = 5 h) and the historical data (median of the last five events = 3 h). The greater consistency between the historical data and the elicitation results is probably also a consequence of the fact that the elicitation took place just a few months after the VS events, and that the experts had more quantitative information at their disposal. Nonetheless, the bulk volume proposed by Ordóñez et al. (2011) seems more appropriate compared with empirical relationships between column height, eruption duration, and erupted volume (Mastin et al. 2009).

Although SPL and PL scenarios were not considered for tephra dispersal and fallout in Ordóñez et al. (2011), some median eruption source parameters suggested by experts (median CM for column height = 17.5 and 23.5 km ACL for SPL and PL, respectively; median CM for duration = 7.87 and 9.8 h for SPL and PL, respectively) are mostly consistent with existing databases and/or empirical relationships (Mastin et al. 2009; Aubry et al. 2021), while the median bulk volumes are smaller than those in the databases (median CM = 24 and 154 Mm^3 for SPL and PL, respectively). Further field studies are needed to improve these results and reduce their uncertainty.

Conclusions

Sangay volcano is currently (May 2024) the most active volcano in Ecuador. Based on instrumental data and historical reconstruction, it has been active since at least for the last 400 years. Most of its eruptions have been weak eruptive activity punctuated by periods of quiescence. We also recognized periods of enhanced eruptive activity every 6 to 63 years, during which eruptive pulses produced far-reaching impacts due to ash fallout and lahars. Expert elicitation allowed us to assess the next 10- and 100-year probability of four eruptive pulse scenarios: strong ash venting (VEI

1–2), violent Strombolian (VEI 2–3), sub-plinian (VEI 3–4), and Plinian (VEI 4–5). The expert judgment is consistent with the historical record, where relatively small eruptive pulses, i.e., SAV and VS, have a high long-term probability of occurrence, while larger eruptions, i.e., SPL and PL, are considered significantly less likely. The uncertainty ranges are especially large for the SPL and PL probabilities, highlighting the need for additional constraints to the recurrence times of these events. The eruption source parameters obtained through expert elicitation also have large uncertainties, highlighting the lack of stratigraphic and volcano-physical constraints at Sangay. Although this study shows that more data are required to reduce these uncertainties, the historical reconstruction and expert elicitation are a first step towards an improved hazard assessment at Sangay volcano. These analyses could serve as an example of conducting first-order hazard assessment at other volcanoes worldwide.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis for the historical reconstruction were performed by Benjamin Bernard, Pablo Samaniego, Francisco J. Vasconez, and Silvana Hidalgo. Material preparation, data collection, and analysis for the elicitation were performed by Benjamin Bernard, Alessandro Tadini, Andrea Bevilacqua, Mattia de' Michieli Vitturi, and Alvaro Aravena. The first draft of the manuscript was written by Benjamin Bernard, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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