



What is the probability of unexpected eruptions from potentially active volcanoes or regions?

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Received: 27 April 2022 / Accepted: 14 October 2022 / Published online: 25 October 2022
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Abstract

Since the start of the twentieth century, 101 potentially active volcanoes have produced their first Holocene eruption, as recorded in the volcanoes of the world (VOTW) database. The reactivation of potentially active volcanoes is often a surprise, since they tend to be less well-studied and unmonitored. The first step towards preparing for these unexpected eruptions is to establish how often potentially active volcanoes have erupted in the past. Here, we use our previously developed FRESH (First Recorded EruptionS in the Holocene) database to estimate the past regional Average Recurrence Interval (ARI) of these unexpected events. Within the most complete portions of the FRESH database, a FRESH (i.e., the first recorded eruption from a potentially active volcano) has occurred as frequently as every ~7 years in the Pacific Ocean region (~50 years of relatively complete record) and ~8 years in Izu, Volcano, and the Mariana Islands region (~150 years of relatively complete record). We use the regional frequency to estimate the annual probability of a FRESH at individual potentially active volcanoes in selected regions of Asia–Pacific, which ranged from 0.003 for Izu, Volcano, and Mariana Islands to 1.35×10^{-5} for Luzon. Population exposure around potentially active volcanoes showed that at volcanoes such as Kendeng (Indonesia) and Laguna Caldera (Philippines), more than 30 million people reside within 100 km of the summit. With this work, we hope to establish how often potentially active volcanoes erupt, while identifying which regions and which potentially active volcanoes may require more attention.

Keywords First recorded eruptions · Eruption probability · Recurrence interval · Potentially active volcanoes

Abbreviations

ARI	Average Recurrence Interval
BCE	Before current era
CE	Current era
FRESH	First Recorded EruptionS in the Holocene
GVP	Global Volcanism Program
VOTW	Volcanoes of the World
VEI	Volcanic Explosivity Index

RCD	Relative Completeness Date
RMS	root-mean-square

Introduction

The degree of understanding we have on the past eruptive activity of particular volcanoes is highly variable. Geological studies, monitoring efforts, and volcanic hazard assessments are, justifiably, often targeted at frequently active volcanoes (refer to glossary in Table 1) (e.g., Merapi, Indonesia (Thouret et al. 2000); Etna, Italy (Branca et al. 2011), or long-dormant active volcanoes (refer to glossary in Table 1) with high population exposures (e.g., Campi Flegrei, Italy ((Orsi et al. 2004); Taupo Volcanic Center, New Zealand (Potter et al. 2015)). As a result, other potentially active volcanoes (refer to glossary in Table 1) tend to be under-studied. For example, around 40% ($n=566$) of the Holocene volcanoes in the Volcanoes of the World (VOTW) database from the Smithsonian's Global Volcanism Program (GVP) lack specific dates of Holocene eruptions (GVP 2013). In addition to the potentially active

Editorial responsibility: L. Sandri

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Table 1 Glossary

Concept	Definition
Active volcano	A volcano that has erupted at least once during the Holocene demonstrated by geological dating or historical observations (Szakács 1994)
Frequently active volcano	“A volcano that has erupted at some point during at least 25 years of the last 100 years (since 1921)” as described in the criteria used by (GVP 2013) to identify noteworthy volcanoes
Long-dormant volcano	As defined in this study, an active or potentially active volcano without recorded eruptions within the last 100 years
Potentially active volcano	A volcano that has likely erupted in the Holocene but lacks specific dates of eruptions, and for which their capacity of erupting is uncertain (Siebert et al. 2011; Whelley et al. 2015). Volcanoes have been categorised as potentially active in the literature if they have: 1) signs of Holocene unrest; 2) fumarolic activity; and/or 3) morphologically young-looking volcanic features (e.g., unvegetated lava flows)
Unexpected eruption	An eruption at a potentially active volcano, for which the precursors may or may not have been detected
GVP Holocene volcano list	List from the VOTW database that contains volcanoes with confirmed eruptions (i.e., active volcanoes) and volcanoes with uncertain or credible evidence of Holocene activity (i.e., potentially active volcanoes) (GVP 2013)

volcanoes already catalogued in the VOTW database, hundreds more remain unidentified or are listed only in regional catalogues (Taisne et al. 2017; Whelley et al. 2015).

Expanding our knowledge of these under-studied potentially active volcanoes is important since the impact of unexpected eruptions (refer to glossary in Table 1) from these volcanoes can be as, or more, significant than those from well-studied active volcanoes for three reasons. Firstly, most potentially active volcanoes do not have local ground monitoring systems (Brown et al. 2015), making it difficult to anticipate and prepare for unexpected eruptions (Loughlin et al. 2015; Siebert et al. 2011). Therefore, we have to rely on global or regional networks (e.g., unrest at Jailolo, Indonesia (Passarelli et al. 2018)) or remote-sensing (e.g., a regional analysis of ASTER sensor data by Reath et al. (2019) to identify background activity and relative changes in potentially active volcanoes.

Secondly, potentially active volcanoes might not have erupted in a long time. Volcanoes with long periods of repose (i.e., long-dormant), particularly closed-conduit felsic volcanoes, are more likely to reawaken with large explosive eruptions (i.e., Volcanic Explosivity Index (VEI) ≥ 4) than volcanoes with short periods of repose (Bebbington 2014; Wadge 1982). The relationship between the period of repose and eruption size is captured in the VOTW database, which reveals that 75% of the VEI 5 and 90% of the VEI ≥ 6 eruptions were preceded by apparent periods of repose longer than 100 years (Siebert et al. 2011). Examples of such eruptions are Tambora (1815), Santa Maria (1902), El Chichón (1982), or Pinatubo (1991), all of which were first historical eruptions (i.e., reported from historical observations) as well as some of the largest and deadliest eruptions in the last two centuries (Siebert et al. 2011).

Thirdly, the population response to renewed volcanic activity can be strongly influenced by lack of generational memory (Cashman and Cronin 2008; Longo 2019; Njome et al. 2010; Pardo et al. 2021), or in the worst case, lack of awareness of

living next to an active or potentially active volcano (Siebert et al. 2011). An example is the first recorded eruption from Lamington (Papua New Guinea) in 1951. Although Lamington had been recognised by van Bemmelen (1939) as an active volcano, the VEI 4 eruption caught the local population by surprise since they did not know Lamington was a volcano (Johnson 2013). As a result, people attributed the signs of unrest and volcanic activity that preceded the paroxysmal phase to religious origins or warlike explosions, and the blast killed approximately 3000 people (Johnson 2020).

Unfortunately, unexpected eruptions from potentially active volcanoes are not rare. According to Burgos et al. (2022), 101 volcanoes have had their first dated Holocene eruption since the beginning of the twentieth century, with nearly 20% of them being a VEI ≥ 3 (Fig. 1). These numbers, together with the reasons presented above, demonstrate the importance of establishing the eruptive potential and assessing the volcanic hazards of potentially active volcanoes to better prepare for future unexpected eruptions.

An important step towards expanding our knowledge on potentially active volcanoes is establishing how often potentially active volcanoes erupt regionally. To do so, we used the First Recorded EruptionS in the Holocene (FRESH) database from Burgos et al. (2022), which contains the first dated Holocene eruption from each volcano in the VOTW database. For this work, we further compiled a database of potentially active volcanoes from the (GVP 2013), Whelley et al. (2015), and Taisne et al. (2017). Using this database, we estimated the probability of having the first recorded eruption from a potentially active volcano, and forecast the expected number of FRESH for a selection of regions in Asia–Pacific with comprehensive surveys of potentially active volcanoes from Whelley et al. (2015) and Taisne et al. (2017). Lastly, we calculated the population exposure around the potentially active volcanoes for the selected regions in Asia–Pacific, considering a radius of 5, 10, 30, and 100 km around the summit.

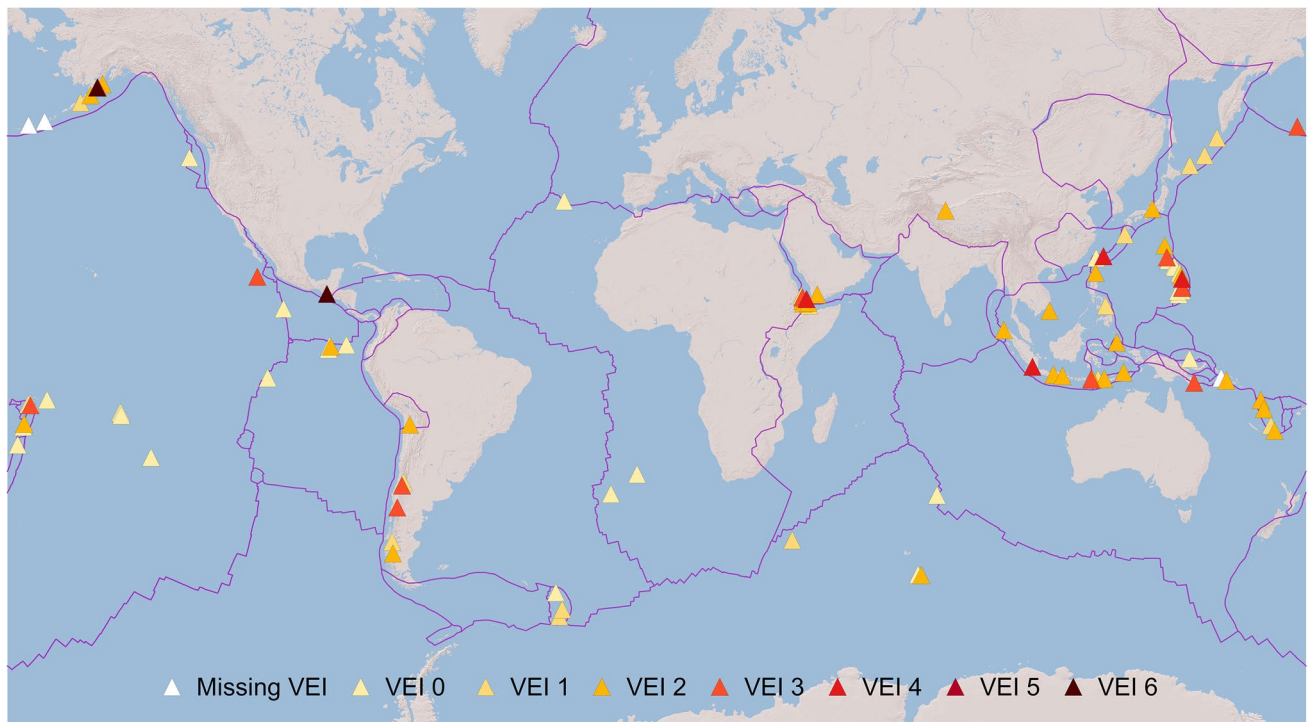


Fig. 1 Volcanoes that had their first recorded Holocene eruption after 1900 CE by VEI. Most of these eruptions are clustered in East and Southeast Asia. Data extracted from the First Recorded EruptionS

in the Holocene (FRESH) database (Burgos et al. 2022). Basemap: ESRI Shaded Relief

This study does not attempt to provide a comprehensive estimate of who is at risk from a future eruption, but rather aims to highlight the importance of paying attention to apparently quiet but potentially active volcanoes by identifying: (i) the regions with higher probabilities of a FRESH due to under-recording, and (ii) which potentially active volcanoes have the highest population exposure. This information can be used to highlight volcanoes that may warrant further investigation.

Methodology

Databases

The FRESH database contains the first dated Holocene eruption from 865 active volcanoes (Burgos et al. 2022). The data in the FRESH database was extracted from the VOTW database (v. 4.7.5, 21 December 2018). Note that each of these 865 volcanoes was a potentially active volcano before its FRESH. The oldest FRESH was at Igwisi Hills (Tanzania) in 10,450 before current era (BCE), and the most recent was at Mariana Back-Arc Segment at 15.5° N (the USA) in 2013 current era (CE). This database, which can be downloaded from the supplementary material in Burgos et al. (2022), includes details from each

FRESH (e.g., eruption start date and size) alongside characteristics of each volcano (e.g., major rock composition and region). We followed the new regional delimitation proposed by Burgos et al. (2022), in which each region contains only subregions with similar degrees of data completeness. This work provided 31 regions, compared to the 19 regions given by the GVP (Siebert et al. 2011).

In order to identify candidates for a future FRESH, we gathered a global database of 1233 potentially active volcanoes, which is available in ESM 1, from three main sources:

- (i) VOTW database: 578 potentially active volcanoes from the GVP Holocene volcano list (refer to glossary in Table 1). Of these potentially active volcanoes, 104 had already been extracted from the GVP by Whelley et al. (2015) and Taisne et al. (2017).
- (ii) Other catalogues: 501 additional potentially active volcanoes were compiled by Whelley et al. (2015) in Indonesia, the Philippines, and Southeast Asia, and by Taisne et al. (2017) in Taiwan, Ryukyu Islands, Izu Islands, Volcano Islands (Japan), Mariana Islands, Melanesia, and Fiji islands from global and regional catalogues (Badan Geologi 2011; Croweller et al. 2012; IAVCEI 1973; Neumann van Padang 1951; PHIVOLCS 2012; Siebert et al. 2011).

- (iii) Remote sensing: 154 additional potentially active volcanoes were identified through remote-sensing studies of geomorphological features by Whelley et al. (2015) and Taisne et al. (2017) in the locations listed in ii.

The probability of having a FRESH at an individual potentially active volcano was estimated only for regions with comprehensive surveys (i.e., the regions of Luzon; North Luzon, Central Philippines, Mindanao, and SE Asia; Indonesia (without Sumatra); Sumatra; Izu, Volcano and Mariana Islands; and Melanesia and Australia as defined in Burgos et al. (2022)). We excluded the regions of Taiwan, Hokkaido, Ryukyu Islands, and Kyushu; and Wallis, Samoan, Fiji, and Kermadec Islands, because the remote-sensing survey carried out by Taisne et al. (2017) in these regions covered only Taiwan, Ryukyu Islands, and Fiji islands. We did not estimate probabilities for individual potentially active volcanoes in other regions of the world because they are likely under-represented since dedicated surveys akin to those of Whelley et al. (2015) and Taisne et al. (2017) have not yet been carried out.

Lastly, we used the 100-m resolution 2020 WorldPop population count dataset (WorldPop 2021) to calculate the population data within 5, 10, 30, and 100 km of each potentially active volcano in the regions of Luzon; North Luzon, Central Philippines, Mindanao, and SE Asia; Indonesia (without Sumatra); Sumatra; Izu, Volcano and Mariana Islands; and Melanesia and Australia, using QGIS. The population data can be found in the ESM 2.

Data completeness

To minimize the effect of eruption under-recording when estimating recurrence intervals and eruption probabilities, we used the most complete portion of the FRESH database. The start of the most complete portion is given by the regional Relative Completeness Date (RCD) proposed by Burgos et al. (2022). These RCDs were defined by applying the root-mean-square (RMS) to the time lapse between the start date of consecutive FRESH and identifying when this statistic changes most significantly. The main advantage of this method is that it identifies multiple change points, of which the most abrupt is identified as the RCD if it is followed by an increase in the FRESH rate (i.e., an improvement in eruption recording). RCDs are available for 22 out of 31 regions, ranging from 7930 BCE for Mexico, Guatemala, Nicaragua, Costa Rica, and Panama to 1964 CE for the Pacific Ocean. For the remaining regions where the FRESH rate was found to be statistically constant over time, or the number of FRESH was too small to identify a change point, the estimations were done using the whole FRESH database for a given region, noting that we might be under-estimating eruption probabilities (Jenkins et al. 2012; Mead and Magill 2014).

FRESH probability

Estimating how often FRESH happened in the past in a given region is important for identifying where we can expect higher numbers of eruptions from potentially active volcanoes in the future, due to past eruption under-recording. We calculated the FRESH frequency, observed since the regional RCD, as described in Eq. 1, with the assumption that the rate of FRESH remains constant during the most complete portion of the catalogue. Thus, the Average Recurrence Interval (ARI) was calculated as follows:

$$\text{ARI}(\Delta t) = \Delta t / n_{\text{FRESH}} \quad (1)$$

where Δt is the interval of time measured in years between the RCD, or oldest FRESH start date if the RCD is not available, and 2018 CE. n_{FRESH} is the number of volcanoes that had their first dated Holocene eruption during Δt , in a given region. For large enough Δt , the probability of a FRESH per year is approximately $1/\text{ARI}(\Delta t)$. With this approach, we assumed that the FRESH database follows a Poisson distribution as suggested for global/regional records (De la Cruz-Reyna 1991; Papale 2018), and that the regional FRESH rate is static.

Assuming that the past FRESH frequency will remain constant in the future, we estimated the current probability (P) of an individual potentially active volcano having a FRESH, see Eq. 2. A complication arises in that each time we have a FRESH, the number of potentially active volcanoes decreases by one. Hence, we need to use the average number of potentially active volcanoes over the period Δt . Assuming that each potentially active volcano within a region is equally likely to produce an eruption, P is given by the following:

$$P = 1 / (\text{ARI}(\Delta t) \overline{n_V}) \quad (2)$$

The average number of potentially active volcanoes ($\overline{n_V}$) is calculated by averaging the yearly number across Δt :

$$\overline{n_V} = \frac{\sum_{k=t_0}^m n_{V_k}}{\Delta t} \quad (3)$$

where n_{V_k} is the number of potentially active volcanoes in year k , t_0 is the RCD or the oldest FRESH start date, and t_n is 2018.

Using Indonesia (without Sumatra) as an example, 49 volcanoes had their first dated eruption in the Holocene (n_{FRESH}) since the RCD (1510 CE). A further 256 volcanoes were considered still potentially active by 2018 CE. Thus, at 1510 CE, there were 305 potentially active volcanoes. Updating the number of potentially active volcanoes for each year between 1510 and 2018 CE, by extracting the yearly number of FRESH, we obtain an average number of potentially active volcanoes across Δt of 281. If we consider that each of these volcanoes is equally likely to produce a

FRESH and that the regional FRESH rate is static, the probability P of having a FRESH for each potentially active volcano in Indonesia (without Sumatra) is 3.4×10^{-4} .

We estimated P for the volcanic regions of Luzon; North Luzon, Central Philippines, Mindanao, and SE Asia; Indonesia (without Sumatra); Sumatra; Izu, Volcano, and Mariana Islands; and Melanesia and Australia, where the potentially active volcanoes were exhaustively catalogued by Whelley et al. (2015) and Taisne et al. (2017).

Based on P , we forecast the yearly number of expected FRESH for the next 1000 years. The aggregation of a number of independent sources means we can consider this as a Poisson process (De la Cruz-Reyna 1991). However, each time a FRESH occurs from this set of volcanoes, the number of volcanoes, and hence the rate, decreases step-wise. Hence, we used Monte Carlo simulation, as follows. Firstly, we generated n random numbers ranging from zero to one for each year, where n is the number of potentially active volcanoes

available in each region each year. Then, we counted how many times the random values were lower than P , indicating the number of FRESH expected in a given year, and consequently, updated the number of potentially active volcanoes left each year. Lastly, we obtained the uncertainty in the forecast from the 10th, 50th, and 90th percentile of the number of expected FRESH by running 100,000 simulations.

Results

Regional FRESH frequency

The FRESH ARI for each region is presented in Table 2. We observe variable ARIs across regions, with approximately one FRESH every 7 years in the Pacific Ocean to approximately one FRESH every 1700 years in the Hawaiian Islands. More than a third of the regions have an ARI of

Table 2 Time window Δt , the date type used to calculate Δt (i.e., C if it is the RCD and O if it is the oldest FRESH eruption) and expected Average Recurrence Interval (ARI), ordered from the highest to lowest annual frequency. Regions with the same letter in parentheses were originally part of the same region in (GVP 2013). Data in this table were derived following the methods and FRESH database of Burgos et al. (2022)

Region	Δt (years)	Date	ARI (years)
Pacific Ocean (a)	54	C	6.75
Izu, Volcano, and Mariana Islands (b)	154	C	7.70
South America	270	C	8.2
Indonesia (without Sumatra) (c)	508	C	10.4
Alaska	258	C	11.2
Melanesia and Australia	183	C	11.4
Indian Ocean (southern) (d)	38	C	12.7
Tonga Islands (e)	244	O	15.25
Kuril Islands	306	C	15.30
Sumatra (c)	248	C	20.7
North Luzon, Central Philippines, Mindanao, and SE Asia (f)	253	C	21.1
Antarctica	199	C	24.9
Africa (northeastern) and Red Sea (g)	387	C	29.8
Africa (northern,western,central) (g)	134	C	44.7
Wallis, Samoan, Fiji, and Kermadec Islands	152	C	50.7
Atlantic Ocean	518	C	51.8
Taiwan, Hokkaido, Ryukyu Islands and Kyushu (b)	418	C	59.7
Kamchatka and Mainland Asia	10,068	O	152.6
New Zealand (e)	838	C	167.6
Middle East and Western Indian Ocean (d)	1,818	C	202
Mexico, Guatemala, Nicaragua, Costa Rica, and Panama (h)	9,948	C	236.9
Canada and Western USA	12,078	O	251.6
Honshu (b)	11,558	O	296.4
West Indies	1,228	C	307
El Salvador and Honduras (h)	1,568	O	313.6
Western Europe, Italy, Turkey, and Western Asia (i)	11,968	O	460.3
Iceland and Arctic Ocean	11,518	O	460.7
Africa (eastern) (g)	12,468	O	779.3
Greece (i)	3628	O	907
Luzon (f)	5518	C	919.7
Hawaiian Islands (a)	10,068	O	1677.9

less than 25 years, most of which are located in subduction zones (e.g., South America or Indonesia (without Sumatra)) and oceanic settings (e.g., Izu, Volcano, and Mariana Islands or Tonga Islands). For the most part, we observe that regions with longer complete records tend to have longer ARIs than regions with shorter complete records, as reflected in the bottom half of Table 2. There are also cases where we use similar time windows and obtain similar ARIs; for example, Alaska and South America (258 and 270 years of relative completeness, respectively), where the ARI in Alaska is 11 years and in South America 8 years. These results could be used to suggest that individual volcanoes have similar eruption rates in both regions. However, the number of active and potentially active volcanoes reported in (GVP 2013) for these regions vary, indicating that individual volcanoes in Alaska erupt more frequently than individual volcanoes in South America. For example, 38.3% ($n = 23$) of the active volcanoes in Alaska produced a FRESH since the RCD versus 28.7% ($n = 33$) of the active volcanoes in South America, and yet South America has more than twice the number of potentially active volcanoes than Alaska in (GVP 2013) (75 versus 28). If volcanoes in both regions had similar eruption frequencies, South America would have reported a higher number of FRESH since the RCD than Alaska. The similarity in the regional ARI of FRESH in

these two regions, despite differing numbers of active volcanoes, suggests that the individual eruption rate is lower in South America than in Alaska, mirroring the finding of Mead and Magill (2014) for the ARI of all eruptions in these regions (i.e., not just FRESH). Likely, this reflects varying magmatic, tectonic, and environmental conditions between the two regions, and potentially also different levels of study.

Additionally, we observe that regions that were originally considered one region in the GVP have significantly different FRESH ARIs, such as the three regions of Izu, Volcano, and Mariana Islands, where a FRESH can be expected every ~8 years; Taiwan, Hokkaido, Ryukyu Islands, and Kyushu, with an expected FRESH every ~60 years; and Honshu, with an expected FRESH every ~300 years, or the two regions of North Luzon, Central Philippines, Mindanao, and SE Asia; and Luzon, where the ARI is ~20 years and ~900 years, respectively.

Potentially active volcanoes

Figure 2 shows the number of potentially active volcanoes identified from global and regional catalogues and remote-sensing surveys, relative to those already identified as active in the VOTW database. We are interested in these potentially active volcanoes since they may erupt unexpectedly in the

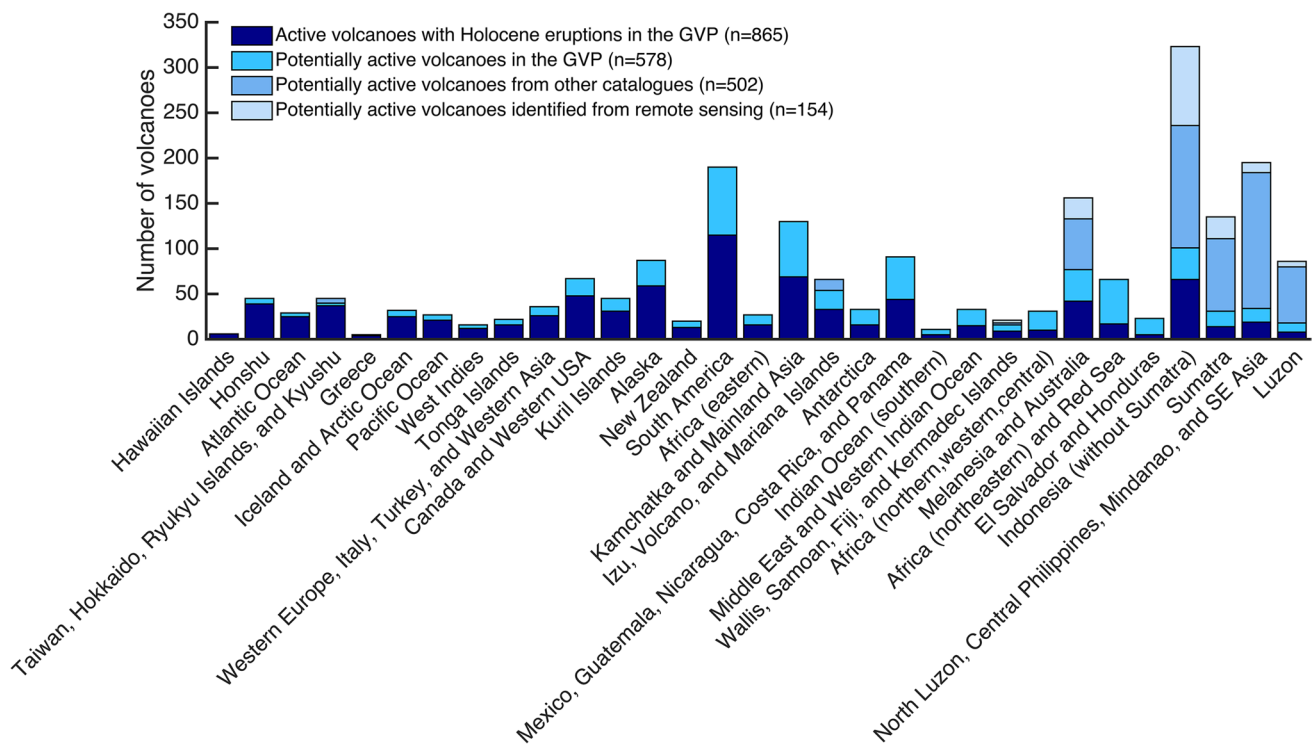


Fig. 2 Number of active volcanoes with dated Holocene eruptions and potentially active volcanoes from the VOTW database, other global and regional catalogues, and remote-sensing surveys per

region ordered by ascending percentage of potentially active volcanoes GVP (2013), Whelley et al. (2015), and Taisne et al. (2017)

future. Considering that recording improves since the RCD, we can assume that most of these potentially active volcanoes have no unrecorded eruptions since this date; otherwise, their first dated eruption would have likely been captured in the FRESH database. Since the completeness date for most regions is older than 100 years, we expect these potentially active volcanoes to be long dormant, which implies that they could reawaken with a large explosive eruption.

Starting from the left side of Fig. 2, in all the regions up to the West Indies, fewer than 25% of their volcanoes are identified as potentially active volcanoes. In contrast, for the last five regions on the right side of the figure more than 75% of the volcanoes are potentially active, although this is largely the result of the targeted studies of Whelley et al. (2015) and Taisne et al. (2017). For those areas without these targeted studies, South America (39.5%, $n=75$); Kamchatka and Mainland Asia (46.9%, $n=61$); Africa (northeastern), and Red Sea (74.2%, $n=49$); and Mexico, Guatemala, Nicaragua, Costa Rica, and Panama (51.6%, $n=47$) have the highest numbers of potentially active volcanoes in the GVP Holocene volcano list. Out of all the regions with potentially active volcanoes from other catalogues or identified from remote sensing (i.e., not just the GVP) (see “Data-bases”), Taiwan, Hokkaido, Ryukyu Islands, and Kyushu have the lowest potentially active volcano percentage (18%, $n=8$). However, Taisne et al. (2017) surveyed only Taiwan and Ryukyu Islands. Therefore, in this region the number of potentially active volcanoes may be under-estimated. We encounter the same issue for Wallis, Samoan, Fiji, and the Kermadec Islands, where only the Fiji islands were studied. In contrast with the region of Taiwan, Hokkaido, Ryukyu Islands, and Kyushu, 57% ($n=12$) of the volcanoes in the region of Wallis, Samoan, Fiji, and the Kermadec Islands are potentially active. Indonesia (without Sumatra) has the highest number of potentially active volcanoes out of all the regions (79.6%, $n=257$) and Luzon has the highest percentage of potentially active volcanoes (91%, $n=78$).

Table 3 Estimated annual probability of having a FRESH at a potentially active volcano P , time window Δt from Table 2, and average number of potentially active volcanoes (\bar{n}_V) over Δt per region ordered from the highest to the lowest annual probability. Estimates are given for regions where extensive surveys by Whelley et al. (2015) and Taisne et al. (2017) had identified potentially active volcanoes not included in the GVP

Region	P	Δt (years)	\bar{n}_V
Izu, Volcano, and Mariana Islands	0.003	154	43
Melanesia and Australia	7.21×10^{-4}	183	121
Sumatra	3.86×10^{-4}	248	125
Indonesia (without Sumatra)	3.44×10^{-4}	508	281
North Luzon, Central Philippines, Mindanao, and SE Asia	2.64×10^{-4}	253	180
Luzon	1.35×10^{-5}	5518	80

FRESH forecast

Based on the FRESH frequencies in Table 2, we estimated the annual probability of having a FRESH at each potentially active volcano in the regions in Table 3. This probability was then used to forecast in Fig. 3, the number of FRESH expected over the next 1000 years in the regions listed in Table 3, where Whelley et al. (2015) and Taisne et al. (2017) carried out extensive surveys to identify potentially active volcanoes.

We obtain the highest probabilities for Izu, Volcano, and Mariana Islands, followed by Melanesia and Australia. Fig. 3a reflects how the high probabilities from Izu, Volcano, and Mariana Islands affect the curve of forecasted FRESH with time, with the rate of FRESH starting to plateau for estimates after the next 400 years. The deceleration of the curve (Fig. 3a) can be mostly explained by the high probability of FRESH at individual potentially active volcanoes, the relatively low number of potentially active volcanoes in the region ($\bar{n}_V=43$), and the fact that we do not consider the formation of new volcanoes (e.g., Paricutin in the Michoacán-Guanajuato volcanic field, Mexico) and the discovery of new

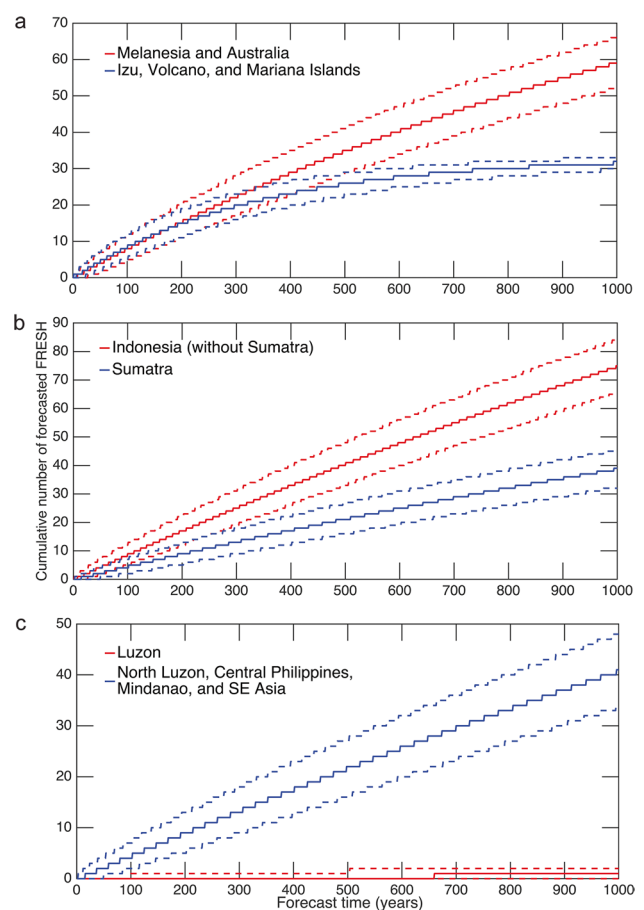


Fig. 3 Cumulative number of forecasted FRESH of any VEI for the next 1000 years. The dashed line represents the 10th and 90th percentiles and the solid line the 50th percentile

potentially active volcanoes in the FRESH forecast. With this last condition, we assume that the number of potentially active volcanoes is finite and that it will be exhausted at some point in time. The plateau is less notable in Melanesia and Australia, although we capture a deceleration in the cumulative number of forecasted FRESH within the next 500 years (Table 4).

Sumatra has a slightly higher annual probability than Indonesia (without Sumatra), but it has fewer potentially active volcanoes available (Fig. 2), as reflected in the forecast of FRESH (Fig. 3b). Lastly, North Luzon, Central Philippines, Mindanao, and SE Asia; and Luzon have the lowest annual probabilities. However, the former has an almost 20 times larger annual probability than the latter. As a result of this low probability, we forecast only 1 FRESH in the next 1000 years for the 50th percentile in Luzon (Fig. 3c).

The short-term forecast (Table 4) shows that we can expect the same number of FRESH (10–90th percentiles) within the next 10, 25, 50, and 100 years in Melanesia and Australia; Izu, Volcano, and Mariana Islands; and Indonesia (without Sumatra). These regions will presumably produce the highest number of FRESH in the short term. In comparison, Sumatra; and North Luzon, Central Philippines, Mindanao, and SE Asia will produce about half the number of FRESH within the next 10, 25, 50, and 100 years.

Discussion

We estimated FRESH ARIs to better understand the threat that potentially active volcanoes might pose in each region (Table 2). The top 5 regions with the shortest ARIs (i.e., Pacific Ocean; Izu, Volcano, and Mariana Islands; South America; Indonesia (without Sumatra); and Alaska) are

regions with relatively recent completeness dates—indicative of numerous volcanoes in these regions being understudied—and frequent volcanic activity due to the high concentration of active volcanoes (i.e., 4 out of 5 regions are located in the Pacific Ring of Fire) (Siebert et al. 2015). Except for the Pacific Ocean region, all these regions have relatively high number of potentially active volcanoes (Fig. 2), which suggests that we will continue recording unexpected eruptions in the future when these potentially active volcanoes reactivate. The low number of potentially active volcanoes in the Pacific Ocean can be explained by the challenges associated with studying submarine volcanism. However, regions dominated by submarine volcanism will benefit from the recent development of ocean exploration programs, such as Seabed 2030 (Mayer et al. 2018), that will help to identify and catalogue new submarine potentially active volcanoes (Beaulieu et al. 2013).

Three of the top 5 regions (i.e., South America, Indonesia (without Sumatra), and Alaska) have numerous records of large explosive eruptions ($VEI \geq 4$) in the Holocene record (GVP 2013). Some of the most notable large explosive eruptions in the world recorded since the 1800s happened unexpectedly at potentially active volcanoes (e.g., Hildreth and Fierstein (2012); VEI 6: Hildreth and Fierstein (2012), Major and Lara (2013); VEI 4: Major and Lara (2013) or at volcanoes without records of historical eruptions (e.g., Tambora (1815)); VEI 7: Siebert et al. (2011) from these regions, all of which classified at that time as long-dormant volcanoes. The tendency to produce large explosive eruptions after long repose is explained by the generation of highly evolved magmas during periods of inactivity (Wadge 1982). Work done by Bebbington (2014) proved that there is a significant probability of the eruption size at Indonesian close-vent volcanoes increasing with the duration of the

Table 4 Number of forecasted FRESH (10–90th percentile) within the next 10, 25, 50, 100, and 500 years

Regions	Time window (years)	Number of forecasted FRESH 50 th percentile [10 th –90 th]				
		10	25	50	100	500
Melanesia and Australia		1 [0, 2]	2 [0, 4]	4 [2, 7]	8 [5, 12]	35 [29, 41]
Izu, Volcano, and Mariana Islands		1 [0, 2]	2 [1, 4]	4 [2, 7]	8 [5, 12]	26 [23, 29]
Indonesia (without Sumatra)		1 [0, 2]	2 [0, 4]	4 [2, 7]	9 [5, 12]	40 [33, 48]
Sumatra		0 [0, 1]	1 [0, 3]	2 [1, 4]	4 [2, 7]	21 [16, 27]
Luzon		0 [0, 0]	0 [0, 0]	0 [0, 0]	0 [0, 1]	0 [0, 1]
North Luzon, Central Philippines, Mindanao, and SE Asia		0 [0, 1]	1 [0, 3]	2 [1, 4]	4 [2, 7]	22 [16, 27]

repose. Meanwhile, a global analysis by Connor et al. (2006) showed that there is a similar probability of having a VEI 4, 5, or 6–7 after more than 1000 years of repose.

The local and regional impacts from an unexpected and large explosive eruption at an unmonitored potentially active volcano today could be severe, especially if the populations living nearby are unaware of their proximity to a potentially active volcano (Siebert et al. 2011). Because of the potential impact of such a scenario, we recognize the importance of looking at the occurrence of FRESH with different eruption sizes. However, the relatively small sample size of FRESH with assigned VEI (496 out of 865; Burgos et al. (2022)) prevented us from estimating the ARI as a function of VEI.

In contrast with the top 5 regions, the bottom half of Table 2 contains well-studied regions with longer FRESH records or with comprehensive geological records reflected in a near-constant rate of FRESH (e.g., Canada and Western USA; and Honshu) (Burgos et al. 2022). As a result of the number of FRESH being spread across a much bigger time window, the ARIs are considerably longer, ranging from several centuries (e.g., Kamchatka to Mainland Asia) to millennia (e.g., Hawaiian Islands). The use of longer time windows, necessitated by the absence of a clear RCD, might lead to overestimation of the ARIs (Jenkins et al. 2012; Mead and Magill 2014). This potential overestimation is further supported by the relatively high number of potentially active volcanoes in some of these regions (e.g., Kamchatka and Mainland Asia; and Mexico, Guatemala, Nicaragua, Costa Rica, and Panama (Fig. 2)), which indicates that an increase in the FRESH rate could be seen in the future.

The estimated annual probability of a FRESH at an individual potentially active volcano (Table 3), which is relatively high in remote regions (i.e., Izu, Volcano, and Mariana Islands; and Melanesia and Australia), shows the importance of paying more attention to apparently quiet, and likely long-dormant, volcanoes. Unfortunately, comprehensive surveys of potentially active volcanoes are available only for very few regions, preventing us from providing probability estimates for other regions. Investing more resources towards studying the Holocene volcanism in remote and/or under-studied regions, even if they are dominated by submarine volcanism, is essential to reduce the potential impacts from future eruptions at potentially active volcanoes. A recent example that illustrates the importance of studying remote volcanism is the Hunga Tonga- Hunga Ha'apai Plinian eruption on January 15, 2022 (Witze 2022). This eruption produced a plume that reached at least 30 km height, a volcanogenic tsunami and tephra fall that damaged all the Tonga Islands, as well as shockwave tsunamis that travelled through the Pacific, causing two fatalities on the coast of Peru (GVP 2022). In the region of Tonga Islands, where Hunga Tonga-Hunga

Ha'apai is located, most active and potentially active volcanoes lack a hazard assessment (Taylor et al. 2016). In the best case, hazard assessments have been based on the last 250 years of volcanic activity because of the short eruptive record in this region (e.g., Niaufo'ou hazard assessment (Taylor 2016)). As a result, hazard assessments could be missing large explosive eruptions with recurrence periods longer than the complete catalogue (e.g., the two VEI 5–6 explosive phases from Tofua volcano tentatively dated from 1000 years ago (Caulfield et al. 2011)). Further difficulties assessing the volcanic hazards in this region stem, for example, from absence of detailed bathymetric data, low population awareness of the effects of volcanic activity, or the lack of a national surveillance (Taylor et al. 2016). Some of these challenges are likely present in other remote regions with or without submarine volcanism.

Population data indicate that even remote regions have potentially active volcanoes with people living in the surrounding areas. The percentage of populated potentially active volcanoes in Izu, Volcano, and Mariana Islands increases from 27.3% ($n=9$) to 48.8% ($n=16$) for radii of 5 and 100 km from the summit, respectively, while in Melanesia and Australia the percentage increases from 37.7% ($n=43$) to 99.1% ($n=113$). Although most potentially active volcanoes in these regions have low population density in the vicinity (i.e., 5- and 10-km radii), unexpected eruptions could threaten those who cannot be evacuated, to passing boats, submarine cables, shipping industry, and international aviation. In addition to the direct threat of a subaerial eruption, submarine eruptions and volcanic island collapse, although unlikely, can generate tsunamis that could affect distant populations. For example, in SE Asia alone, around 25% and 15% of volcanogenic tsunamis were triggered by explosive submarine activity and flank failure, respectively (Paris et al. 2014; Plank et al. 2020).

In comparison, in the densely populated regions of Indonesia (without Sumatra); Sumatra; Luzon; and North Luzon, Central Philippines, Mindanao, and SE Asia, the percentage of potentially active volcanoes populated within a 5-km radius ranges from 70.2% ($n=85$) in Sumatra to 88.5% ($n=69$) in Luzon. As expected, 100% of the potentially active volcanoes in these regions have people living within 100 km of the summit. Despite the high population count obtained for numerous potentially active volcanoes in these regions, it is important to note that some potentially active volcanoes are less likely to erupt in the future than others, and that many might be extinct. Following Whelley et al.'s (2015) classification of volcanoes based on the morphology and the conduit state, we could prioritise studying potentially active volcanoes classified as well-plugged stratocones and calderas, since they often have long repose

periods and more potential for generating large explosive eruptions (Bebbington 2014; Wadge 1982). Considering the largest radius, the most populated well-plugged stratocone is Kendeng in Java (Indonesia), with nearly 40 million people living within 100 km of the summit. This stratovolcano, which is classified as a Pleistocene volcano by (GVP 2013), has been identified as potentially active by Whelley et al. (2015) due to its relatively youthful-looking morphology. However, the lack of detailed geological studies of this volcano makes establishing its eruptive potential very challenging. The most populated caldera within a 100-km radius is Laguna Caldera in Luzon (Philippines) (nearly 33 million people), located southeast of Manila City. Although Whelley et al. (2015) identified this caldera as potentially active, PHIVOLCS classifies it on its website as inactive (PHIVOLCS 2012). The discrepancy between sources reflects the need to perform more geological studies to confirm any Holocene activity. However, the conventional definition of active volcanism, which considers the Holocene as the age limit, should be applied to calderas with caution, since calderas are long-living systems with cycles of volcanic activity that can last millions of years (Bouvet de Maisonneuve et al. 2021).

Improving the geological records at certain potentially active volcanoes is one essential step towards being better prepared for unexpected eruptions. Another essential step is monitoring the background activity at potentially active volcanoes in order to detect any precursory signals leading to a potential reawakening. Monitoring the background activity in potentially active volcanoes could be crucial to reducing impacts, since long periods of repose do not necessarily result in long periods of unrest (Acocella et al. 2015; Phillipson et al. 2013; Sandri et al. 2017). One example of an unexpected and recent FRESH that might have been forecasted if real-time and continuous monitoring data had been available at the time (Trusdell et al. 2005) is the VEI 3 eruption at Anatahan volcano (2003) in the Mariana Islands. This eruption, whose onset was detected by satellite imagery, produced an initial plume reaching 13.4 km, disrupting regional aviation traffic for three days, and prompting occasional flight cancellations at Saipan's and Guam's International Airports (Guffanti et al. 2005). Another example is the first dated eruption from Nabro (Eritrea) in 2011 (VEI 4). This eruption was preceded by several weeks of seismicity captured by the seismic network from neighbouring countries. However, the information was not made available to the local authorities during the unrest. Fortunately, 12,000 people were rapidly evacuated due to the seismicity felt a few hours before the eruption, including 3000 people who lived inside the caldera (Goitom et al. 2015). In practice, installing a ground-based monitoring system is not viable in most of the cases, due to factors such as

limited resources or difficulties in access. In these cases, we should rely on remote-sensing data, such as surface radiance variations (Girona et al. 2021) and InSAR (Biggs et al. 2014; Pritchard et al. 2018), which could be used to identify which potentially active volcanoes have shown long-term unrest in the last decades. Additionally, remote-sensing data could be used to identify new potentially active volcanoes in the regions not covered by Whelley et al. (2015) and Taisne et al. (2017), which would allow the work described in this paper to be expanded to other parts of the world.

Conclusions

Forecasting eruptions from potentially active volcanoes is crucial to better prepare for unexpected eruptions after long periods of repose. To establish how often potentially active volcanoes have erupted in the past, we used the First Recorded EruptionS in the Holocene (FRESH) database and the Relative Completeness Dates (RCDs) from Burgos et al. (2022) to calculate the probability of future unexpected eruptions in different regions and at different potentially active volcanoes. We found that regions with relatively recent completeness dates located in subduction zones (e.g., approximately one FRESH every 8 years in South America) and/or those in remote areas (e.g., approximately one FRESH every 8 years Izu, Volcano, and Mariana Islands) have shorter Average Recurrence Interval (ARI). Conversely, the longer ARIs are obtained for well-studied regions with long FRESH records (e.g., approximately one FRESH every 1700 years in Hawaiian Islands) and/or regions with near-constant rates of FRESH throughout the Holocene (e.g., approximately one FRESH every 250 years in Canada and Western USA). The difference in the ARIs can be partly explained by the contrasting degree of completeness between less studied regions and regions with comprehensive geological records. We found that regions with recent completeness dates tend to have a higher proportion of potentially active volcanoes, which is eventually translated into more FRESH eruptions.

The FRESH ARI was used to estimate the annual probability of a FRESH at individual potentially active volcanoes in Indonesia (without Sumatra); Sumatra; Izu, Volcano, and Mariana Islands; Melanesia and Australia; North Luzon, Central Philippines, Mindanao, and SE Asia. Probability estimates ranged from 0.003 in Izu, Volcano, and Mariana Islands to 1.35×10^{-5} in Luzon. Population exposure in regions with remote volcanoes, such as Izu, Volcano, and Mariana Islands; and Melanesia and Australia, shown that the number of potentially active volcanoes with population exposed to unexpected eruptions increased with the radius. Despite the high population

exposure obtained for some potentially active volcanoes (e.g., nearly 40 million people living within 100 km of Kendeng (Indonesia)), it must be noted that some potentially active volcanoes are less likely to erupt, and many might be extinct. To confirm their eruptive potential more geological studies at individual potentially active volcanoes are required. Furthermore, remote-sensing techniques could confirm if a given potentially active volcano has shown recent signs of unrest.

Recent history has shown that unexpected eruptions from potentially active volcanoes can produce severe impacts, especially in populated areas, since this type of volcanoes often lacks a monitoring network, hazard assessments, or emergency plans, and the population may be unaware of the volcano's existence. This study helps to identify which regions and potentially active volcanoes could be prioritised in future studies in order to better prepared for unexpected eruptions.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00445-022-01605-0>.

Acknowledgements We are grateful to the anonymous reviewers for their thoughtful and constructive comments which improved the manuscript, and to Laura Sandri for her editorial handling of the manuscript. We would like to thank Pavel Adamek for language editing and proof-reading the manuscript. We would also like to thank Ed Venzke for his help navigating the Smithsonian's Global Volcanism Program.

Funding This research was supported by the Earth Observatory of Singapore via its funding from the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative. This work comprises EOS contribution number 475. Mark Bebbington was supported by the Resilience to Nature's Challenges Volcano Program, New Zealand (contract number GNS-RNC047).

Declarations

Conflict of interest The authors declare no competing interests.

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