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Are eruptions reliable precursors to marine volcano collapses?

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Volcanoes are sources of numerous threats including lava flows, pyroclastic flows, ash dispersal and landslides or sector collapses. In addition to these commonly known volcanic hazards, volcano-induced tsunamis can occur in the marine environment, introducing a major hazard that can affect populations located far away from the volcanoes. Existing tsunami warning systems generally do not account for volcano-generated tsunamis, due to the multiple source mechanisms that can cause such tsunamis, a limited understanding of precursory signals for these events, and the need for local detection rather than remote sensing. Among these source mechanisms of volcanic tsunamis, sector and lateral collapses are at the high risk-low frequency extreme of risk matrices. Marine volcanoes grow in specific environments, with factors like marine clays, constant full saturation, sediment transport and remobilization, interaction with ocean dynamics, and sea level changes that may impact edifice stability in distinct ways. The majority of historically documented marine volcano collapses occurred at erupting volcanoes, suggesting that eruptions could serve as a remotely detectable warning signal for collapses. However, careful examination of temporal sequences of these examples reveals that collapses do not always follow eruptions. Consequently, there is a need for identifying other, more robust precursors to volcano collapse, in particular in the marine environment, where the consequences of collapses may be widespread.

KEYWORDS

coastal and oceanic volcanoes, volcanic unrest, hazards, warning system, volcano collapse

1 Introduction

Volcano collapses have the potential to generate massive and destructive landslides, as demonstrated by the 1980 collapse of Mount St. Helens, which involved a volume of ~2.7 km^3 (Moore et al., 1981; Voight et al., 1981). In marine environments, the sudden displacement of large amounts of material into the water can trigger tsunamis with far-reaching impacts on coastal areas, as seen in the 2018 collapse of Anak-Krakatau in Indonesia.

Historical records indicate that collapses of marine volcanoes have resulted in ~15,000 fatalities over the past 400 years (Day, 2015; Grilli et al., 2019). There have been at least 10 documented cases of tsunamigenic volcano collapses (e.g., Day, 2015; Dufresne et al., 2021), and geological records provide evidence of giant collapses involving the mobilization of tens to thousands of cubic kilometers of material (Blahůt et al., 2019). Many Pleistocene and Holocene volcanoes (represented by black triangles in Figure 1) show signs of collapse or flank instability. Yet, in 2015, 10.6% (781 million) of the global population lived in Low Elevation Coastal Zones (LECZ), which make up only 2.1% of Earth's land area and are vulnerable to marine hazards, including volcanogenic tsunamis (Supplementary Table S1). LECZ refers to connected coastal areas below 10 m of elevation (colored areas in Figure 1). Furthermore, international commerce and commodity supply are also vulnerable to tsunamis due to their reliance on global maritime traffic and coastal infrastructure, such as telecommunication cables, production platforms, and hydrocarbon pipelines (Clare et al., 2019). Projections indicate that exposure and vulnerability to tsunamis will increase. Neumann et al. (2015) predict a disproportionate population growth in LECZ by 2060, with 12.3% (1.4 billion) of the world's population living in these areas. In Southeast Asia, home to nearly half of the known active volcanoes (~48%), the population in LECZ is expected to increase from ~590 million in 2015 to ~950 million in 2060. Consequently, it is urgent to assess the hazards associated with volcano collapses and tsunamis and develop forecasting and early warning strategies.

Scientists have long been investigating volcano collapses and their associated hazards. Giachetti et al. (2012) studied volcano-generated tsunamis triggered by a hypothetical collapse of Anak-Krakatau, highlighting the regional damage such an event would cause and emphasizing the need to include tsunami hazards in volcano monitoring. However, no warning was issued before the 2018 collapse of Anak-Krakatau (Zorn et al., 2023), which resulted in a tsunami and caused 437 deaths along nearby shores (Grilli et al., 2019; Walter et al., 2019). Despite a small earthquake with a local magnitude ML = 2–3 (Walter et al., 2019), there was no significant earthquake associated with the collapse that could trigger the warning system. In fact, most Tsunami Early Warning Systems (TEWS) do not currently consider volcanic tsunamis (Paris et al., 2014; Paris, 2015), including the Indonesian system (Ina-TEWS), which is designed for earthquake-generated tsunamis after the destructive 2004 tsunami caused by an earthquake. One exception is the TEWS at Stromboli Island, where Italian authorities established a monitoring system based on tide gauges surrounding the island after the 2002 tsunami triggered by submarine and subaerial landslides in the Sciara del Fuoco (Bellotti et al., 2009; De Girolamo et al., 2014). Although local TEWS can effectively mitigate hazards related to volcano collapse, these examples indicate that such warning systems are often established reactively following an event. To enable proactive measures before a volcano collapse, it is crucial to identify the highest-risk volcanoes and understand the precursor signals indicating an impending collapse.

Evidence of flank instability at La Palma, Canary Islands, was identified 2 decades ago (Day et al., 1999), with limited follow-up studies (González et al., 2010). It was not until the recent magmatic unrest at Cumbre Vieja volcano in 2021 that concerns about the possibility of volcano collapse at La Palma reawoke and sparked interest in the scientific community (González, 2022) and the public. The number of scientific publications (Periáñez, 2021; Fernández et al., 2022; González, 2022; Romero et al., 2022) and conference abstracts (Geersen et al., 2023; Miranda-Hardisson et al., 2023; Rodríguez-Losada et al., 2023; Walter et al., 2023) addressing flank instability or collapse at La Palma increased during the 19 months following the eruption. In contrast, only three references were published during the equivalent preceding period (Abadie et al., 2020; Arnaud et al., 2021; Fernández et al., 2021).

The increased interest in flank instability stems from the perception that marine volcano collapses are more prone to occur during or after an eruption, rather than during non-eruptive periods. However, to our knowledge, there is no evidence in the existing literature to support this link. It is crucial to understand the origin of this idea, as it may lead to the formation of a flawed paradigm with the potential for erroneous conclusions and devastating consequences, as demonstrated by the Tohoku-oki and Fukushima catastrophe (Lacassin and Lavelle, 2016). Therefore, the first objective of this perspective paper is to identify why erupting volcanoes may be perceived as more susceptible to collapse. The second objective is to examine whether collapses require an eruption and, consequently, whether eruptive activity could serve as an indicator of potential collapse at marine volcanoes. To achieve this, we conduct a comprehensive analysis of the available literature on historical marine volcano collapses, examining the sequence of eruptive activities and collapses, as well as additional factors influencing volcano stability. Additionally, we explore how uncertainties in historical and geological records, along with human risk perception, can challenge this apparent assumption.

2 Terminology and geological background

We hereafter use the generic terms "volcano collapse" or simply "collapse" to describe both sector or lateral collapses, that affect the core, conduit, or summit of the volcanic edifice and flank collapses that only affect a smaller portion of the flank. The term "marine volcano" incorporates both coastal and island volcanoes. Therefore, we refer to all tsunamis caused by slope instability at volcanoes as volcano collapse tsunamis.

Keating and McGuire (2000) have identified 23 preconditioning factors which promote edifice instability in marine environments. These factors can be divided into two categories: endogenetic (intra-edifice) and exogenetic (extra-edifice) factors. Endogenetic processes are associated with unstable foundations such as pelagic clays and rubble zones, decollement surfaces linked to intrusions, thermal alteration, edifice pore pressure and faulting (Figure 2). Exogenetic failures are associated with mechanically weak zones in the edifice (for example, caused by hydrothermal alteration), steep slopes, overloaded flanks, earthquakes, tilting, uplift, ice/snow coverage, rapid climate change and extreme climatic events, and weathering (Figure 2). While endogenetic failures are more significant during the constructive stages of volcanism, exogenetic failures continue throughout the history of volcanic islands (Keating and McGuire, 2000). The preconditioning state of marine volcanoes is vital, and a critical threshold is eventually reached when the driving force on the rock mass exceeds the resisting force of the zone of weakness, resulting in major slope failures.

In most cases, a final trigger or a combination of triggers can also set the rock mass in motion, which may be related to or independent of the preconditioning factors. Triggers are typically short-lived dynamic events that suddenly cause a system in a static equilibrium to collapse (Voight and Elsworth, 1997). These triggers are either 1) rapid stress changes caused by new magma body propagating towards the surface (e.g., Belousova and Belousov, 1995; Siebert et al., 1995), or 2) an increase in ground accelerations induced by volcanic or tectonic earthquakes (e.g., Endo et al., 1989; Inoue, 2000; Schaefer et al., 2013). Capra (2006)

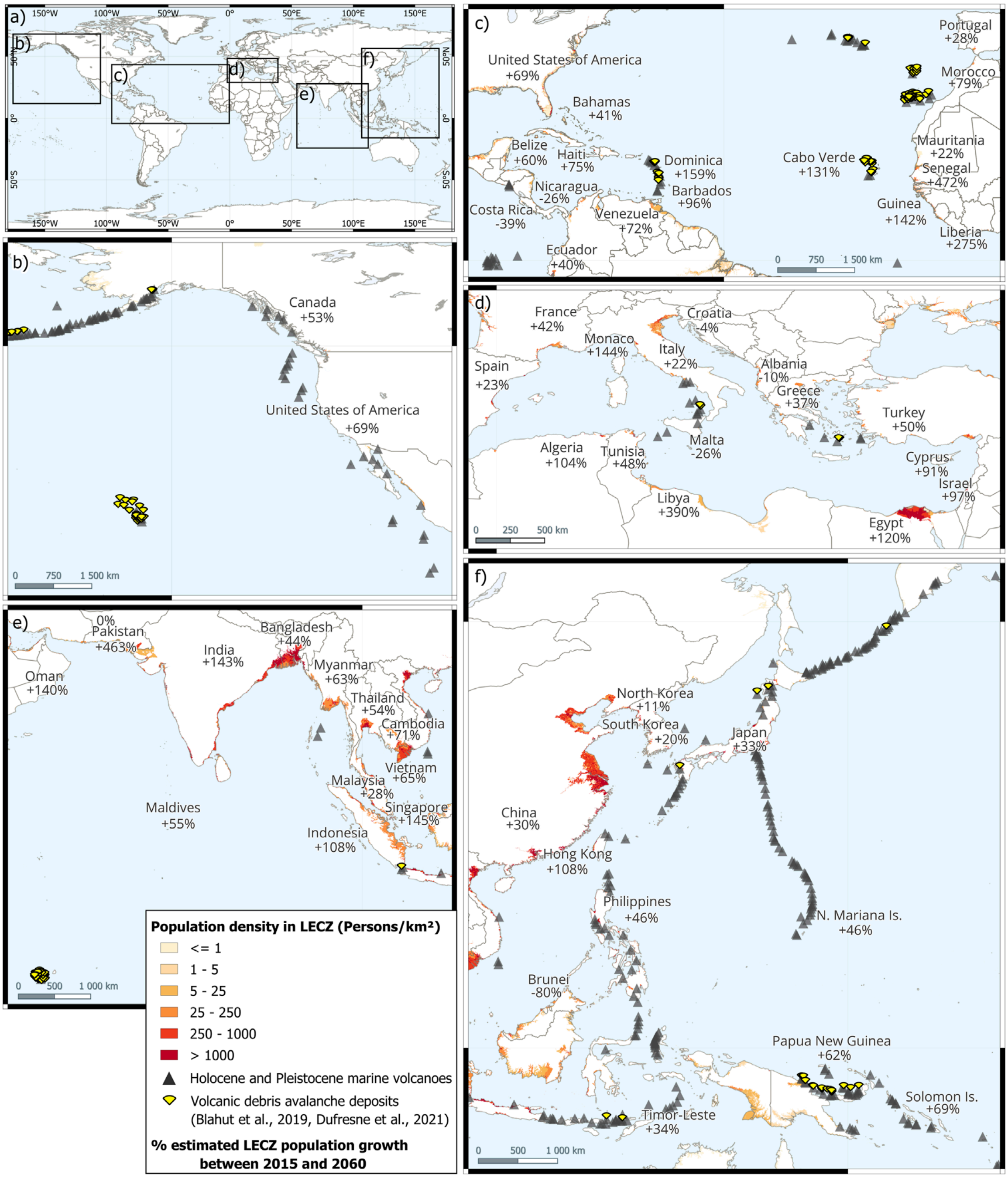

FIGURE 1
(A) Location of the close up views of **(B)** Northeast Pacific Rim, **(C)** Atlantic Ocean, **(D)** Mediterranean Sea, **(E)** Indian Ocean and **(F)** West Pacific Rim. Representation of the population density (color scale) in Low Elevation Coastal Zones (LECZ, colored area) in 2020 along with marine volcanoes reported to be active during the Pleistocene and the Holocene (black triangles, extracted from Global Volcanism Program, 2013). Population densities come from GPWv411 database (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018) and elevation filter for LECZ estimate come from Center for International Earth Science Information Network - CIESIN - Columbia University and CUNY Institute for Demographic Research - CIDR - City University of New York (2021). The yellow inverted triangles indicate the location of Volcanic Debris Avalanche Deposits from Blahůt et al. (2019). Predictions of population growth in LECZ for 2060 are indicated as growth percentage (see scenario C from Neumann et al., 2015; Supplementary Table S1).

proposed that climatic changes could also trigger volcano collapses, but due to the inherent uncertainties in deposit dating and climate fluctuations, establishing a direct cause-and-effect relationship is more challenging than demonstrating the potential role of climate as a destabilizing factor.

3 Data and results

We identified nine volcano collapses that occurred from 1600 onwards and generated tsunamis, by comparing Volcanic Debris Avalanche Deposits (VDAD, Day et al., 2015; Dufresne et al., 2021)

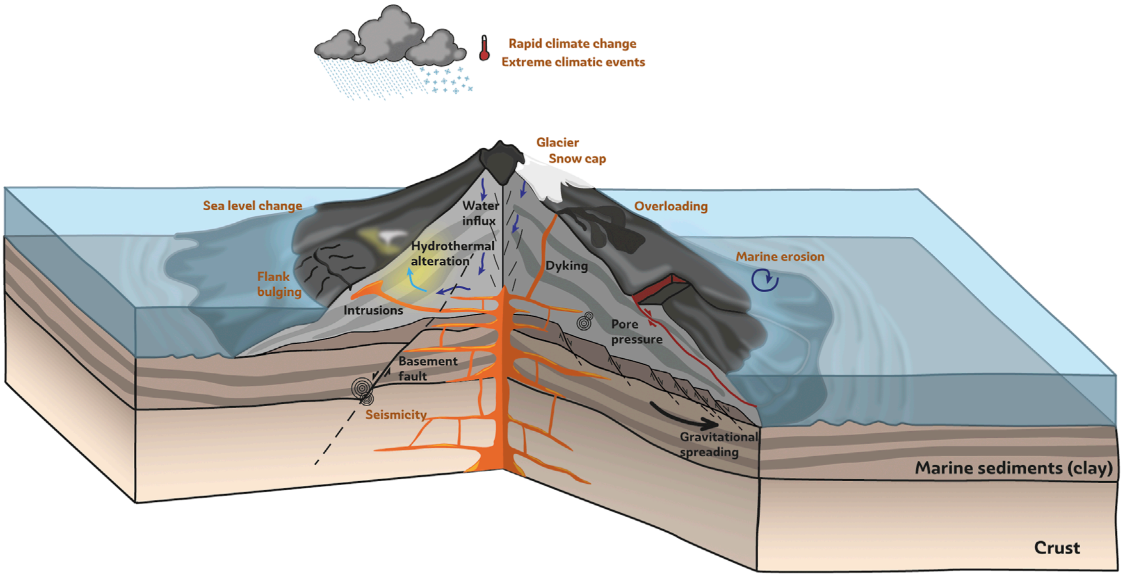

FIGURE 2
Cartoon (not to scale) illustrating the structures of oceanic volcanoes along with the different endogenetic (in black) and exogenetic (in brown) preconditioning factors of volcano collapse (based on McGuire, 1996; Keating and McGuire, 2000).

and volcanic tsunami (Paris et al., 2014; Day, 2015; Paris, 2015) databases. Due to insufficient documentation, the volcano landslides from 1966 and 1971 at Tinakula volcano (in Solomon Island) were not included.

The earliest historical collapse occurred at Hokkaido Komagatake, an andesitic stratovolcano in northern Japan. Geological studies show that after 5,000 years of dormancy, *new magma intruded* into the volcanic edifice in 1640, followed by two sector collapses in different directions: one purely subaerial (Onuma lobe) with ~0.3 km^3 and one mobilizing both subaerial and submarine parts of the volcano (Shikabe lobe) with volumes ranging from 1.42 to 1.70 km^3. The second collapse was accompanied by a blast and a tsunami (maximum local wave run-up ~8 m), followed by a plinian eruption (Yoshimoto and Ui, 1998; Yoshimoto et al., 2007; Furukawa et al., 2008).

At Oshima-Oshima, a volcanic island southwest of Hokkaido in the Japan Sea, geological studies and historical documents indicate that after 1,500 years of dormancy, the volcano experienced activity between 1741 and 1790 (Katsui and Yamamoto, 1981). A few *days after the eruption* started on 18 August 1741 the most violent phase of the eruption was associated with a sector collapse of the north flank on August 29 (total of 2.4 km^3 from subaerial and submarine part of the volcano) triggering a destructive tsunami (run-up >14 m, Satake and Kato, 2001; Day, 2015).

The deadliest recorded volcano collapse tsunami (Auker et al., 2013) occurred on 21 May 1792, when the southern lava dome (subaerial, 0.34 km^3) of Mayu-yama volcano, part of the Unzen volcanic complex, collapsed (Ozeki et al., 2005). The subaerial volcanic debris avalanche entered the sea, and generated a tsunami that struck nearby areas (maximum local run-up >10 m). The collapse followed a *period of seismic activity* (Siebert et al., 1987) but no explosive eruption was documented at Mayu-yama, while Fugen-dake, another volcano of the Unzen complex, was erupting (Katayama, 1974). *Pore fluid pressurisation* may have also contributed to the development of the collapse structure (Figure 2; Siebert et al., 1987).

Augustine volcano in the Aleutians is a complex of overlapping summit lava domes with repeated major edifice collapses through geological times, which have produced large volcanic debris avalanches and related tsunamis (Siebert et al., 1995). The most recent one took place in August 1883 with few precursors indicating the *ongoing phreatic eruption*. While the duration of the 1883 eruption is uncertain, the paroxysmal phase was marked by a collapse of the upper edifice on 6 October 1883 mobilizing a volume of 0.3 km^3 from the subaerial part of the volcano. It generated a tsunami with a run-up of 7–9 m at nearby Port-Graham (Siebert et al., 1995).

In Papua New Guinea, Ritter Island stratovolcano was known to be frequently active when on 13 March 1888 a collapse disintegrated about 2.4 km^3 of its cone, initiating a tsunami with run-up waves >15 m (Day et al., 2015). While evidence for eruptions immediately before the collapse is lacking, submarine sampling documents an unusually large and compositionally anomalous submarine eruption occurring after the collapse (Watt et al., 2019). In addition, seismic reflection imaging shows *long-term spreading* of its flank prior to the collapse (Figure 2; Karstens et al., 2019).

Paluweh (Rokatenda) volcano in the Lesser Sunda Islands is formed by overlapping craters and several lava domes. On 4 August 1928, an eruption occurred *after almost 300 years of quiescence*, which was accompanied by a significant landslide (unconstrained volume) that triggered a tsunami (run-up ranging from 5 to 10 m, Latter, 1981; Day et al., 2015). However, there is no evidence indicating whether the eruption or the collapse occurred first.

On 8 January 1933 a collapse (0.5 km^3) occurred at Kharimkotan (Harimkotan) stratovolcano in the northern Kuriles, followed by a strong explosive eruption (Belousova and Belousov, 1995).

Following the collapse, a tsunami was triggered with a maximum local run-up reaching 20 m. Belousov et al. (2007) has suggested that the *magma was deeper at the moment of collapse*, such that no lateral blasts were generated.

In 1979, the southern flank (subaerial) of Iliwerung volcano collapsed (0.05 km^3), although the volcano was not erupting. This collapse resulted in tsunami waves with a maximum run-up of less than 10 m (Lassa, 2009; Paris et al., 2014). Yudhicara et al. (2015) have shown that *hydrothermal alteration of the rocks and soil* in the geothermal environment was probably the trigger of this collapse (Figure 2).

Stromboli volcano in the Tyrrhenian Sea, Italy, is a highly active stratovolcano, displaying continuous Strombolian explosive activity for 2,000–5,000 years. This activity involves periodic ejection of bombs and lapilli from the volcanic vents, occasionally punctuated by significant or paroxysmal explosions (Calvari et al., 2021). In the Holocene, Stromboli volcano has experienced several collapses, with some reaching volumes of up to 1–2 km^3 (Tibaldi, 2001). Despite involving only 0.02 km^3 of material (aerial and submarine), the recent collapses in 2002 at Stromboli generated a tsunami with a maximum run-up of 10 m. These collapses occurred 2 days after the onset of an effusive eruption, following a period of extraordinary strombolian activity (Brusca et al., 2004; Acocella, 2021). The aerial collapse was directly observed, including pre-collapse helicopter surveys that helped understand the collapse mechanism. Di Traglia et al. (2023) determined that the collapse was triggered by a *lateral magma intrusion*, which exerted significant thrust at high altitude, resulting in the destabilization of the entire slope.

The most recent event occurred at Anak-Krakatau, a stratovolcano in the Sunda strait in Indonesia. Following an intense yet ordinary eruptive period of several months (Cutler et al., 2022), its southwestern flank -including the summit area-collapsed on 22 December 2018 (~ 0.18–0.31 km^3) generating a maximum tsunami run-up of 13 m. While it was unclear whether the magmatic activity was directly leading to the collapse (Cutler et al., 2022), long-term deformation records indicated *lateral motion* for over a decade before the event (Zorn et al., 2023).

4 Discussion

4.1 Why are erupting marine volcanoes perceived as more prone to collapse?

Among historical volcano collapses attributed to flank instabilities, four occurred on erupting volcanoes (Oshima-Oshima, Augustine, Stromboli and Anak-Krakatau), three took place during periods of quiescence that later led to renewed eruptions (Hokkaido Komagatake, Ritter Island and Kharimkotan), one occurred on a non-erupting volcano with potential eruptions at neighboring volcanoes (Mayu-yama), and one collapse occurred without an eruption (Iliwerung). The Paluweh volcano event lacks sufficient data for a definitive classification, but it is likely to align with either the first or second category. Overall, most historical collapses were accompanied by eruptions (9 out of 10, including eruptions at neighboring volcanoes), either preceding or following the collapse. Without considering the exact sequence of events, this observation could lead to the interpretation that collapses of marine volcanoes predominantly occur on actively erupting ones.

Our human comprehension of risk, which to some extent, relies on images and associations (Slovic et al., 2004), might contribute to perceiving erupting volcanoes as more prone to collapse. These images and associations are often influenced by media coverage, which tends to focus more on erupting volcanoes compared to non-erupting ones, potentially shaping our perception of the associated threat. Even experts may be vulnerable to various heuristics and biases, especially when data or knowledge limitations come into play and intuition or subjective assumptions are involved (e.g., Tversky and Kahneman, 1973; 1974; Kahneman et al., 1982).

We suggest that both historical events and human perception contribute to the closer consideration of actively erupting marine volcanoes. However, such observations and perceptions should not be used as the sole scientific evidence to draw conclusions, particularly regarding precursory signals or mitigation strategies.

4.2 Are eruptions reliable precursors to marine volcano collapses?

The historical collapses identified in this study emphasize the significant role of eruptions in destabilizing volcanoes. However, the fact that eruptions followed collapses in four (possibly five) cases indicates the influence of other factors in the initial destabilization process. In some cases, eruptions may even be a consequence rather than the trigger of the collapse. Indeed, the sudden pressure relief resulting from a collapse and the interaction of hot magma with water can promote intense explosive eruptions. This was likely the case at Tenerife, where at least three major caldera-forming eruptions were induced by volcano collapse (Hunt et al., 2018). Additionally, terrestrial records provide evidence of collapses and deformations unrelated to eruptions. For example, collapses at Mombacho and Socompa volcanoes have been linked to gravitational spreading facilitated by weak hydrothermally altered or pre-existing structural features (van Wyk de Vries and Francis, 1997; van Wyk de Vries et al., 2001). Similarly, the recent signals observed at the dormant Damavand volcano in northern Iran has been attributed to long-term, slow, gravity-driven deformation, potentially indicating gravitational spreading (Shirzaei et al., 2011). Therefore, eruptive activity alone is not a robust precursor for forecasting collapses at volcanoes.

4.3 Limitations

While existing historical collapses provide valuable insights into the role of eruptions and other contributing factors in destabilizing volcanoes, a lack of comprehensive data limits our complete understanding of these phenomena. Although it is possible to rely on human testimony for historic events, reconstructing the exact sequence of events for historical marine volcano collapses can be challenging due to scarcity or incompleteness of accounts, especially when collapses occur on uninhabited or remote volcanic islands such as Oshima-Oshima, Ritter Island, Augustine, and Kharimkotan. Only the collapse of Stromboli was extensively documented in near real-time (Di Traglia et al., 2023). Furthermore, identifying and accurately characterizing small events (>0.1 km^3), such as the collapse at Paluweh, can be difficult, and large events at intraplate volcanoes are absent in historical records. To better assess the role of eruptions in marine volcano collapses, more well-documented case studies are needed. In the meantime, it is essential to use the current scientific state-of-the-art to proactively address the hazards associated with collapses at marine volcanoes.

5 Conclusion

Investigations of historical marine volcano collapses, geological examples, and conceptual models of preconditioning factors and triggers reveal that collapses can occur on both erupting and non-erupting volcanoes, and at various stages before, during, or after eruptions. Nevertheless, limiting our view to historic events of collapses and associated tsunamis, which all (except one) occurred on apparently erupting volcanoes, and combine it with our human perception, which relies on images and associations, may lead us to perceive erupting marine volcanoes as more prone to collapse as non-erupting ones. This finding is significant as it cautions against adopting a paradigm that exclusively focuses on collapse hazards in actively erupting marine volcanoes. Such a paradigm could lead to inaccurate hazard assessments, as observed in the case of the Tohoku-oki earthquake and tsunami (Lacassin and Lavelle, 2016). Prior to that event, it was commonly believed that segmented subduction zones like the one in Japan could not generate Mw 9+ earthquakes due to the absence of previous observations. Consequently, earthquake and tsunami mitigation measures in Japan were designed accordingly, disregarding evidence of similarly sized tsunamis in geological records. The Tohoku-oki earthquake shattered this paradigm.

Given the growing population living in vulnerable areas and our increasing reliance on seafloor infrastructures we need to develop strategies for assessing marine volcano stability and identify robust precursors. These tasks require the integration of a diverse and multidisciplinary community to tackle the geomechanical, geometrical, and magmatic aspects of preconditioning factors and triggers of marine volcano collapses. While some precursors may be generalized across volcanoes (or possibly types of volcanoes), assessing the stability conditions requires case-by-case analyses. Successfully meeting these challenges requires a united and collaborative effort from the scientific community. This is possible and timely considering rapid advances in monitoring technologies and capabilities in modeling and data analyses.

Data availability statement

The dataset for LECZ delineations and population distribution in LECZ in 2015 can be found at https://doi.org/10.7927/d1x1-d702. Population density can be located at https://doi.org/10.7927/H49C6VHWßor the population predictions in 2060, dataset come from Neumann et al. (2015) and are available at https://doi.org/10.1371/journal.pone.0118571.s004. Volcanic debris avalanches deposits come from Blahůt et al. (2019) and are available at https://www.irsm.cas.cz/ext/giantlandslides.

Author contributions

MU conceptualized the study and acquired the funding. SF led the writing of the original draft and designed the figures with the support of EK and CB. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1130561/full#supplementary-material

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