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RESEARCH LETTER

10.1029/2025GL115727

Controls on Water-Magma Interactions at Hydraulically-Charged Volcanic Islands

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Key Points:

- Shifts between magmatic and phreatomagmatic activity over the life span of volcanic fields may reflect fluctuations in groundwater levels
- Long-term changes in hydroclimate influenced water-magma interactions at Flores Island but not on shorter timescales (Holocene)
- At ocean island volcanoes with perched aquifers, variations in the mass eruption rate are crucial for triggering phreatomagmatism

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Andrade, M., Hernández, A., Pimentel, A., Cruz, J. V., Ramos, A. M., Ludwig, P., et al. (2025). Controls on water-magma interactions at hydraulically-charged volcanic islands. *Geophysical Research Letters*, *52*, e2025GL115727. https://doi.org/10.1029/2025GL115727

Received 7 MAR 2025
Accepted 1 SEP 2025

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Abstract The interaction of rising magma with groundwater can produce phreatomagmatic explosions, which, given their enhanced explosivity and unpredictability, increase the hazard potential of volcanic eruptions. To investigate the link between groundwater occurrence and phreatomagmatism, we compare the volcanic record of Flores Island (Azores) with regional climate reconstructions. Flores is an ideal case study as it experienced multiple magmatic and phreatomagmatic eruptions during the Holocene and Pleistocene. Our results show that at a broader scale (>10 ka), magmatic volcanism prevailed during dry/colder periods, whereas phreatomagmatism preferentially occurred during wet/warm periods. At a shorter timescale (<10 ka), however, water-magma interactions were primarily controlled by variations in eruption rates, with rainfall variability having a secondary role, as phreatomagmatism occurred even during low precipitation periods. This study reinforces that on island volcanoes with perched aquifers and prone to monogenetic volcanism, eruption rates rather than short-term hydroclimate changes control the triggering of phreatomagmatism.

Plain Language Summary The explosivity of volcanic eruptions may increase when magma interacts with groundwater (phreatomagmatism). On islands, freshwater reserves are strongly dependent on rainfall, which can be highly variable over time. Climate changes throughout Earth's history, resulted in periods with more or less rainfall and possibly, to variations in the abundance of water resources in certain regions over time. By combining past climate and volcanic records from Flores Island (Azores), we explore how fluctuations in groundwater may control the explosivity of volcanic eruptions on islands with abundant water resources. Previous studies revealed that Flores Island experienced multiple eruptions in the past 300,000 years, with phreatomagmatic eruptions occurring predominantly during the Holocene (last 11,700 years). Our results show a general correlation between long-term climate variations and eruption explosivity. However, short-term climatic variations during the Holocene cannot explain the occurrence or absence of water-magma interactions. Based on this, we conclude that on islands with abundant aquifers, explosive water-magma interactions are primarily controlled by the rate at which magma reaches the surface and, critically, the rate at which the magma recedes, that is, how rapidly the eruption ends.

1. Introduction

When ascending toward the surface, magma can encounter groundwater stored in aquifers or surface water in marine and inland environments. The thermal and hydrodynamic contact between magma and water may increase the efficiency of magma fragmentation (Németh & Kósik, 2020; White, 1996; Zimanowski et al., 2015), exacerbating volcanic explosivity. This is common in monogenetic basaltic volcanoes, which often experience changes between magmatic and phreatomagmatic activity (Martí et al., 2011; Planagumà et al., 2023; Zanon & Viveiros, 2019). Variable water-magma interactions throughout eruptions depend on a complex interplay between intrinsic factors (e.g., mass eruption rate, magma physico-chemical properties, conduit geometry) and environmental conditions (e.g., hydrological characteristics such as rainfall regime, infiltration rate, surface runoff, and groundwater occurrence) (e.g., Cassidy et al., 2018; Smith & Németh, 2017).

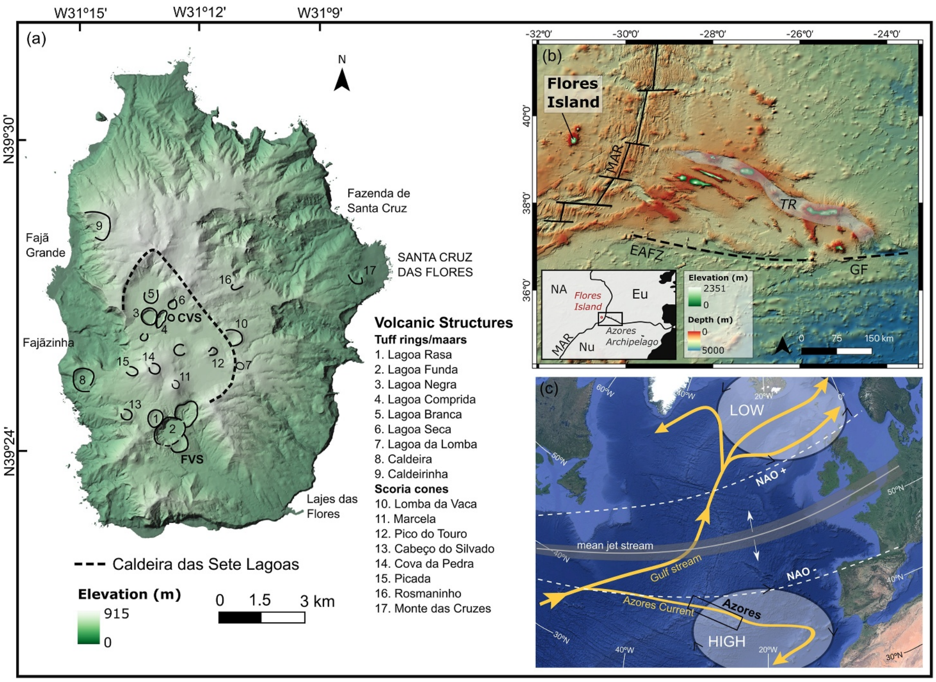

Figure 1. Geological and climatic settings of the study area. (a) Map of Flores Island showing the location of magmatic (scoria cones) and phreatomagmatic (tuff rings/maars) vents; CVS—Comprida Volcanic System and FVS—Funda Volcanic System; (b) Geotectonic setting of the Azores at the triple junction of the North American (NA), Eurasian (Eu), and Nubian (Nu) lithospheric plates (main morphotectonic structures: MAR—Mid-Atlantic Ridge, EAFZ—East Azores Fracture Zone, TR—Terceira Rift, and GF—Gloria Fault); (c) Map of the North Atlantic showing the main atmospheric and oceanic currents influencing the climate in the Azores (modified from Stewart et al. (2017) and Goslin et al. (2018)). Yellow arrows correspond to warm ocean surface currents. White dashed lines show the preferential position of the jet stream depending on the NAO phases. See Data Availability Statement section for elevation and bathymetry data sources.

Several studies have examined how these different factors influence magma-water interactions in different settings and timescales (e.g., Farquharson & Amelung, 2020; Foote et al., 2022; Kshirsagar et al., 2016; Nowell et al., 2006; Pedrazzi et al., 2022). Environmental controls have been particularly examined in the Transmexican Volcanic Belt, where long-term rainfall variability seems to have influenced the eruptive style of some monogenetic volcanoes (e.g., Agustín-Flores et al., 2021; Kshirsagar et al., 2015). Similar influences have been observed in other settings such as the Bakony-Balaton Highland Volcanic field (Kereszturi et al., 2011) and the Kamchatka Peninsula (Belousov, 2006). Despite its importance for accurate volcanic hazard forecasting, a detailed scientific understanding of how water-magma interactions respond to environmental changes remains limited. This is particularly relevant on volcanic islands, especially the ones with abundant water resources (e.g., Hawaii, Azores, west Pacific or Caribbean Islands). These islands often have a small size, isolated geography, and high sensitivity to climate, orographic and atmospheric variations (tropical or temperate, high and low altitudes, or under the influence of trade winds and westerlies) (Veron et al., 2019).

Volcanic islands have complex hydrogeological functioning that depends on several factors, such as the age and internal structure of the volcanoes, their size and topography, and recharge variability. Most exhibit a low-hydraulic-gradient basal groundwater body in equilibrium with the ocean, and inland upper dike-compartmented or perched aquifers (the "Hawaiian/La Reunion" model, Cruz, 2003; Peterson, 1972; Prada et al., 2005; Won et al., 2006). Others, follow the "Canary Islands" model, which considers a continuous basal aquifer with a hydraulic gradient that follows surface topography (Custódio, 1978, 2004).

Flores Island (Azores) is an ideal setting to study groundwater's role in modulating volcanism as it experienced multiple magmatic and phreatomagmatic monogenetic eruptions during the Holocene and Middle-Late Pleistocene. This is attested by the numerous scoria cones, tuff rings, and maars that shape the island's topography (Figure 1a). The recent stratigraphy of Flores also shows that small-volume and mildly explosive basaltic eruptions can rapidly shift into violent explosive events as a result of water-magma interactions (M. Andrade

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et al., 2022, 2023). Flores' edifice contains abundant groundwater and surface water resources, as reflected by the abundance of springs, perennial streams, lakes, peatlands, and its dense vegetation. However, the Azorean hydroclimate displays a large inter-annual variability, which can result in fluctuations in surface and groundwater levels (Hernández et al., 2016, 2017; Sáez et al., 2025). Accordingly, humid periods would allegedly favor the generation of phreatomagmatism when compared to dry periods.

Through the integration of Flores' volcanic and paleohydroclimatic records (see Text S1 in Supporting Information S1), this study attempts to better understand how long-term and short-term (multimillennial to centennial timescales) rainfall variability may influence eruptive styles and consequently the hazard of volcanic eruptions. Moreover, it attempts to determine the dominant factors controlling shifts in magmatic/phreatomagmatic styles in the context of small-volume monogenetic eruptions at hydraulically charged ocean island volcanoes. This study corresponds to a first-order approach to the problem, paving the way for future studies on how climate inter-annual variability modulates volcanism.

2. Middle-Late Pleistocene and Holocene Volcanism

Flores is the westernmost island of the Azores Archipelago, which straddles the triple junction of the North American (where Flores sits), Eurasian, and Nubian lithospheric plates (Figure 1b). The island's volcanism dates back to 2.16 Ma and was characterized by major eruptive phases separated by long quiescence periods (50–400 kyr, Azevedo & Portugal Ferreira, 2006). At ∼300 ka, a caldera collapse formed a depression in the center of the island, presently at 500 m asl (Hildenbrand et al., 2018). Locally known as *Caldeira das Sete Lagoas* (Figure 1a), this depression is currently filled with lavas and pyroclasts from monogenetic basaltic eruptions of Middle-Late Pleistocene and Holocene ages.

Flores' Holocene eruptive history includes six small-volume basaltic eruptions (Table S1 in Supporting Information S1, M. Andrade et al., 2021, 2022, 2023), Hawaiian and Strombolian in style, which frequently shifted to phreatomagmatic phases. They formed several tuff rings and maars 150 m to ∼1 km wide (Figure 1a), most of which are currently occupied by lakes as deep as 114 m. Holocene volcanism was limited to a period of ∼3,100 years (∼3–6 ka), with the last four eruptions clustering within ∼250 years. The recurrence rate is 1.6×10^{-3} eruptions/yr (estimated following Connor and Conway (2000)), however, during periods of clustered volcanic activity, recurrence intervals were <100 years.

Limited volcano-stratigraphic and geochronological data precludes a detailed reconstruction of Flores' Middle-Late Pleistocene eruptive history. Nonetheless, ∼30 scoria cones and associated lava flows indicate widespread volcanism in the central uplands during this period (Figure 1a), with predominance of magmatic activity over phreatomagmatism. This is supported by the predominance of lava-flow successions throughout the exposed caldera-filling sequence (M. Andrade et al., 2023). Although ages of individual eruptions are unknown, they can be constrained to <314 ± 30 ka (K/Ar, Hildenbrand et al., 2018, Table S1 in Supporting Information S1).

3. Climatic and Hydrological Setting

Since the early Holocene, rainfall variability in the Azores has been mostly influenced by the NAO (Hernández et al., 2016), which is manifested by the anomaly between the Iceland sub-polar low and the Azores sub-tropical high-pressure poles (Figure 1c). Positive NAO phases shift westerlies northward, causing dry conditions in the Azores, while negative phases bring them south, increasing rainfall (Figure 1c). The Azores Current, a south-eastern branch of the Gulf Stream (Figure 1c), also influences the region by transporting warm equatorial waters to the polar regions (Klein & Siedler, 1989).

At Flores, monthly data sets of accumulated precipitation over 3 hydrological years show that rainfall prevails throughout all seasons. "Drier" months (June and July) experience significant precipitation of up to 108 mm/month, whereas rainier months record up to 861 mm/month, a value that is ∼8 times higher (Figure S1a in Supporting Information S1).

The elevation of Flores and its steep topography forces westerlies' moist-rich air upwards, resulting in an uneven distribution of precipitation with relief (Figure S1b in Supporting Information S1). Rip fog (wet-fog-catch or hidden precipitation) captured by the cloud forest in the central uplands further exacerbates this effect. Consequently, rainfall is heavily skewed toward higher elevations, with mean precipitation values at the coast being 2–3 times lower than at the central uplands (Azevedo, 1998, Figure S1b in Supporting Information S1). Part of that

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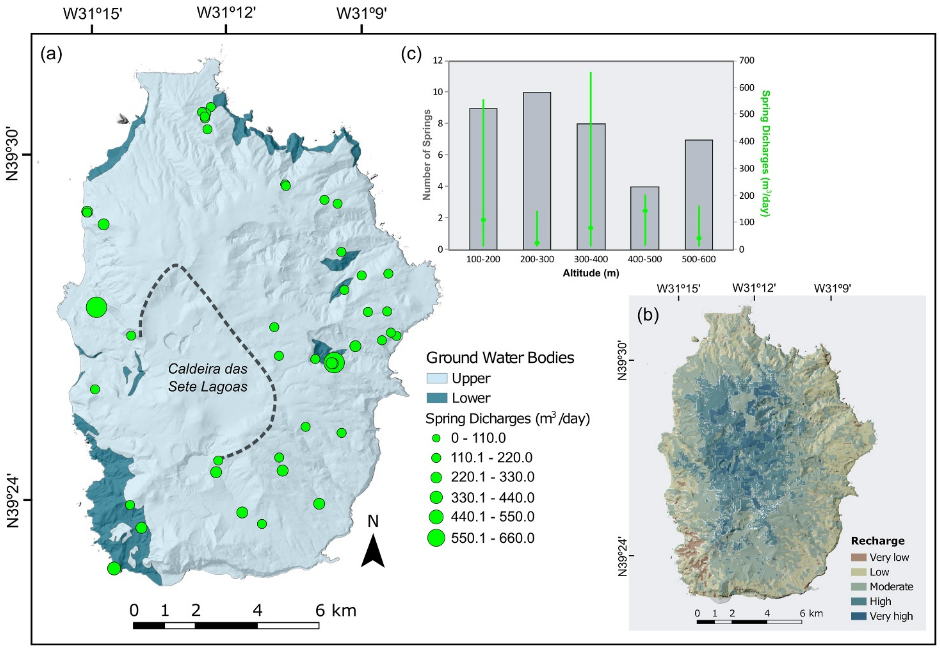

Figure 2. (a) Upper (semi-confined/unconfined perched aquifers at altitude) and Lower (fresh and salt water lenses close to sea-level) groundwater bodies delimitation at Flores with the distribution and discharge rates of the springs across the island, (b) preferential groundwater recharge zones delimitation, and (c) number of springs in the Upper unit per 100 m-altitude intervals and respective discharge rates. Green line extends from the minimum to maximum values and green squares mark the median value of discharge rates. Data from Secretaria Regional do Ambiente e do Mar (2022).

water ends up retained in crater lakes, which store $\sim 1.83 \times 10^7$ m^3 of water (C. Andrade et al., 2019), but also by bogs, fens, and peatlands (*Sphagnum*-dominated), which cover 17% of the island and store an estimated volume of water of 2.2×10^7 m^3 (Pereira et al., 2022). These reservoirs (Figure S2 in Supporting Information S1) regulate infiltration and ensure steady water release year-round, mitigating the effects of summer groundwater recharge reduction.

The Azorean Islands typically follow the "Hawaiian/La Reunion" model, with the perched-water bodies being frequently drained out by springs at higher elevations (Cruz, 2004; Cruz & Soares, 2018; Cruz et al., 2015). At Flores, two superimposing hydrogeologic units are present, the Upper and the Lower groundwater bodies (Figure 2a, Secretaria Regional do Ambiente e do Mar, 2022). Groundwater recharge in the Upper unit was estimated as 1.54×10^8 m^3/yr, 75.5% of which occurs from October to March, being the lowest in July (5.9 mm) and the highest in January (173.6 mm) (Cruz et al., 2021). Estimations of the recharge rates are 27.2% and 31.3% for the Lower and Upper units, respectively. The recharge is higher in the central uplands, where rainfall is higher but also where recent, highly porous, volcanic products prevail (Figure 2b). In contrast, recharge is lower at the drier lowlands (<500 m asl), where less permeable, older geological formations crop out (Azevedo, 1998). The volume of water that is not infiltrated is drained over the island's surface, forming a dense drainage network composed of numerous perennial streams (Figure S1c in Supporting Information S1), with surface runoff estimated at 1.94×10^8 m^3/yr (Cruz et al., 2021). The distribution of springs shows that even at high altitudes (>400 m) there are perched-aquifer discharges, some of which exhibit mean daily flow rates up to 200 m^3/day (Figure 2c).

4. Rainfall Variability Versus Volcanism

Present day hydrology of Flores Island, reveals substantial year-round groundwater storage in the uplands despite the important seasonal changes in precipitation. Over the Holocene, rainfall oscillations were stronger and followed trends of centennial to millennial timescales (Figure 3 and Figure S3 in Supporting Information S1). This, means that conditions of more/less rainfall persisted throughout longer periods, having therefore greater potential

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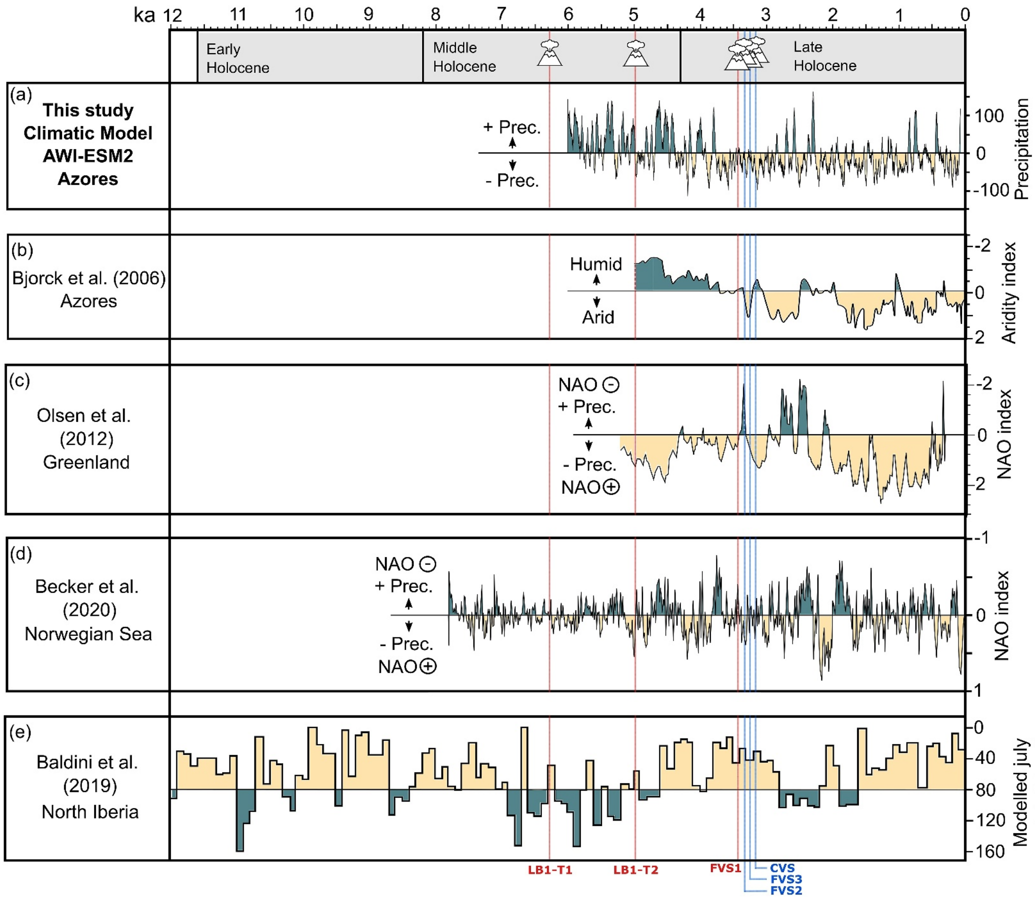

Figure 3. Paleoclimate reconstructions for the North Atlantic over the Holocene. (a) Simulated mean annual precipitation at the Azores obtained from the global climate model AWI-ESM2 (Table S4, https://doi.org/10.5281/zenodo.17079274), (b) aridity index reconstructed using lake sediments from Pico Island, Azores (Björck et al., 2006), (c) NAO index reconstructed using a lake sediment record from southwestern Greenland (Olsen et al., 2012), (d) NAO index reconstruction based on southeastern Norwegian Sea sediment cores (Becker et al., 2020), and (e) precipitation variability based on North Iberian speleothems (Baldini et al., 2019). Red (magmatic) and blue (phreatomagmatic) lines mark the timing of Flores' Holocene eruptions.

to change groundwater storage in the uplands, and so, influence the eruptive style of volcanic eruptions in that area.

Of the six Holocene eruptions recorded at Flores, the three oldest were exclusively magmatic, whereas the most recent ones experienced phreatomagmatic activity (Figure 3). Available proxy-based data covering the timing of the oldest Flores' Holocene eruption (LB1-T1, 6,280 cal yr BP) suggest dry conditions in the North Atlantic at that time (Figures 3d and 3e). Albeit purely magmatic, the second Holocene eruption (LB1-T2, 4,990 cal yr BP) correlates with a humid period. This is attested by our model-based precipitation reconstruction and the proxy-based reconstruction by Björck et al. (2006) (Figures 3a and 3b), even though the NAO indexes obtained for other regions across the North Atlantic point to predominant positive phases (drier conditions, Figures 3c–3e).

The last four eruptions occurred during the Late Holocene, over a continuous dry period, as attested by our modeled precipitation for the Azores (Figure 3a), proxy-based climate reconstructions for North Iberia (Figure 3e), and by lake water level reconstructions across the Azores, which suggest a lowstand phase during this period (Sáez et al., 2025). Yet, our model shows that this period was characterized by a reduction in the precipitation anomalies when compared with the variations before and after, suggesting low amplitude changes of precipitation around the average value. Further climate reconstructions indicate, however, that this period was characterized by short-term (multidecadal/centennial) rainfall variability (Figures 3b–3d), with magmatic and phreatomagmatic eruptions coinciding with both dry and wet phases (Figure 3). The reconstruction by Olsen

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et al. (2012) shows positive values of the NAO (low rainfall) during the purely magmatic FVS1 eruption and a negative peak (high rainfall) coincident with the phreatomagmatic FVS2 eruption (Figure 3c). However, this peak is brief and does not overlap with the following phreatomagmatic events (FVS3 and CVS), which occurred under drier conditions according to this reconstruction. The higher resolution NAO reconstruction by Becker et al. (2020) shows much more high-frequency variability during the time of FVS and CVS eruptions, with FVS1 (purely magmatic) and CVS (phreatomagmatic) eruptions coinciding with humid periods, and FVS2 and FVS3 phreatomagmatic eruptions with drier periods, pattern that is also observed in Björck et al. (2006) reconstruction. However, rainfall variability during this period is short-termed and smoother-than-usual, with the maximum and minimum peaks of the NAO index rarely exceeding 0.5 and −0.5, respectively, suggesting almost neutral NAO phases and therefore relatively stable rainfall conditions during the time of FVS and CVS eruptions.

At a broader scale, when compared with the last glacial cycle, the Holocene was a short, warm, and humid period, characterized by weak climatic oscillations (Figure S3 in Supporting Information S1). Over the last ∼300 ka (maximum age for the Middle-Late Pleistocene volcanism), the climate has been cooler and drier, with the only exception occurring at ∼120 ka during the Marine Isotope Stage 5e (Martin-Garcia, 2019; Martrat et al., 2007; Naughton et al., 2016). Despite the limited number of observations, and assuming that magmatic activity concentrated at approximately 0.4–0.2 ka (Azevedo & Portugal Ferreira, 2006, Figure S3 in Supporting Information S1), data suggests that magmatic eruptions have dominated during cold/dry periods (Middle-Late Pleistocene), while phreatomagmatic eruptions prevailed during warmer/wetter periods (the Holocene).

5. Discussion

Experimental (Valentine et al., 2014) and field (Planagumà et al., 2023) observations showed that most phreatomagmatic eruptions are sourced from explosions occurring <200 m below the surface. Deeper explosions are usually contained (not erupting) even when magma rises through highly productive aquifers. The lack of drilled wells prevents the establishment of a detailed mapping of the Upper groundwater unit at Flores. However, our data on the spring's spatial distribution show the occurrence of highly productive perched aquifers at elevations greater than 400 m (Figure 2c). Considering that the topographic surface of the *Caldeira das Sete Lagoas* depression ranges around 500–600 m asl, this demonstrates the widespread potential for phreatomagmatism across the central uplands.

Flores topography has changed little during the Late Pleistocene and Holocene, meaning that the island's capacity to accommodate perched aquifers in its uplands remained similar in the last 300 ka. Since geological and hydrogeological conditions of the substrate did not change, the uneven distribution of phreatomagmatism over time (with more frequent phreatomagmatic eruptions during the Holocene) suggests that water reserves may have been lower during the Middle-Late Pleistocene, when climate was colder and drier.

Despite the predominance of phreatomagmatism in the Holocene when compared with the Middle-Late Pleistocene, this period experienced both magmatic and phreatomagmatic events (M. Andrade et al., 2021, 2022, 2023). Such variations cannot be explained by the low-magnitude climatic oscillations of the Holocene. For example, in the FVS area (Figure 1a), a Holocene volcanic edifice from a magmatic eruption is overlapped by a maar (M. Andrade et al., 2022), showing that geochemically and rheologically similar magmas ascending through the same aquifer-hosting volcanic sequence resulted in eruptions with distinct eruptive styles (Figure 1a). This, together with the no-correlation between eruptive styles and the Holocene short-term NAO variations, shows that characteristics of the substrate and hydrological changes, may have had a subordinate role in determining eruption explosivity on Flores during the Holocene.

As in other monogenetic volcanoes (e.g., Montsacopa or Orakei, Martí et al., 2011; Németh et al., 2012), water-magma interactions at Flores always occurred during the final phase of an eruption or during a later stage of a volcanic system's evolution, after it has experienced magmatic activity (M. Andrade et al., 2022, 2023). This shows that Flores' Holocene eruptions usually started as magmatic events but, later on, groundwater was able to enter the shallow conduit. The entrance of groundwater in the volcanic conduit is primarily controlled by the stress equilibrium between the magma and country rocks, which, in turn, is a function of the mass eruption rate (Houghton & Schmincke, 1989; Schliz-Antequera et al., 2024).

A high mass eruption rate ensures high magma overpressure in the conduit/eruptive fissure, which, additionally to a high thermal gradient with the country rock, eventually allows magma to cross an aquifer without significant

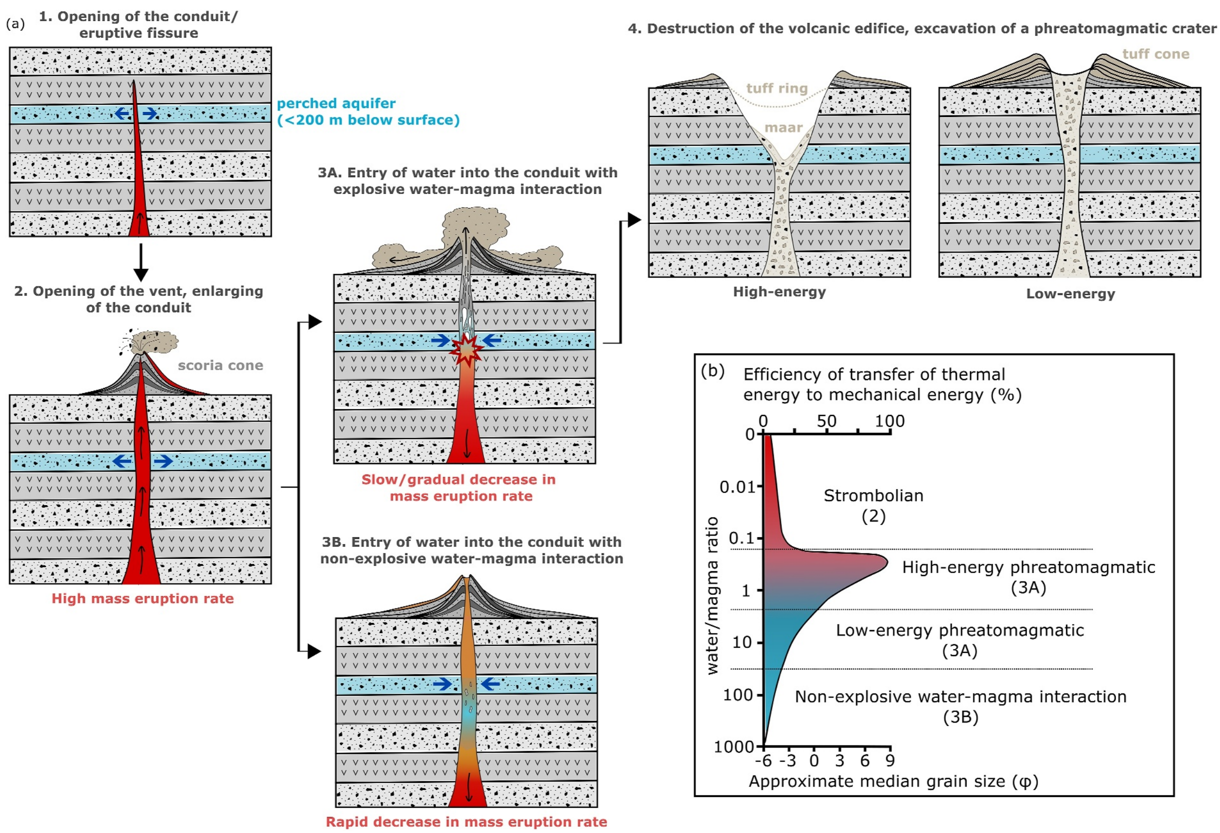

Figure 4. (a) Schematic diagram showing a conceptual model for water-magma interactions during small-volume basaltic eruptions with initial high-mass eruption rate as a function of the speed of decrease in mass eruption rate. Non-explosive water-magma interactions are suggested for rapid magma retreats, and explosive water-magma interactions for slow/gradual decreases in mass eruption rate; (b) efficiency of thermal energy transfer to mechanical energy, resulting from the interaction of magma with water as the mass ratio function of magma to water. The efficiency percentage controls the explosivity and magma fragmentation degree, and consequently the eruptive style (modified from Wohletz (1983)).

magma-water mingling (Gisbert et al., 2009; Figure 4a). However, when the eruption rate wanes, magma overpressure and thermal gradients decrease, allowing water percolation into the conduit, which will mix with the magma, potentially increasing the explosivity of the eruption (Figure 4). Experimental works suggest maximum kinetic energy for fuel:coolant mass ratios of ∼3:1 (Wohletz, 1983). Under these conditions, high-energy phreatomagmatic eruptions typically produce maars and tuff rings. In contrast, when larger volumes of water enter the conduit, water-magma interactions often result in lower-energy eruptions. These, commonly form wet and cold (<100°C) surges, originating tuff cone structures (Németh & Kósik, 2020; Wohletz & Sheridan, 1983; Figure 4). However, optimal fragmentation conditions require efficient magma-water mingling, which in the natural environment depends, upon many factors, on the length scale, system geometry, and fluid dynamics (White & Valentine, 2016). Therefore, although indicative, any direct assumptions derived from these ratios should be treated with caution, since intense phreatomagmatic explosions may occur at different ratios if the right mingling and triggering conditions are met.

The geological record shows that phreatomagmatic explosions at Flores were generally preceded by an increase in the extrusion of accidental lithics (M. Andrade et al., 2022, 2023), suggesting excavation of the conduit walls during periods of high-mass eruption rates (Gisbert et al., 2009; Sulpizio et al., 2005). We therefore suggest that the widening of the conduit during an initial pulse of high-mass eruption rate, followed by an eruption rate decrease (negative feedback), resulted in a decline in magma overpressure, as there was a wider conduit to accommodate a smaller volume of magma (Wadge, 1981). Consequently, when the magma fragmentation level falls below the existing water table, groundwater is able to enter the conduit, increasing the efficiency of magma fragmentation (Figure 4), triggering violent phreatomagmatic explosions with the generation of maar and tuff ring structures, as occurred at Flores (M. Andrade et al., 2022, 2023). The rate at which basaltic magma is discharged

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may vary substantially during an eruption, and therefore, phreatomagmatism may occur at any eruption stage. However, for most basaltic eruptions, a rapid increase in magma discharges up to a maximum typically occurs at the beginning of the eruption, which is followed by a decay, sometimes exponential, over a longer period (Bonny & Wright, 2017; Wadge, 1981).

Hence, we also suggest that an exceedingly rapid drop in the mass eruption rate (associated with a decrease in magma overpressure) may instead lead to a rapid retreat of magma in the conduit, inhibiting phreatomagmatism (Figure 4a). In this scenario, large amounts of water may flood the conduit, resulting in water/magma mass ratios that are too high to generate phreatomagmatic fragmentation (Figure 4b). In these situations, the eruption may eventually end without generating phreatomagmatism. This might have been the case of the FVS1 eruption, since its geological record only shows a magmatic phase despite its close temporal and spatial proximity to major phreatomagmatic events, namely the FVS2 and FVS3 eruptions (M. Andrade et al., 2022).

Observations suggest that the eruptive style at Flores was influenced by long-term variations in the water availability. However, robust conclusions are limited by the small number of observations. Despite that, our findings are comparable with observations in São Miguel Island (eastern Azores), where a change in eruptive style from predominantly magmatic to predominantly phreatomagmatic is recorded at ∼5 kyr ago (Guest et al., 1999; Queiroz et al., 2015; Wallenstein et al., 2015).

Phreatomagmatism has also been reported in many volcanic islands (e.g., Vanuatu, Samoa, New Zealand, Jeju, and Canary Islands), particularly along coastal areas or where rift zones meet the sea (Clarke et al., 2009; Go et al., 2017; Houghton & Nairn, 1991; Németh & Cronin, 2009). Studies that focus on phreatomagmatism triggered by groundwater high on island edifices are rarer, however, highlighting the importance of this study. Similarities to Flores are found, for example, in the observations by McPhie et al. (1990), White and Schmincke (1999), and Geshi et al. (2019) for Hawaii, La Palma and Miyakejima volcanoes, where these authors also attributed variations in the eruption rates to changes in eruptive style from magmatic to phreatomagmatic. These studies, however, focus on single eruptions and do not examine water/magma interactions in the same location, over multiple events, to isolate the parameters controlling water/magma interactions. As a first-order approach, our study provides a basis for further investigation in other volcanic islands worldwide.

6. Conclusions

Despite the relatively low number of eruptions recorded at Flores, our study shows that at hydraulically charged volcanic islands with high infiltration rates and perched aquifers within the first 200 m below the surface, magma-water interactions can be influenced by long-term, prominent changes in the rainfall regime (e.g., during glacial-interglacial transitions). At Flores dry/colder periods (Middle-Late Pleistocene) were dominated by magmatic eruptions, whereas phreatomagmatism became more frequent during wet/warm periods (Holocene).

In contrast, short-term, low-amplitude climatic fluctuations within the Holocene appear insufficient to explain changes in eruptive style. At hydraulically charged volcanic islands, groundwater reserves during periods of less rainfall are apparently sufficient for water-magma interactions to occur. At this shorter timescale, water-magma interactions seem instead to be primarily controlled by variations in eruption rates.

Our findings suggest that, under current conditions, future eruptions at Flores—or similar hydraulically charged volcanoes—would likely involve water-magma interactions. These interactions could increase eruptive explosiveness and unpredictability, with major implications for hazard assessment. This is particularly important in settings where past activity was dominated by small basaltic eruptions, which may cause underestimation of future hazards.

This study highlights the complexity of unraveling climate/volcanism interactions and how the availability of well-dated, high-resolution climate and volcanic reconstructions is critical to establish possible causal links between climate and eruptive style. Crucially, to obtain more robust correlations and better tackle the critical problem of climate/volcanism feedback systems, more studies across different settings and timescales are necessary.

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Data Availability Statement

The accumulated monthly precipitation used to analyze the temporal and spatial rainfall variability at Flores Island is from the Rede Hidrometereológica dos Açores (Hydrometeorological Network of the Azores Regional Government), available on Tables S2 and S3 in Supporting Information S1. Analysis and graphical representation of accumulated monthly precipitation (Figure S1 in Supporting Information S1) were performed using R (v.4.2.0) (R Core Team, 2023), using the "ggplot2" package (Wickham, 2016). The R script used to plot the data is available in Text S2 in Supporting Information S1 and the R project with the script and data sets is available at Zenodo repository: M. Andrade et al. (2025) (https://doi.org/10.5281/zenodo.17079274). The earth system model used for paleoprecipitation reconstructions is available at https://fesom.de/models/awi-esm/. The resulting data is presented in Supporting Information S1 (Table S4) and is available at Zenodo repository: M. Andrade et al. (2025) (https://doi.org/10.5281/zenodo.17079274). The digital elevation model of Flores Island was generated from a 1:25000 scale digital altimetric database and purchased to CIGeoE (https://www.igeoe.pt). Bathymetry in Figure 1b from EMODnet Bathymetry Consortium (2018), https://doi.org/10.12770/18ff0d48-b203-4a65-94a9-5fd8b0ec35f6.

Acknowledgments

MA and JSB are funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—509166013. MA acknowledges the financial support given by the Fundação para a Ciência e Tecnologia (FCT) through her doctoral grant (SFRH/BD/138261/2018). AH is funded by the Spanish Ministry of Science and Innovation through the Ramón y Cajal Scheme (RYC2020-029253-I). AP is supported by a CEEC Institutional contract funded by FCT (https://doi.org/10.54499/CEECINST/00024/2021/CP2780/CT0003). PL is supported by the Helmholtz "Changing Earth" program. We thank Alberto González Casarrubios for providing the Rscript to plot the rainfall data. We also acknowledge Dr. K. Németh and Dr. D. Pedrazzi for their review and comments that helped to improve the manuscript. Open Access funding enabled and organized by Projekt DEAL.

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