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Supporting Information for

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

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Introduction

This document contains a detailed description of the methodology used to conduct the study and provides all the necessary data to replicate it. It also includes additional figures, such as field photographs of the water reservoirs in the uplands of Flores Island, as well as extra paleoclimate reconstructions at different timescales that support the argumentation in the main manuscript.

Text S1. Methodology

Considering that Flores Island has not experienced considerable changes in its topography over the last 300 ka, a short-term temporal analysis of the monthly and annual accumulated precipitation values is conducted for three hydrological years to characterise the spatial distribution of rainfall on the island. To this end, we analyse the values recorded at five udometric stations distributed across different elevations on the island between October 2018 and September 2020 and October 2023 and September 2024 (Rede Hidrometereológica dos Açores; Figure S1, Tables S2 and S3). The selection of this time intervals is limited by the short instrumental record and the large gaps in data for Flores Island, corresponding these to the only complete hydrological years available on record.

To analyse the long-term variations in the annual precipitation in the Azores region (31.5°-24.5°W, 36.5°-40°N), we used existing data from a transient simulation with the AWI-ESM2 climate model (Moreno et al., 2023). AWI-ESM2 is an extension of the AWI climate model version 2 (AWI-CM2; Sidorenko et al., 2019) for Earth system modelling. It consists of an atmospheric component ECHAM6 (Stevens et al., 2013), including a land-surface model (JSBACH) representing multiple plant functional types and two types of bare surface (Loveland et al., 2000; Raddatz et al., 2007), and is coupled to the ice-ocean module FESOM2, which utilises a multi-resolution dynamical core based on a triangle grid and a finite volume discretisation (Danilov et al., 2017). The Holocene transient simulation using AWI-ESM2 starts at 6 ka and continues until 1950 CE, with dynamic vegetation, and is initialised from a 1000-year Middle Holocene spin-up. A resolution of 1.875°x1.875° (in lat/lon) and 47 vertical levels are employed in the atmosphere. The ocean applies multi-resolution (up to 25 km) with 46 vertical levels. The orbital forcing is derived from Berger (1978) and greenhouse gas concentrations are taken from Köhler et al. (2017). Precipitation anomalies were calculated using 30 years running averages. Results are presented in Table S4.

The analysis of the volcanism, hydroclimate, and hydrogeology of Flores Island was conducted through a detailed revision of previous studies and technical reports provided by the Government of the Azores (Azevedo et al., 1991; Azevedo and Portugal Ferreira, 2006; Andrade et al., 2021, 2022, 2023; DROTRH, 2021). Given the limited time frame of paleoprecipitation reconstructions for the Azores region, we also analyse the NAO reconstructions obtained from records in different regions across the North Atlantic, including North Iberia, Norwegian Sea, and Greenland, whose values reflect the NAO position, and therefore can be linked to precipitation in the Azores.

Text S2. R script for plotting Figure S1

```
library(gridExtra)
library(scales)
library(ggplot2)
library(reshape2)
library(dplyr)
library(tidyr)
library (cowplot)


Sys.setlocale("LC_TIME", "C")

regression <- read.csv2("Dataset/Regression.csv", header = TRUE)
Azores <- read.csv2("Dataset/Azores.csv", header = TRUE)

station_order <- c("Ponta.Delgada",
                   "Fazenda.de.Santa.Cruz",
                   "Terreiros",
                   "Pico.da.Casinha",
                   "Lagoa.da.Caldeira.Rasa")

Azores_long <- Azores %>%
  pivot_longer(cols = all_of(station_order), names_to = "Station", values_to = "Precipitation") %>%
  arrange(factor(Station, levels = station_order), Date)

Azores_long <- Azores_long %>%
  group_by(Station) %>%
  mutate(Cumulative_Precipitation = cumsum(Precipitation)) %>%
  ungroup()

colors <- c("#fedc97", "#b5b682", "#7c9885", "#28666e", "#033f63")
names(colors) <- station_order

plot1 <- ggplot(Azores_long, aes(x = Date)) +
  geom_bar(aes(y = Precipitation, fill = factor(Station, levels = station_order)), alpha = .8,
         stat = "identity", position = position_stack(reverse = TRUE)) +
  geom_line(aes(y = Cumulative_Precipitation, color = factor(Station, levels = station_order), group
= Station),
          size = 1) +
  scale_fill_manual(values = colors) +
```

```
  scale_color_manual(values = colors) +
  scale_y_continuous(limits = c(0, 3500), breaks = seq(0, 3500, by = 500)) +
  scale_x_discrete()
labs(title = "Monthly and Cumulative Precipitation per Station (Stacked - Inverted Order)",
     x = "Date",
     y = "Precipitation (mm)") +
  theme_classic() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1),
        legend.position = "none")

plot2 <- ggplot(regression, aes(x = Elevation, y = pp..mm.yr.,
                                color = factor(Station, levels = station_order))) +
  geom_point(size = 3) +
  geom_smooth(method = "lm", se = FALSE, color = "black", linetype = "dashed", size = 0.5) +
  geom_smooth(method = "lm", formula = y ~ poly(x, 2), se = FALSE, color = "black", linetype =
"dashed", size = 0.5) +
  scale_color_manual(values = colors) +
  geom_text(aes(label = Station), hjust = -0.1, vjust = 1.5, size = 3) +
  scale_x_continuous(breaks = seq(0, 600, by = 100), limits = c(0, 600)) +
  scale_y_continuous(limits = c(1000, 3000), breaks = seq(1000, 3000, by = 500)) +
  labs(title = "Relationship between Elevation and Annual Precipitation",
       x = "Elevation (m)",
       y = "Precipitation (mm/year)") +
  theme_classic() +
  theme(axis.text.x = element_text(angle = 0), legend.position = "none")

layout <- rbind(c(1),
                c(2, 3))

empty_plot <- ggplot() + theme_void()

grid.arrange(plot1, plot2, empty_plot, layout_matrix = layout)
```

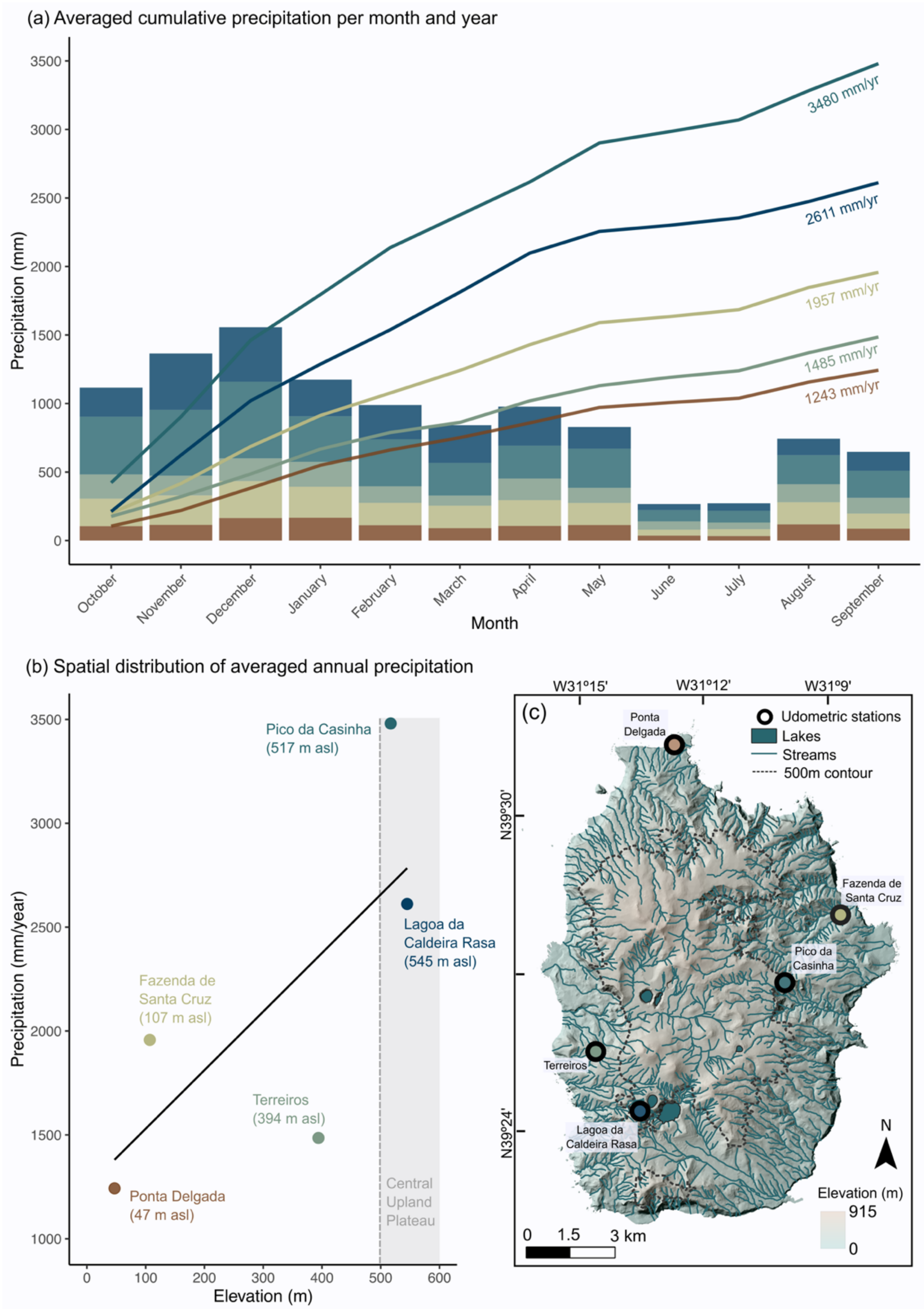

Figure S1. Hydrological setting of Flores Island. **(a)** averaged cumulative precipitation per month and year at five different udometric stations across the island for three hydrological years (Oct. 2018-Sep. 2019, Oct. 2019-Sep. 2020 and Oct. 2023-Sep. 2024; Text S2; Table S2 and S3), **(b)** spatial distribution of the average annual precipitation for the same hydrological years as a function of elevation (Text S2), **(c)** hydrographic map of Flores Island showing the main streams and location of the five udometric stations.

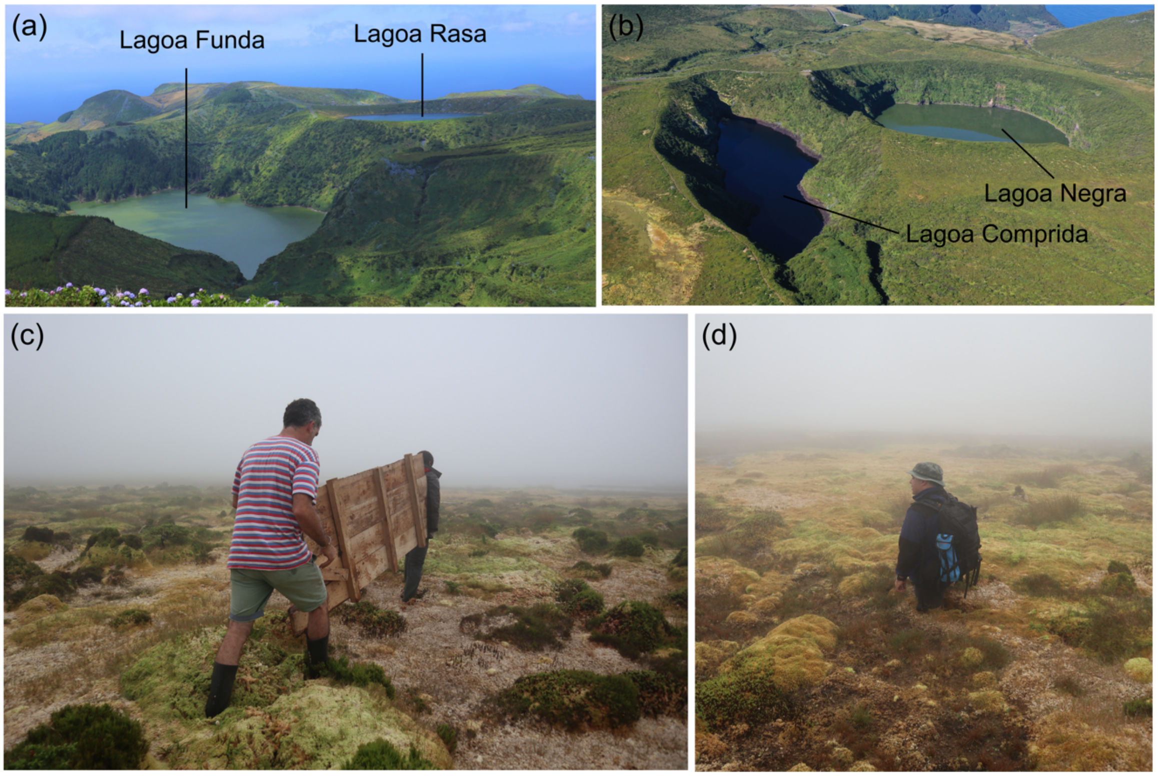

Figure S2. Field photographs showing the two main types of water reservoirs at the surface: **(a)-(b)** volcanic craters (maars and tuff rings) currently occupied by lakes, **(c)-(d)** bog/peatlands in the northern part of Flores uplands.

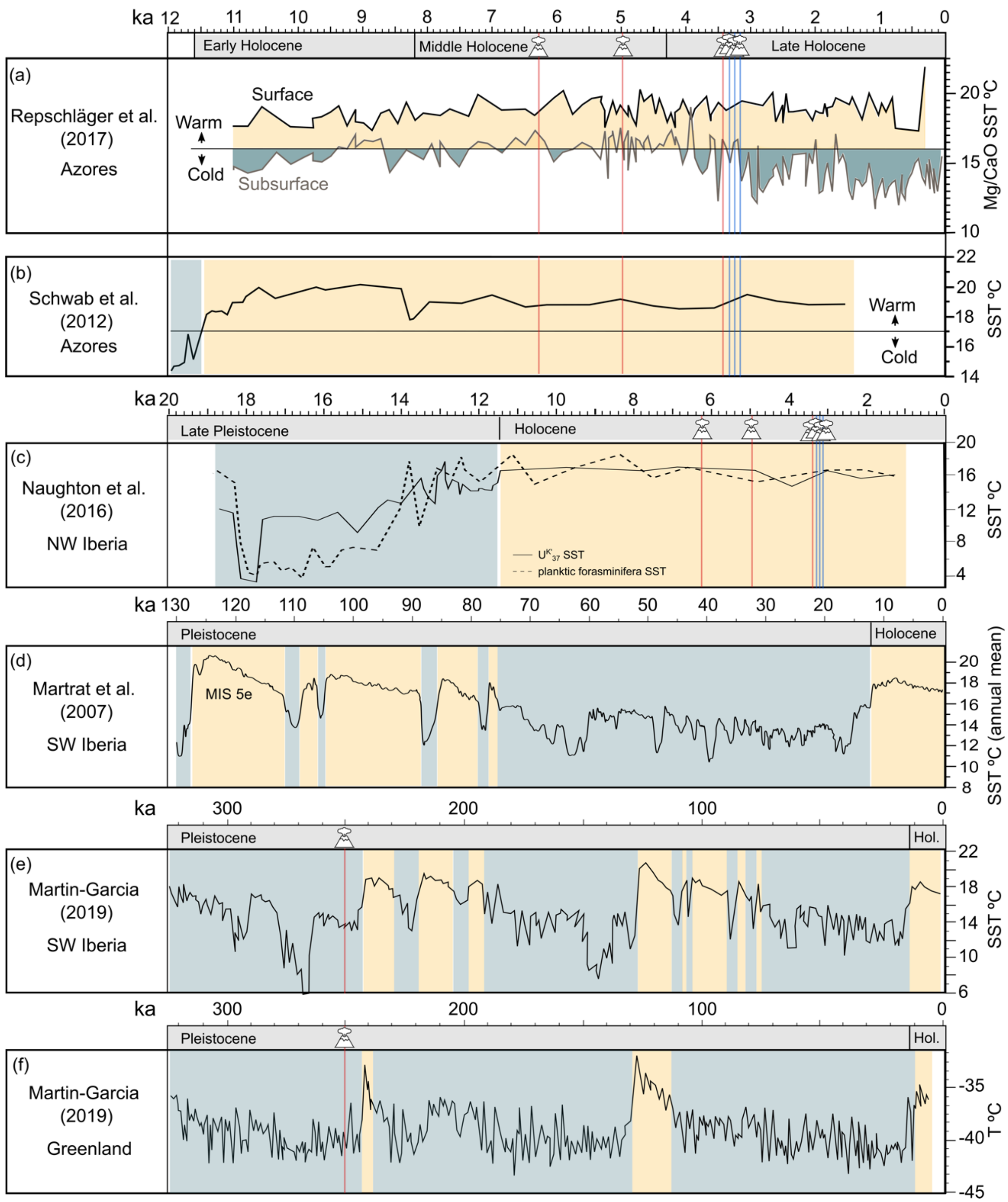

Figure S3. Paleotemperature reconstructions for the North Atlantic over different timescales. **(a)** and **(b)** show Sea Surface Temperature (SST) reconstructions for the Holocene in the Azores region (Repschläger et al., 2017; Schwab et al., 2012); **(c)**, **(d)** and **(e)** show SST variations along the Iberian Margin over the last 20ka, 130ka and 320kam respectively (Naughton et al., 2016; Martrat et al., 2007; Martin-Garcia, 2019); and **(f)** shows Greenland's variations in temperature over the last 320ka (Martin-Garcia, 2019). Evaluation of the different curves show that the Holocene has been a warm period with weak climatic oscillations when compared with the Mid- and Late-Pleistocene, which was in general colder and characterized by greater amplitude temperature variations. Red and blue lines mark the timing of Flores' Holocene magmatic and phreatomagmatic eruptions, respectively.

Source (eruption)	Eruptive Style	Age	Source
Comprida Volcanic System (CVS)	Hawaiian/Strombolian, phreatomagmatic	3183 (-43/+50) cal yr BP	Andrade et al. (2023)
Funda Volcanic System (FVS3)	phreatomagmatic	3254 (-47/+16) cal yr BP	Andrade et al. (2022)
Funda Volcanic System (FVS2)	Violent Strombolian, phreatomagmatic (?)	3333 (-10/+42) cal yr BP	Andrade et al. (2022)
Funda Volcanic System (FVS1)	Hawaiian/Strombolian	3428 (+38) cal yr BP	Andrade et al. (2022)
Unknown (LB1-T2)	Strombolian	4990 cal (-773/+685) yr BP	Andrade et al. (2021)
Unknown (LB1-T1)	Strombolian	6280 cal (-578/+626) yr BP	Andrade et al. (2021)
Lagoa da Lomba	phreatomagmatic	> 20 ka	Andrade et al. (2021)
Caldeira	phreatomagmatic	Unknown	-
Caldeirinha	phreatomagmatic	Unknown	-
Picada	Hawaiian/Strombolian	< 314 ka	Hildenbrand et al. (2018)
Rosmaninho	Hawaiian/Strombolian	230 ± 120 to 270 ± 110 ka	Azevedo & Portugal Ferreira (2006)
Cova da Pedra	Strombolian	< 314 ka	Hildenbrand et al. (2018)
Monte das Cruzes	Hawaiian/Strombolian	< 314 ka	Hildenbrand et al. (2018)
Lomba da Vaca	Strombolian/phreatomagmatic	< 314 ka	Hildenbrand et al. (2018)
Marcela	Strombolian	< 314 ka	Hildenbrand et al. (2018)
Pico do Touro	Strombolian	< 314 ka	Hildenbrand et al. (2018)
Cabeço do Silvado	Strombolian	< 314 ka	Hildenbrand et al. (2018)

Table S1. Summary of the known Flores' Holocene and Mid to Late Pleistocene volcanic eruptions.

Date	Ponta Delgada (47 m asl)	Fazenda de Sta Cruz (107 m asl)	Terreiros (394 m asl)	Pico da Casinha (517 m asl)	Lagoa da Caldeira Rasa (545 m asl)
01.10.18	68,495	136,913	159,299	223,701	285,033
01.11.18	109,611	207,401	126,799	860,774	811,824
01.12.18	241,696	288,901	194,502	624,964	748,607
01.01.19	195,102	197,19	158,3	283,441	269,584
01.02.19	270,21	398,384	264,8	683,611	517,609
01.03.19	118,812	207,497	69	320,93	238,239

01.04.19	75,196	142,898	95,9	209,425	313,021
01.05.19	133,099	172,604	124,3	313,891	40,49
01.06.19	61,006	68,199	89,998	107,988	0
01.07.19	39,8	77,081	34,5	104,714	0
01.08.19	135,801	115,6	103,901	218,97	101,6
01.09.19	69,899	63,197	81,801	134,497	90,893
01.10.19	104,301	176,52	175,805	627,739	31,203
01.11.19	45,4	95,504	56,2	161,678	113,529
01.12.19	128,691	306,578	136,703	717,13	244,846
01.01.20	131,893	253,602	129,897	390,124	220,143
01.02.20	31,493	91,717	41,999	159,095	104,921
01.03.20	61,896	122,903	60,6	170,204	127,213
01.04.20	148,082	268,791	196,997	307,395	338,965
01.05.20	67,097	117,9	47,403	212,532	197,673
01.06.20	18	37,403	37,791	56,303	51,797
01.07.20	18,7	55,108	48,704	80,401	83,998
01.08.20	164,6	245,871	173,807	275,381	180,479
01.09.20	81,793	159,492	160,508	289,189	197,057
01.10.23	143,189	288,181	193,904	413,878	318,986
01.11.23	187,4	343,242	248,081	419,797	308,108
01.12.23	120,103	216,001	165,827	336,286	199,002
01.01.24	171,599	228,991	257,078	325,48	311,085
01.02.24	33,8	0	55,61	184,282	129,087
01.03.24	89,294	163,695	90,796	225,086	459,014
01.04.24	97,9	151,595	180,006	203,389	202,086
01.05.24	139,499	192,81	160,096	329,608	237,086
01.06.24	26,3	27,098	53,798	82,794	81,196
01.07.24	37,8	20,494	62,002	72,087	80,794
01.08.24	53,297	123,14	116,302	145,297	74,005
01.09.24	107,395	109,599	102,778	169,006	125,31

Table S2. Monthly accumulated precipitation values (in mm) at five different udometric stations on Flores Island for the hydrological years of Oct 2018-Sep 2019, Oct 2019-Sep 2020 and Oct 2023-Sep 2024 (Rede Hidrometereológica dos Açores).

Station	Elevation (m)	Precipitation (mm/yr)
Ponta Delgada	47	1243
Fazenda de Santa Cruz	107	1957
Terreiros	394	1485
Pico da Casinha	517	3480
Lagoa da Caldeira Rasa	545	2611

Table S3. Average of the annual accumulated precipitation values at five different udometric stations on Flores Island for the hydrological years of Oct 2018-Sep 2019, Oct 2019-Sep 2020 and Oct 2023-Sep 2024 (Rede Hidrometereológica dos Açores).

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Table S4. Azores paleoprecipitation model results.