Supplementary Information

Seawater-magma interactions sustained the high column during the 2021 phreatomagmatic eruption of Fukutoku-Oka-no-Ba

Maeno, F.[1*], Kaneko, T.[1], Ichihara, M.[1], Suzuki, Y.J.[1], Yasuda, A.[1], Nishida, K.[1], and Ohminato, T.[1]

1: Earthquake Research Institute, the University of Tokyo
1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
* Corresponding author: fmaeno@eri.u-tokyo.ac.jp

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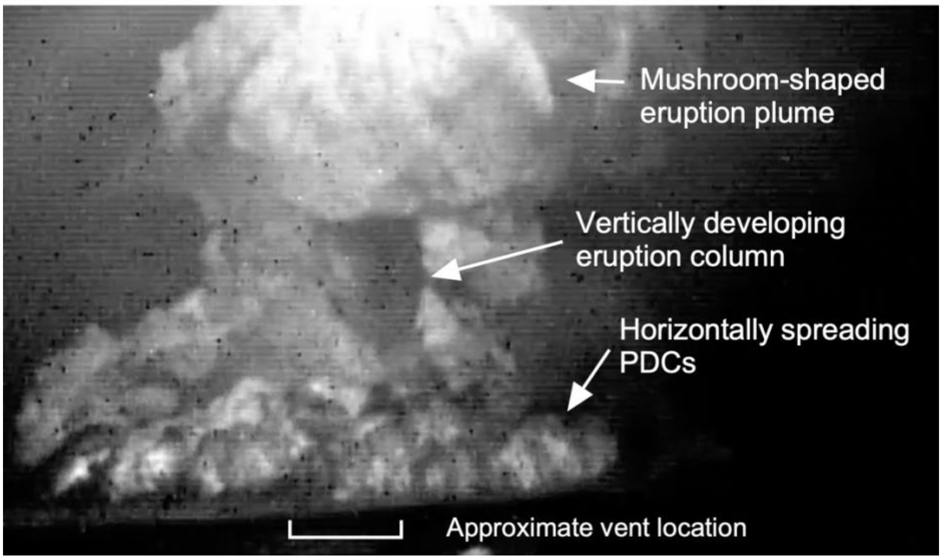
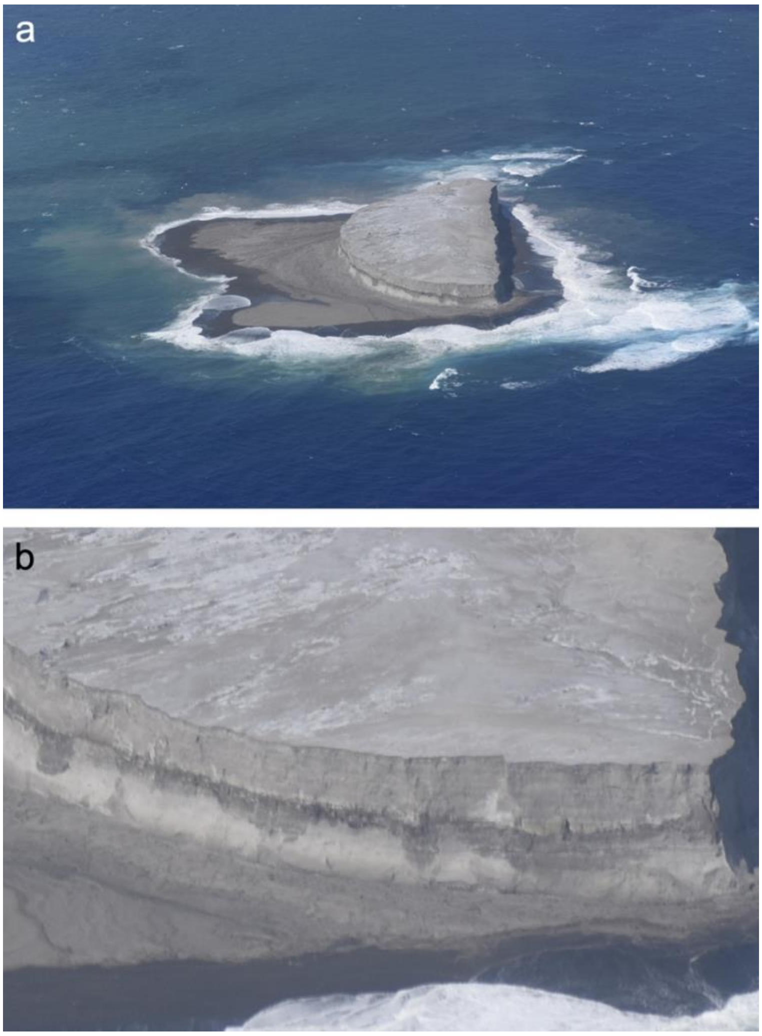
Phase 1: Relatively high-discharge period



Supplementary Figure 1 | Infrared photo of the 2021 FOB eruption. The FOB eruption generated mushroom-shaped convective plumes and laterally spreading pyroclastic density currents during a relatively high-discharge period of Phase 1b. The image was taken at 15:00-15:30 JST on 13 August 2021, from 6,000 m above sea level and approximately 90 km north of the volcano by the Japan Coast Guard[1].

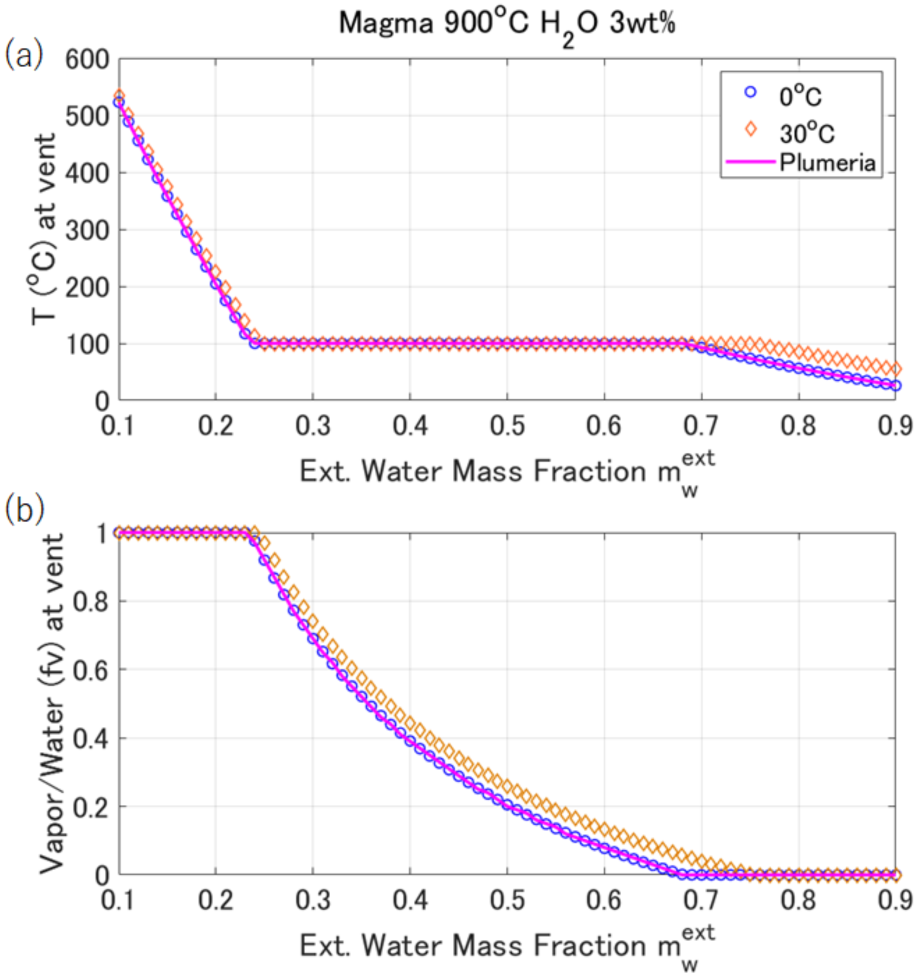


Supplementary Figure 2 | Photos of a new islet of FOB. a, The western island produced by the 2021 FOB eruption, taken on 12 October by the Japan Coast Guard[1]. **b**, Magnification of the island. The cone components are massive, poorly sorted, loose pyroclastic units. It appears to consist of two major layers.

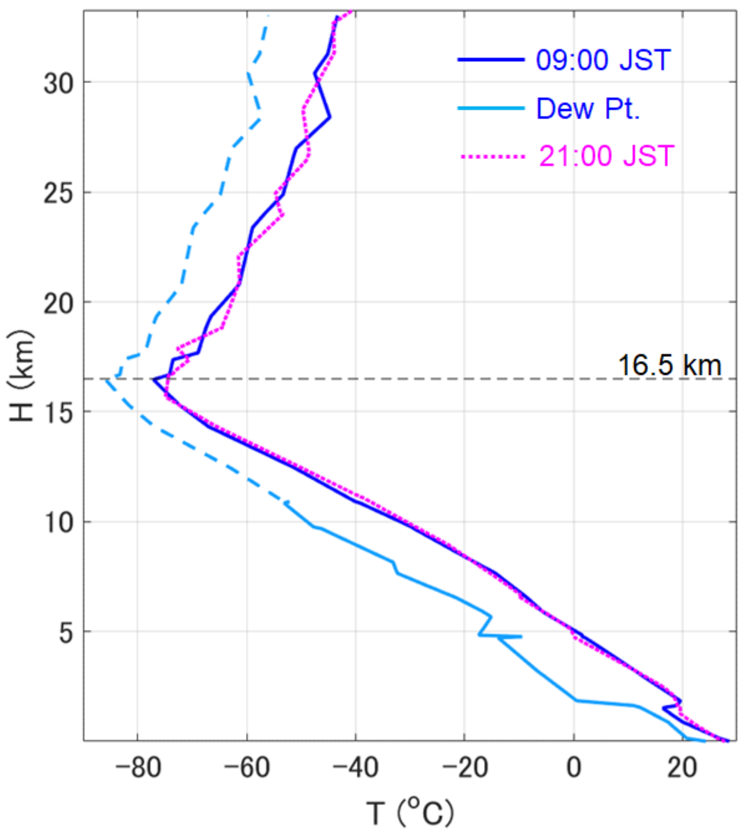
Supplementary Table 1 | Physical conditions and virtual input parameters to Plumeria

Physical parameters					Virtual parameters		
m_w^{ext}	f_v	T (°C)	m_w	x	$\hat{T}_m$ (°C)	$\hat{n}_0$	$\hat{m}_w^{ext}$
0.20	1.0000	225.2	0.9	0.1289	225	0.9000	0
0.30	0.7420	100		0.1473	400	0.8503	0.3321
0.32	0.6689	100		0.1516	400	0.8393	0.3776
0.36	0.5451	100		0.1611	400	0.8166	0.4547
0.40	0.4442	100		0.1718	400	0.7927	0.5175
0.42	0.4005	100		0.1777	400	0.7803	0.5447
0.20	1.0000	225.2	0.95	0.0644	225	0.9500	0
0.30	0.7420	100		0.0736	400	0.9236	0.3455
0.40	0.4442	100		0.0859	400	0.8910	0.5412
0.42	0.4005	100		0.0889	400	0.8837	0.5699
0.44	0.3605	100		0.0920	400	0.8762	0.5962
0.20	1.0000	225.2	0.8	0.2577	225	0.8000	0
0.30	0.7420	100		0.2946	400	0.7121	0.3054
0.36	0.5451	100		0.3222	400	0.6585	0.4144
0.38	0.4922	100		0.3326	400	0.6405	0.4436
0.40	0.4442	100		0.3436	400	0.6225	0.4702
0.20	1.0000	225.2	0.7	0.3866	225	0.7000	0
0.30	0.7420	100		0.4418	400	0.5841	0.2786
0.36	0.5451	100		0.4832	400	0.5207	0.374
0.38	0.4922	100		0.4988	400	0.5003	0.3996
0.20	1.0000	225.2	0.6	0.5155	225	0.6000	0
0.30	0.7420	100		0.5891	400	0.4653	0.2519
0.36	0.5451	100		0.6443	400	0.3997	0.3337
0.20	1.0000	225.2	0.5	0.6443	225	0.5000	0
0.30	0.7420	100		0.7364	400	0.3547	0.2252

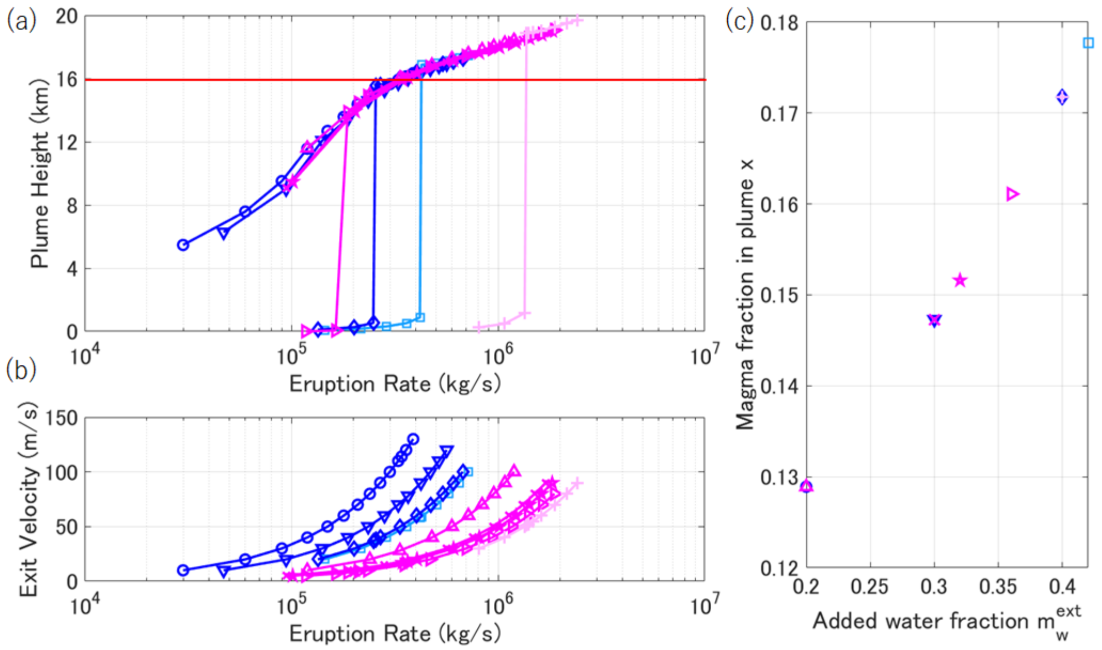
m_w^{ext}: mass fraction of external water added to the initial mixture; f_v: vapour phase mass fraction of H_2O; T: temperature of initial mixture; m_w: water mass fraction of initial mixture; x: magma mass fraction in in plume; $\hat{T}_m$: virtual magma temperature; $\hat{n}_0$: virtual mass fraction of H_2O in whole magma; $\hat{m}_w^{ext}$: virtual mass fraction of external water added to the initial mixture.



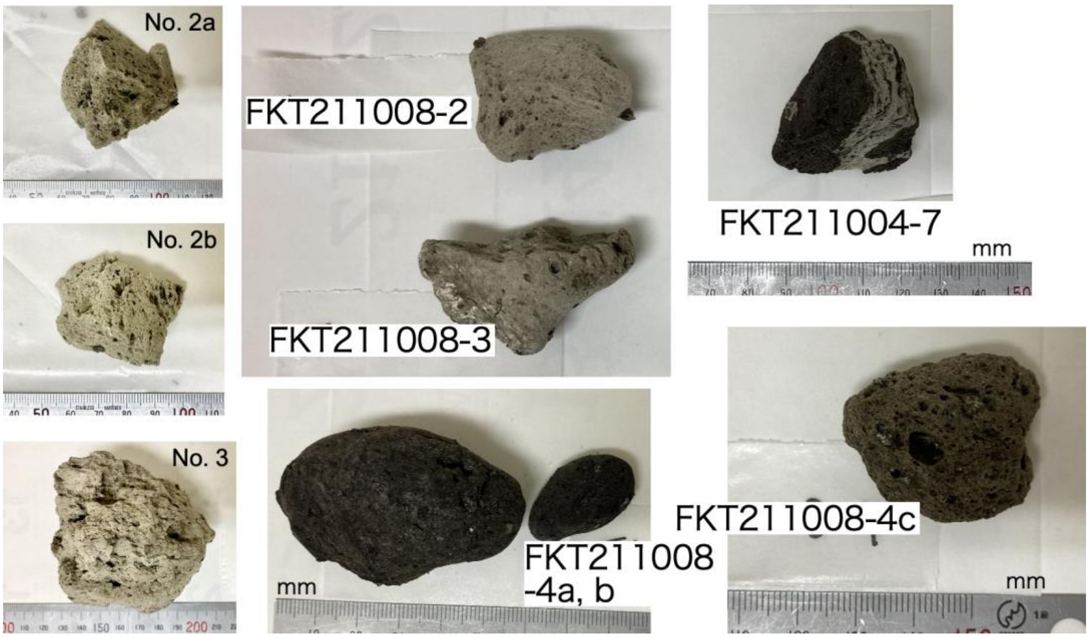
Supplementary Figure 3 | The relation between the external mass fraction added to magma and the representative physical parameters at the vent. (a) The relation between the external mass fraction added to magma (m_w^{ext}) and the temperature (T). (b) The relation between the external mass fraction added to magma (m_w^{ext}) and the vapour mass fraction of total water in the plume (f_v) at the vent. The blue circles are for the external water temperature of 0°C, consistent with the output values of Plumeria[2, 3] (the magenta line). The orange diamonds represent the external water temperature of 30°C and are used in this study. See Supplementary Note 1 for details.



Supplementary Figure 4 | Atmospheric structure at the 2021 FOB eruption. The atmospheric temperature (blue line) and the dew point (light blue line) used in the plume calculation. The data were taken by the radiosonde at 09:00 JST on 13 August at the Japan Meteorology Agency, Chichijima Observatory. The dew points above 11.03 km (dashed line) were not from the data but were estimated by the Tetens equation[4], assuming a humidity of 20%. The temperature measured at 21:00 JST on 13 August (magenta line) is displayed for comparison. See Supplementary Note 1 for the details.



Supplementary Figure 5 | The relation between the total magma discharge rate and the representative physical parameters obtained by Plumeria. (a) The relation between the total magma discharge rate M_e and the plume height H_p, assuming a water mass fraction in plume (m_w) of 0.9. The given exit velocities are shown in (b). The initial magma temperature is fixed at 900 and the added water fraction (m_w^{ext}) is varied as in the horizontal axis of (c). The cases for exit diameters of 100 m and 200 m are shown by blue and magenta colors, respectively. The light-colored cases did not yield 16-km high plumes. The marker types are common among all of (a)-(c), indicating the values of m_w^{ext}. The plume height of 16 km is achieved with M_e of $3 - 4 \times 10^5$ kg/s. See Supplementary Note 1 for the details.



Supplementary Figure 6 | Pumice samples from the 2021 FOB eruption used for whole-rock major element analyses. Although textural and colour variations exist, whole-rock major element compositions are not varied (Supplementary Data 1). Most of the pumice clasts (more than 90%) are white-grey, as shown in No. 2a, 2b, and 3 and FKT211008-2 and 3. Black-coloured portions (FKT211004-7) and individual black pumice (FKT211008-4a, b, and c) are minorly present. The black colour has been interpreted as reflecting higher groundmass crystallinity due to nano-scale crystallization[5].

Supplementary Note 1 | Plume modelling

1. Introduction

The eruption of Fukutoku-Oka-no-ba (FOB) formed 16-km-high white plumes. We estimate the magma discharge rate required to create the 16-km-high plume. The essential feature of this eruption was the existence of a large amount of pumice that should have provided thermal energy to the plume but did not rise in the plume. We apply a user-friendly plume model, Plumeria[3] to calculate the relation between the eruption parameters and the plume height. To incorporate the thermal energy from pumice, we adjusted the input parameters of the software to represent the water-rich high-enthalpy mixture at the vent. Below we use 'magma' to describe the nonvolatile part of magma and 'whole magma' to represent magma, including magmatic H_2O.

2. Method

2.1 Adjusting the input parameters

The Plumeria model[2] assumes a homogeneous and equilibrium flow of mixtures consisting of magma, water (vapour, liquid, and ice), and entrained air. The software determines the mixture property at the vent (temperature T, H_2O mass fraction m_w, and vapour phase mass fraction of H_2O f_v), calculating the enthalpy balance with the input parameters (whole magma temperature T_m, mass fraction of magmatic H_2O in whole magma n_0, and mass fraction of external water added to the initial mixture m_w^{ext}). The external water temperature is fixed at 0 °C. Then, using the mixture property and given vent diameter $2r_0$ and exit velocity u_0, the total mass discharge rate M is determined. All the input material (magma and external water) is assumed to be ejected together so that the magma discharge rate is $(1 - m_w)M$.

To incorporate the thermal energy from the floating pumice, we independently calculate the enthalpy balance to obtain T and f_v, assuming T_m of 900 °C and n_0 of 0.03. The amount of external water is varied in the range of $0.1 < m_w^{ext} < 0.9$. We have confirmed that our calculation yields equivalent values of T and f_v to Plumeria if the external water temperature is set at 0 °C (**Supplementary Fig. 3**). Then, the external water temperature is assumed to be 30 °C, which is realistic around the FOB in August. The obtained T and f_v are also shown in **Supplementary Fig. 3** as functions of m_w^{ext}.

The mass fraction of H_2O with the above parameters is $m_w^0 = m_w^{ext} + (1 - m_w^{ext})n_0$. Then, we assume a new H_2O mass fraction in the plume as m_w $(> m_w^0)$. Namely, only a fraction $x = (1 - m_w)/(1 - m_w^0)$ of magma goes into the plume. We calculate virtual magma temperature $\hat{T}_m$, mass fraction of H_2O in whole magma $\hat{n}_0$, and external water at 0 °C added to the initial mixture $\hat{m}_w^{ext}$ with which the Plumeria software has the specific mixture property at the vent (T, f_v, m_w). Note that the values of (T, f_v, m_w) are essential for plume dynamics, and the assumed values (T_m, n_0, m_w^{ext}) to obtain them are physical, while the virtual values $(\hat{T}_m, \hat{n}_0, \hat{m}_w^{ext})$ are just technical for applying the Plumeria software to the current problem. When $f_v = 1$, $(\hat{T}_m, \hat{n}_0, \hat{m}_w^{ext}) = (T, m_w, 0)$. When $1 > f_v > 0$, T=100 °C. Then, we assume $\hat{T}_m$=400 °C and calculate the following equations:

$$(1 - \hat{m}_w^{ext})(1 - \hat{n}_0)h_m(\hat{T}_m) + (1 - \hat{m}_w^{ext})\hat{n}_0 h_v(\hat{T}_m) + \hat{m}_w^{ext} h_l(\hat{T}_w) = (1 - m_w)h_m(T) + m_w f_v h_v(T) + m_w(1 - f_v)h_l(T), \quad (S1)$$

$$\hat{m}_w^{ext} + (1 - \hat{m}_w^{ext})\hat{n}_0 = m_w, \quad (S2)$$

where h_m, h_v, and h_l are the enthalpy of a unit mass of magma, water vapour, and liquid water, respectively, and $\hat{T}_w$ is the external water temperature in Plumeria, which is 0 °C.

For the total mass discharge rate, M, evaluated by Plumeria, $(1 - m_w)M$ represents the magma mass discharge rate in the plume. Then, the erupted magma discharge rate M_e, including the floating pumice, is

$$M_e = (1 - m_w)M/x = (1 - m_w^0)M. \quad (S3)$$

2. 2 Atmospheric structure

The atmospheric data are measured by radiosonde, twice a day (at 09:00 and 21:00 JST) at Chichijima, 330 km to the north of FOB. We downloaded them from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html). The Plumeria uses the pressure, temperature, and dew point as functions of height. In the upper layers where dew point data were missing, we assumed a humidity of 20% and calculated the dew point using the following Tetens equation[4] extended below 0 °C:

$$P_v = 610.78\exp\left(\frac{21.875T_d}{T_d + 265.5}\right), \quad (S4)$$

where P_v is the vapour pressure in Pa and T_d is the dew temperature in °C. **Supplementary Fig. 4** shows the atmospheric structure used with Plumeria. It shows a thin tropopause at 16.5 km high.

3. Results

We run the Plumeria for the input properties listed in **Supplementary Table 1**. Using the results of the Plumeria calculation for the mass discharge rate M and plume height H_p, we obtain the relation between the total eruption rate M_e in Eq. (S3) and H_p.

Supplementary Fig. 5 shows the relation for the water mass fraction in the plume of 0.9, assuming exit diameters of 100 m (blue) and 200 m (magenta). The $M_e - H_p$ relations are nearly identical when the plume heights reach 16 km. Regardless of the added water fractions to magma (m_w^{ext}) or the diameters, 16-km high plumes are formed with M_e of $3 - 4 \times 10^5$ kg/s. The exit velocities that give these results are smaller than 100 m/s, which is reasonable. When too much water is added ($m_w^{ext} > 0.4$), the plume becomes too high or collapses.

In **Fig. 4** in the main text, we vary the water mass fraction in the plume from 0.5 to 0.95, fixing the exit diameter at 100 m. In the range of the parameters, we obtain 16-km high plumes with an eruption rate M_e of $3 - 6 \times 10^5$ kg/s.

The above results have constrained that the water-rich 16-km-high plume of the FOB is formed by an eruption rate of $3 - 6 \times 10^5$ kg/s. Assuming a nine-hour sustained plume, the erupted mass is estimated to be $1 - 2 \times 10^{10}$ kg. We regard these values as the lower limit, considering it accounts for only the magma that is thermally in equilibrium with the water at the vent.

Supplementary References

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