First timeseries record of a large-scale silicic shallow-sea phreatomagmatic eruption

Fukashi Maeno (✉ fmaeno@eri.u-tokyo.ac.jp)

The University of Tokyo

Takayuki Kaneko

The University of Tokyo

Mie Ichihara

The University of Tokyo

Yujiro Suzuki

JAMSTEC

Atsushi Yasuda

The University of Tokyo

Kiwamu Nishida

University of Tokyo <https://orcid.org/0000-0001-6778-8080>

Takao Ohminato

The University of Tokyo

Article

Keywords:

Posted Date: February 11th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1272855/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Communications Earth & Environment on November 1st, 2022. See the published version at <https://doi.org/10.1038/s43247-022-00594-4>.

Abstract

Phreatomagmatic eruptions are one of the most common styles of volcanic eruptions on Earth^{1–2}. Recent studies have highlighted the importance of the eruption depth and magma discharge rate on the eruptive behaviour of underwater volcanoes^{2–7}. Even though voluminous silicic eruptions in shallow-water environments are likely to be intense and hazardous, such eruptions mostly appear in geological records^{7–12} and the nature of this type of eruption is therefore poorly understood. Here, we show the first timeseries record of a large-scale silicic phreatomagmatic eruption that occurred at the Fukutoku-Oka-no-Ba volcano, Ogasawara, Japan, on 13 August 2021. The eruption started on the seafloor at a depth of < 70 m and breached the sea surface, resulting in a 16-km-high, steam-rich sustained eruption column. The total magma volume was $\sim 0.1 \text{ km}^3$, including the subaerial tuff cone and the 300-km² pumice raft, most of which can be explained by the effective accumulation of pyroclasts near the vent resulting from interactions between the eruption plume and the ambient water. This eruption provides a rare opportunity to investigate the process of a large-scale phreatomagmatic eruption in a shallow sea and contributes to our understanding of the nature, dynamics, and hazards of submarine volcanism.

Introduction

Phreatomagmatic eruptions, caused by the interaction of magma and external water, are one of the most hazardous types of volcanic eruptions on Earth^{1,2}. Such eruptions can significantly impact areas around volcanoes by generating high-energy pyroclastic density currents (PDCs), strong pressure waves and tephra-laden jets^{13–16}. The explosivity of phreatomagmatic eruptions increases when a certain amount of external water is incorporated and a higher energy-exchange efficiency from magmatic heat to mechanical energy is achieved^{17–22}. Therefore, the mixing conditions and the ratio of external water to magma are important to understand the explosivity and eruption style of subaqueous eruptions. The explosivity and eruption style are also related to the water depth of the eruption and the magma discharge rate^{2–7}. In general, shallow-water environments result in more explosive eruptions than deep-water or dry conditions. Even small-volume eruptions with low magma discharge rates can be explosive, as often observed in Surtseyan-type eruptions^{13–16}. For large-volume eruptions, the explosivity and eruption style may change dramatically if the eruptions occur in a shallow-water environment where external water is efficiently involved^{7–12}; conversely, if the eruptions occur in a deep-water environment, the explosivity is suppressed by the high pressure^{4–6}. However, direct observational data of such large-scale phreatomagmatic eruptions are limited. Only the geological record can provide information concerning the possible surface phenomena of these eruptions^{7–12}, although recent remote-sensing tools, including satellites and the global infrasound monitoring network, have captured some smaller cases^{23–27}. The explosive submarine eruption that occurred in Tonga on 15 January 2022 may be one of the examples of large-scale phreatomagmatic eruptions in the shallow sea; however, the physical and chemical processes and related parameters of the eruption are under debate. Accordingly, how such eruptions proceed and their impacts in real space and time are poorly constrained. The 2021 Fukutoku-

Oka-no-Ba (FOB) eruption may be the first to reveal the processes involved with a large-scale eruption of this type.

The FOB volcano is one of the active volcanoes in the Izu-Ogasawara arc (Fig. 1a). On 13–15 August 2021, a large explosive eruption occurred at this volcano (Fig. 1b). Prior to the eruption, the depth of the summit of the volcano was 40–50 m b.s.l. (below sea level) and a slightly deeper fissure (~ 70 m b.s.l.), where the 2021 eruption began, existed on its northern side (Fig. 1c). We analysed the process of this eruption using satellite imagery, aerial photos, infrasound, plume modelling, and geochemistry. The eruption began with a sustained plume, which breached the overlying sea water and reached a height of 16 km a.s.l. (above sea level) in hours²⁸. As a result, the eruption reclaimed the shallow sea and produced a tuff cone (Fig. 1c). The eruption also produced a 300-km² pumice raft (Fig. 1d), which was dispersed by ocean currents more than 1,000 km west of the volcano. The pumice raft reached the coastal areas of the Pacific Ocean along the Japanese archipelago and caused damage to coastal infrastructure. A chemical analysis of the pumice clasts indicates that the eruption consisted of trachytic-trachydacitic magma with glass compositions reaching 68 wt.% SiO₂. Therefore, the eruption was a large-scale silicic explosive phreatomagmatic eruption, the first ever recorded in modern history.

Results

Timeseries data

Himawari-8 satellite and infrasound remote observations suggest that the FOB eruption began at 05:55 JST on 13 August 2021 (Fig. 2a, b). The eruption occurred in four phases. Phase 1 consisted of a continuous plume phase that began at 05:55 JST on 13 August and lasted for ~ 14 h with fluctuations until ~ 20:00 JST on 13 August. The period 12:00–19:00 JST was more intense with sustained plumes. Phase 2 was a 14-hour pulsating phase, characterised by frequent strong infrasound signals. The period 05:30–06:30 JST on 14 August was more intense with a sustained plume. Phase 3 consisted of 24 h of intermittent weak explosions and sparse strong explosions until 09:00 on 15 August. In Phase 4, the activity decayed. Phase 1 was the most powerful and produced the major eruptive products. It generated a continuous, white-coloured vigorous plume directed to the west. At approximately 08:00 JST on 13 August the pumice raft was confirmed to be spreading circularly from the source (Fig. 2c). The development of the pumice raft was observed for the first 4 h until the source area was covered by the eruption plume in the satellite view. After the cessation of Phases 1–3, the pumice raft drifted westward and was carried by ocean currents.

Plume characteristics of Phase 1

In the periods of 12:00–19:00 JST on 13 August and from 05:30–06:30 JST on 14 August, sustained eruption columns developed (blue bars in Fig. 2b). The most vigorously erupted columns formed in the 1 h following 14:00 JST and in the 20 min from 12:45 JST on 13 August. These eruption columns formed thin laterally spreading clouds with a 15–20-km radius at 16 km a.s.l. (Fig. 2a), which corresponds to the

tropopause height (SI). The eruption column was entirely white-coloured, indicating a steam-rich eruption. The thin laterally spreading clouds (Fig. 1b) were similar to an 'anvil cloud' or 'incus', which is often observed when the upper portion of a strong cumulonimbus spreads out in the shape of an anvil along the tropopause²⁹. These clouds differ from those observed in (Sub-)Plinian eruptions in which more vigorous, thicker pyroclast-laden 'umbrella clouds' with a grey/brown colour develop³⁰. The FOB eruption column may have contained fine-grained ash; however, its shape, colour, and spreading behaviour along the tropopause did not provide evidence for a large amount of pyroclasts being suspended in the column. The area covered by the entire eruption cloud reached $\sim 10^5 \text{ km}^2$ at approximately 15:00 JST on 13 August. However, there is no report or evidence of ashfall on any ships or boats in the downwind area or on the neighbouring Minami Ito island, 6 km south-southwest of the source.

Thermal anomaly

No thermal anomaly was detected in the near-source region, even when the root of the eruption column was clearly observable from Himawari-8. An aerial observation by the Japan Coast Guard (JCG) with an infrared camera at 15:00–15:30 JST on 13 August captured hot pyroclastic material being ballistically ejected; however, the thermal anomaly was likely too small to be detected by satellites. A reasonable interpretation is that most of the heat issued from the rising magma was consumed in the rapid vaporisation of seawater before it could be detected by thermal monitoring.

Tuff cone and pumice raft formation

The eruption formed a new tuff cone with an $\sim 1\text{-km}$ -diameter crater around the vent; however, this cone was rapidly eroded by waves and separated into western and eastern islands. The cone can be seen in a satellite image taken on 14 August. The height of the cone was $\sim 15 \text{ m}$ at maximum, and the cone components were massive, poorly sorted loose pyroclastic units, suggesting multiple depositional processes. These islands disappeared by early 2022. From 15:00–15:30 JST, 13 August, during the most intense phase, the JCG airplane repeatedly observed laterally spreading PDCs at the source. Therefore, a major component of the new islands was likely formed via near-vent depositional processes such as partial collapses of the eruption column. The volume of the tuff cone is estimated to have been $0.04\text{--}0.07 \text{ km}^3$.

A brown-coloured pumice raft began to form at 08:00 JST on 13 August and spread against the direction of the wind and ocean currents. The edge of the pumice raft reached $\sim 4 \text{ km}$ southeast from the source by 12:00 JST on 13 August (Fig. 2c), suggesting a spreading speed of $\sim 1 \text{ km/h}$ upstream before being drifted by ocean currents. The area of the pumice raft reached $\sim 300 \text{ km}^2$ at 01:00 JST on 15 August. Most of the pumice raft appeared to originate from the vent location. The growth of the pumice raft cannot be explained by the direct deposition of fallout from the eruption plume because the upwind area was never covered by the plume as a result of the strong easterly wind during the observation period. In the downwind direction, the formation of the pumice raft was not observed, indicating that the eruption plume did not contain a large amount of pumice clasts dispersed in the distal direction. Therefore, most of the pumice raft is thought to have been directly generated from the vent during Phase 1. The volume of

the pumice raft was estimated to be $0.1\text{--}0.3\text{ km}^3$. Therefore, the sum of the volumes of the tuff cone and pumice raft is $0.1\text{--}0.4\text{ km}^3$ ($0.04\text{--}0.1\text{ km}^3$ dense rock equivalent, DRE).

Modelling a steam-rich eruption plume

The magma discharge rate required to form the 16-km-high eruption column in Phase 1 was estimated using a one-dimensional eruption plume model^{31,32} that includes the effect of the phase change of the external water. The effect of an amount of pumice that should have provided thermal energy to the plume but did not rise in the plume was also considered in this study (SI). The results indicate that a magma discharge rate of $3\text{--}6 \times 10^5\text{ kg/s}$ is sufficient to explain the observed plume height if only a fraction ($0.3\text{--}3 \times 10^5\text{ kg/s}$) goes into the plume (Extended data Fig. 6). Assuming a nine-hour sustained plume (blue bars in Fig. 2b), the erupted mass is estimated to be $1\text{--}2 \times 10^{10}\text{ kg}$, corresponding to $0.004\text{--}0.008\text{ km}^3$ in DRE. Because some fraction of the eruptive material is deposited in the proximal area, the contribution of the magma to the distant fallout tephra is significantly reduced compared with these values.

SO₂ emissions

The SO₂ emissions were observed by the TROPOMI instrument installed on the Sentinel-5 Precursor satellite. The mass of SO₂ emitted during the 15 h of activity was $2.1 \times 10^7\text{ kg}$. We also analysed the SO₂ concentrations of the silicic matrix glass of the pumice and the melt inclusions (MIs) of plagioclase, which is a major phenocryst in the products. The degassed SO₂ was estimated to be 73.3 ppm from the difference between the SO₂ concentrations of the matrix glass and the MIs. Using this SO₂ concentration and the observed amount of SO₂, the mass of the erupted magma is estimated to be $2.9 \times 10^{11}\text{ kg}$, corresponding to 0.11 km^3 DRE. Therefore, the total erupted volume estimated from the SO₂ balance can be mostly explained by the sum of the geology-based and the model-based tephra volume estimates without assuming any other source.

Discussion And Summary

The eruptive volume of the FOB eruption has large uncertainties; however, a comparison between the volumes estimated from the geology and from the SO₂ emissions indicates that it likely reached $\sim 0.1\text{ km}^3$ DRE. This eruptive scale, the high eruption plume, and the voluminous pumice raft caused by continuous magma discharge differ from the features of well-observed phreatomagmatic explosions, such as Surtseyan eruptions, which are characterised by a series of discrete events with a relatively low magma discharge rate^{16,19}. Plumes from Surtseyan eruptions rarely rise to high altitudes (generally less than 10 km) because their thermal flux is generally low^{2,19}. Instead, this type corresponds to Phases 2 and 3 of the FOB eruption. The magma discharge rate of Phase 1 is similar to those of (Sub-)Plinian eruptions, which are characterised by sustained explosive eruptions, discharging hot pyroclast and gas mixtures with a tall eruption column and resulting in the widespread dispersion of large amounts of pyroclasts^{33–35}. However, the style of the FOB eruption also differs from these types because most of the

pyroclasts accumulated near the vent and were consumed to form the tuff cone and pumice raft. Infrasound also does not indicate features of sustained explosive eruptions.

The features of Phase 1 of the FOB eruption may be explained by the effective decoupling of coarse pyroclasts from the eruption plume caused by the interaction between the eruption plume and the seawater. In this process, the gas–pyroclast mixture above the submarine vent (50–100 m b.s.l.) penetrates the seawater and atmosphere. First, the mixture ingests the ambient seawater and develops an eruption plume, possibly in a manner similar to deep submarine eruptions^{4–6}. Then, the plume reaches the sea surface that acts as the boundary between two ambientes with different densities, where it may split into two parts (Fig. 3): (1) a breaching part into the atmosphere caused by the upward migration of the mixture and heating, where the seawater flashes to steam and is rapidly accelerated, and (2) a remaining part in the water that is decelerated by the increasing density resulting from mixing with liquid water. Underwater, lighter parts may form density currents composed of a slurry of hot water and pyroclasts along the sea surface, and denser parts may form submarine density currents along the seafloor^{36, 37}. After ejection of the material into the atmosphere, there may be a further decoupling of the large poorly fragmented clasts and the wet, cold gas–pyroclast mixture, which may result in partial column collapse and the generation of PDCs. The remaining buoyant parts of the plume rise and form a steam-rich convective plume that carries highly fragmented fine material. A large amount of floating pumice might result from sedimentation from subaerial PDCs and/or directly from the slurry gushing from the submarine vent (Fig. 3). The circular spread of the pumice raft from the source indicates that the slurry discharge was sufficient to drive an upstream current. The volume of the pumice raft is estimated to have reached 50–90% of the total erupted volume. This is similar to a silicic deep submarine eruption in which ~ 70% of the eruptive products were dispersed as a pumice raft⁴.

Phase 1 was followed by the Phase 2 and 3 Surtseyan eruptions, reflecting both the upward migration of the vent position and the decrease in the magma discharge rate (Fig. 3). The transition of the eruption style was likely significantly affected by the eruption depth and magma discharge rate. Phase 1 demonstrated an eruption style that appears when certain conditions of eruptions (depth of < 100 m, magma discharge rate of < 10^7 kg/s) are met. While a buoyant steam-rich plume was generated, tephra dispersal processes might have been significantly affected via the interaction of magma and seawater in the shallow-water environment. It is difficult to categorise this eruption into previously defined eruption styles such as ‘Surtseyan’ or ‘Plinian’^{33–34}. ‘Phreatoplinian’ may potentially describe this type of eruption; however, this eruption was defined based on its deposit characteristics, such as its extensive dispersion of voluminous fine-grained ash, because of its intense fragmentation and perhaps higher magma discharge rate^{8–11}. Conversely, we have no evidence of a large amount of fine-grained ash being generated in the FOB eruption and the proposed near-vent processes may be different. The large-scale silicic phreatomagmatic eruption with a steam-rich sustained eruption column observed in the FOB can be called the ‘Ultra-Surtseyan’ eruption.

The FOB eruption provides an important opportunity to explore the processes of large-scale silicic submarine eruptions in shallow-water environments. The surface phenomena, eruptive products, and emplacement processes of such eruptions may significantly differ from those of deep submarine eruptions and dry explosive eruptions. To examine these problems, we need to comprehensively survey submarine deposits. Such information is essential to constrain the eruption and enhance our knowledge of submarine volcanism.

Declarations

Acknowledgements

This research was supported by Grant-in-Aid for scientific research (No. 20KK0075) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and by the Earthquake and Volcano Hazards Observation and Research Program of MEXT (ERI03 and ERI17). The authors thank JMA for the seismometer data and rock samples, the JMA Meteorological Observatory at Chichijima for the atmospheric data, and JCG for the photos of the eruption used in this study.

Author contributions

TK and FM analysed the satellite and aerial observation data. MI and YJS conducted plume modelling. MI and KN analysed the infrasound data. AY analysed XRF and EPMA datasets. FM, TK, MI, YJS, AY, and TO discussed the conceptualisation of the study and contributed to constructing the eruption chronology. All authors discussed the eruption process, cooperated in revisions, and approved this submission.

Corresponding author

Correspondence to F. Maeno.

Competing interests

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.

Additional information

Supplementary Information on plume modelling is available for this paper.

References

1. White, J.D.L., Smellie, J.L. & Clague, D.A. Explosive submarine volcanism. AGU Geophys. Monograph **140**, 379 (2003).
2. Houghton, B., White, J.D.L. & Van Eaton, A.R. Phreatomagmatic and related eruption styles. In *The Encyclopedia of Volcanoes (Second Edition)*, eds. Sigurdsson, H., et al. (London, Academic Press), 537–552 (2015).
3. Koyaguchi, T. & Woods A.W. On the formation of the eruption columns following explosive mixing of magma and surface water. J. Geophys. Res. **101**, 5561–5574 (1996).
4. Carey, R. J., et al. The largest deep-ocean silicic volcanic eruption of the past century. Sci. Adv. **4**, e1701121 (2018).
5. Cas, R.A.F. & Simmons, J.M. Why deep-water eruptions are so different from subaerial eruptions. Frontiers in Earth Sciences **6**, 198 (2018).
6. Manga, M., et al. The pumice-raft forming 2012 Havre submarine eruption was effusive. Earth Planet. Sci. Lett. **489**, 49–58 (2018)
7. White, J.D.L., Schipper, C.I. & Kano, K. Submarine explosive eruptions. In *The Encyclopedia of Volcanoes (Second Edition)*, eds. Sigurdsson, H., et al. (London, Academic Press), 553–569 (2015).
8. Self, S. & Sparks, R.S.J. Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water. Bull. Volcanol. **41**, 196–212 (1978).
9. Sparks, R. S. J., Wilson, L. & Sigurdsson, H. The pyroclastic deposits of the 1875 eruption of Askja, Iceland. Philos. Trans. R. Soc. London Ser. A **299**, 241–273, doi:10.1098/rsta.1981.0023 (1981).
10. Self, S. Large-scale phreatomagmatic silicic volcanism: a case study from New Zealand. J. Volcanol. Geotherm. Res. **17**, 433–469 (1983).
11. Allen, S.R. & Cas, R.A.F. Rhyolitic fallout and pyroclastic density current deposits from a phreatoplinian eruption in the eastern Aegean Sea, Greece. J. Volcanol. Geotherm. Res. **86**, 219–251 (1998).
12. Carey, R. J., Houghton, B. F. & Thordarson, T. Tephra dispersal and eruption dynamics of wet and dry phases of the 1875 eruption of Askja Volcano, Iceland. Bull. Volcanol. **72**, 259–278, doi:10.1007/s00445-009-0317-3 (2010).
13. Thorarinsson, S., et al. The submarine eruption off Westman Islands, 1963-4. Bull. Volcanol. **27**, 435–445 (1964).
14. Moore, J.C., Nakamura, K. & Alcaraz, A. The 1965 eruption of Taal volcano. Science **151**, 955–960 (1966).
15. Waters, A.C. & Fisher, R.V. Base surges and their deposits: Capelinhos and Taal volcanoes. J. Geophys. Res. **76**, 5596–5614 (1971).
16. Kokelaar, B.P. The mechanism of Surtseyan volcanism. J. Geol. Soc. **140**, 939–944, doi:10.1144/gsjgs.140.6.0939 (1983).

17. Peckover, R.S., Buchanan, D.J., & Ashley, D.E.T.F. Fuel-coolant interactions in submarine volcanism. *Nature* **245**, 307–308 (1973).
18. Wohletz, K. Explosive magma-water interactions: thermodynamics, explosion mechanisms, and field studies. *Bull. Volcanol.* **48**, 245–264 (1986).
19. Sheridan, M.F. & Wohletz, K. Hydrovolcanism: basic considerations and review. *J. Volcanol. Geotherm. Res.* **17**, 1–29 (1983).
20. Kokelaar, B.P. Magma-water interactions in subaqueous and emergent basaltic volcanism: *Bull. Volcanol.* **48**, 275–289, doi:10.1007/BF01081756 (1986).
21. Moitra, P., Sonder, I & Valentine, G.A. The role of external water on rapid cooling and fragmentation of magma. *Earth Planet. Sci. Lett.* **537**, 116194 (2020).
22. Durig, T., et al. Deep-sea eruptions boosted by induced fuel-coolant explosions. *Nature Geosci.* **13**, 498–503 (2021).
23. Vaughan, R.G. & Webley, P.W. Satellite observations of a surtseyan eruption: Hunga Ha’apai, Tonga. *J. Volcanol. Geotherm. Res.* **198**, 177–186 (2010).
24. Green, S.N., et al. Hydroacoustic, infrasonic and seismic monitoring of the submarine eruptive activity and sub-aerial plume generation at South Sarigan, May 2010. *J. Volcanol. Geotherm. Res.* **257**, 31–43 (2013).
25. Lyons, J.J., et al. Infrasound from giant bubbles during explosive submarine eruptions. *Nature Geosci.* **12**, 952–958 (2019).
26. Fee, D., et al. Seismo-acoustic evidence for vent drying during shallow submarine eruptions at Bogoslof volcano, Alaska. *Bull. Volcanol.* **82**, 2 (2020).
27. Schneider, D.J., et al. Satellite observations of the 2016-2017 eruption of Bogoslof volcano: aviation and ash fallout hazard implications from a water-rich eruption. *Bull. Volcanol.* **82**, 29 (2020).
28. Tokyo Volcanic Ash Advisory Center. Advisory No. 2021/1 (Fukutoku-Oka-no-ba) issued at 00:27 UTC, 13 August 2021, <https://ds.data.jma.go.jp/svd/vaac/data/index.html>, accessed on 29 November 2021.
29. Cotton, W.R., Bryan, G. & van den Heever, S.C. Cumulonimbus clouds and severe convective storms. In *Storm and cloud dynamics*, eds. Cotton, W.R., Bryan, G. & van den Heever, S.C. International Geophysics Book Series **104**, 315–454 (2014).
30. McKee, K. et al. Evaluating the state-of-the art in remote volcanic eruption characterization Part I: Raikoke volcano, Kuril Islands. *J. Volcano. Geotherm. Res.* **419**, 107354 (2021).
31. Mastin, L.G., "Plumeria 2.3.1," <https://vhub.org/resources/1194> (2011).
32. Mastin, L.G., A user-friendly one-dimensional model for wet volcanic plumes. *Geochemistry, Geophysics, Geosystems* **8**, Q03014. doi:10.1029/2006GC001455 (2007).
33. Walker, G.P.L. Explosive volcanic eruptions: A new classification scheme: *Geologische Rundschau* **62**, 431–446, doi:10.1007/BF01840108 (1973).

34. Pyle, D. M. The thickness, volume and grainsize of tephra fall deposits. *Bull. Volcanol.* **51**, 1–15 (1989).
35. Cioni, R., Pistolesi, M. & Rosi, M. Plinian and sub-plinian eruptions. In *The Encyclopedia of Volcanoes (Second Edition)*, eds. Sigurdsson, H., et al. (London, Academic Press), 519–535 (2015).
36. Kano, K., Yamamoto, T. & Ono, K. Subaqueous eruption and emplacement of the Shinjima Pumice, Shinjima (Moeshima) Island, Kagoshima Bay, SW Japan. *J. Volcanol. Geotherm. Res.* **71**, 187–206 (1996).
37. Fiske, R.S. et al. Tephra dispersal from Myojinsho, Japan, during its shallow submarine eruption of 1952–1953. *Bull. Volcanol.* **59**, 262–275 (1998).

Methods

Satellite and infrasound monitoring

A timeseries analysis of the eruption was performed using optical and infrared images captured by the Himawari-8 satellite. An infrasound station at Chichijima, Ogasawara, 330 km north of the Fukutoku-Okanobu (FOB) volcano, detected signals of the explosions originating from the source (Fig. 1a). Infrasonic signals from the FOB were identified by the simultaneous detection at the infrasound station and another seismic station, which is ~1 km away and sensitive to infrasound³⁸, with a corresponding time lag. Using the TROPOMI instrument installed on the Sentinel-5 Precursor satellite, the SO₂ flux was estimated to be 1.4×10^6 kg/h for the first 7 h of the eruption, assuming a 15-km eruption plume³⁹. This flux was used to estimate the mass of the SO₂ emissions during the 15-hour intense phase of the eruption.

Volume estimation

The volume of the tuff cone was estimated from the topographic change at the source before and after the eruption based on the bathymetry data⁴⁰ and the location and dimension of the new islands according to the JCG airplanes and satellite observations (Fig. 1c). The dimensions and components of the tuff cone were inferred from photos taken on 12 October by JCG (Extended Data Fig. 2). The volume of the pumice raft was estimated based on its area and thickness immediately after the major eruptive phases. The thickness of the pumice raft was assumed to be 0.3–1 m based on recent submarine eruptions^{41, 42}. In the DRE volume calculation, the bulk densities of the tuff cone (tephra deposit) and the pumice raft were assumed to be 1250 kg/m³ and 500–800 kg/m³, respectively.

Plume modelling

The plume rise height is primarily determined by the heat flux or mass discharge rate from the source because the development of a plume is driven by the conversion of thermal energy to potential energy. Under high humidity conditions in the atmosphere, latent heat is released during the phase change from steam to liquid water and then to ice as the eruption plume rises, causing an increase in plume height. Another 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. In plume modelling, we applied the user-friendly plume model 'Plumeria'^{31, 32}, which includes the effect of the phase change of water, to calculate the relation between the eruption parameters and plume height (see Supplementary Information for details). To incorporate the thermal energy from the pumice that did not rise in the plume, we adjusted the input parameters of the software to represent the water-rich high-enthalpy mixture at the vent (Extended Data Fig. 3–6). To achieve a plume height of 16 km, the necessary mass discharge rate was estimated to be $3\text{--}6 \times 10^5$ kg/s. The temperature dependence is small compared with that of the mass discharge rate.

Chemical analysis

Pumice samples from the 2021 FOB eruption were taken by the Japan Meteorological Agency at 25° 30.3 N, 138° 53.3 E on 22 August 2021 during a survey cruise and at Minami Daito on 4 October 2021; samples were also acquired by Minami Daito Village at Minami Daito on 8 October 2021 and by our research group on Okinawa Island on 20 November 2021. We performed microscope observations and conducted whole-rock major element analyses using X-ray fluorescence spectrometry (ZSX Primus II, Rigaku Co., Ltd., Tokyo, Japan) and groundmass and mineralogical analyses using an electron probe microanalyser (EPMA, JXA-8800R, JEOL Ltd., Tokyo, Japan) with an acceleration voltage of 15 kV, a beam current of 12 nA, and a beam diameter of 10 μm at the Earthquake Research Institute, University of Tokyo. On the basis of the microscope observations, all the products from the 2021 FOB eruption include phenocrysts of plagioclase, clinopyroxene, Fe–Ti oxides, olivine, and apatite. Plagioclase is the most abundant phenocryst. The whole-rock chemical compositions for the 13 samples of the FOB products are 61.7–64.0 wt.% SiO_2 , 1.3–2.5 wt.% MgO , and 9.6–11.1 wt.% $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and are classified as trachyte or trachydacite. The ranges of the chemical compositions of the 2021 products are the same as those of past eruptions. The chemical compositions of the groundmass (GM) glass vary over a linear trend ranging from 56–68 wt.% SiO_2 , reflecting a mixture of mafic magma, even though silicic GM is the main component. The silicic melt inclusions (MIs) in plagioclase have 65–67 wt.% SiO_2 . We also measured SO_3 for the silicic GM ($n = 95$) and silicic MIs in a plagioclase phenocryst ($n = 32$) using EPMA. The SO_3 concentrations of the silicic GM and silicic MIs were 334 ppm ($1\sigma = 336$ ppm) and 425 ppm ($1\sigma = 178$ ppm), respectively. The SO_3 concentrations were recalculated as SO_2 concentrations, and finally the degassed SO_2 was estimated to be 73.3 ppm from the difference between the SO_2 concentrations of the silicic GM and silicic MIs.

Methods references

38. Nishida, K. & Ichihara, M. Real-time infrasonic monitoring of the eruption at a remote island volcano using seismoacoustic cross correlation. *Geophy. J. Inter.* **204**, 748–752 (2016).
39. Support to Aviation Control Services,
https://sacs.aeronomie.be/TROPOMIalert/2021/08/alertsTROPOMI_20210813_04h11_210.php?alert=20210813_052436_210, accessed on 29 November 2021.
40. Ito, K. et al. Volcanic topography of Fukutoku-Okanoba volcano in Izu-Ogasawara arc after the 2010 eruption. *Rep. Hydrograph. Oceanograph. Res.* **47**, 9–13, in Japanese (2011).
41. Jutzeler, M., et al. On the fate of pumice rafts formed during the 2012 Havre submarine eruption. *Nature Comm.* **5**, 3660, doi:10.1038/ncomms4660 (2014).
42. Jutzeler, M., et al. Ongoing dispersal of the 7 August 2019 Pumice raft from the Tonga Arc in the southwestern Pacific Ocean. *Geophy. Res. Lett.* **47**, e1701121, doi:10.1029/2019GL086768 (2020).

Figures

Figure 1

(a) Location map of the Fukutoku Oka-no-Ba (FOB) volcano. (b) Photo of the FOB eruption at ~15:00 JST on 13 August 2021, taken from 6,000 m above sea level and approximately 90 km north of the volcano by the Japan Coast Guard. (c) Bathymetry around FOB prior to the 2021 eruption⁴⁰. The new islets and the vent area are indicated by the red areas and the dashed line, respectively. The photo was taken by GeoEye-1 on 22 August 2021. (d) Distribution of the pumice raft (grey zone) extending from the source; photo taken by Himawari-8 at 09:57:30 JST.

Figure 2

(a) Development of the FOB eruption plume captured by Himawari-8 at five representative times. (b) Timeseries of the diameter (north–south direction) of the eruption plume captured by Himawari-8 (upper) and infrasound data at 5–15 Hz recorded at Chichijima (bottom). The inverted triangles indicate infrasound signals confirmed to be from the FOB direction. The eruption is divided into four major phases: Phase 1, the initial intense phase; Phase 2, the pulsating phase; Phase 3, intermittent and sparse strong explosions; and Phase 4, decay. (c) Magnification of the source area at the beginning of Phase 1.

Figure 3

Idealized near-source processes of the phreatomagmatic explosions that occurred at the FOB volcano on 13–15 August 2021.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryFiles.docx](#)