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EXPRESS LETTER

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Water sampling using a drone at Yugama crater lake, Kusatsu-Shirane volcano, Japan

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Abstract

Remote sampling of water from Yugama crater lake at Kusatsu-Shirane volcano, Japan, was performed using a drone. Despite the high altitude of over 2000 m above sea level, our simple method was successful in retrieving a 250 mL sample of lake water. The procedure presented here is easy for any researcher to follow who operates a drone without additional special apparatus. We compare the lake water sampled by drone with that sampled by hand at a site where regular samplings have previously been carried out. Chemical concentrations and stable isotope ratios are largely consistent between the two techniques. As the drone can fly automatically with the aid of navigation by Global Navigation Satellite System (GNSS), it is possible to repeatedly sample lake water from the same location, even when entry to Yugama crater lake is restricted due to the risk of eruption.

Keywords: Drone, Crater lake, Kusatsu-Shirane volcano, Water chemistry, Volcanic unrest

Introduction

Regular sampling of lake water at hot crater lakes is commonly used to monitor volcanic systems (e.g., Giggenbach and Glover 1975; Hurst et al. 1991; Rowe et al. 1992; Martinez et al. 2000; Ohba et al. 2008; Rouwet et al. 2016). Data on temporal changes in lake water chemistry are useful for identifying and predicting volcanic activity such as phreatic and phreatomagmatic eruptions (Mastin and Witter 2000; Schaefer et al. 2008; Morrissey et al. 2010). Therefore, regular water sampling and water chemistry analysis are the most straightforward and valuable methods for providing early warning of an eruption.

However, sampling of crater lake water by hand is difficult during volcanic unrest due to the probability of a volcanic eruption. At most of Japan's active volcanoes, including Kusatsu-Shirane (Fig. 1), the Japan Meteorological Agency issues warnings in the case of volcanic unrest. When intensive earthquake swarms or small explosions are detected, the volcano alert level is set to 2 or 3 to provide warning and inform the public. Under such conditions, entry is not permitted to the summit area of Kusatsu-Shirane volcano. Although sampling of the lake water is important for monitoring purposes, it is hampered by the difficulty in accessing Yugama crater lake during high alert levels.

Unmanned air vehicles (drones) have been utilized at many volcanoes (Gomez and Purdie 2016) to measure the components in volcanic gas (e.g., McGonigle et al. 2008; Shinohara 2013; Mori et al. 2016), ground surface temperature (e.g., Harvey et al. 2016; Nishar et al. 2016; Chio and Lin 2017), and the magnetic field (Hashimoto et al. 2014), in addition to assisting with 3D modeling of the terrain (e.g., Westoby et al. 2012; Moussallam et al. 2016). Drones have recently been developed that can fly for several km with a payload exceeding 1–2 kg and are therefore valuable as a device of sampling lake water from remote sites. Schwarzbach et al. (2014) sampled water using a drone equipped with a pump, with the drone hovering at a height of 1–2 m above the water surface. Ore et al. (2015) used special sensors and a dedicated software system for drone flights to enable the drone to pass close to the water surface for water sampling purposes.

Dense acidic gases such as HCl and SO_2 are emitted from hot hyper-acidic crater lakes at active volcanoes (Shinohara et al. 2015; Capaccioni et al. 2017), which

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can be problematic for drones. During volcanic unrest (including phreatic eruptions), perturbations of the water surface and strong upward air currents caused by enhanced lake water evaporation can further hamper efforts to sample water near the lake surface. To use a drone safely at active volcanoes with crater lakes, we tested a simple method of water sampling using a drone at Yugama crater lake, launching the drone from a remote site located 2 km north of the lake center. In this paper, we describe and discuss the water sampling procedure.

Outline of Kusatsu-Shirane volcano

Yugama crater lake at Kusatsu-Shirane volcano is classified as a *high-activity crater lake* (Rouwet et al. 2014), which is a hot crater lake with temperatures 10–15 °C higher than the ambient air temperature (due to the emission of volcanic gas and hot water from subaqueous fumaroles on the lake floor, Ohba et al. 2008; Terada and Hashimoto 2017). The lake water has a pH of ~1.0 and contains high concentrations of Cl and SO_4 ions, which show marked changes in response to volcanic activity (Ohba et al. 2008).

Recent volcanic activity at Kusatsu-Shirane volcano has been characterized by frequent phreatic eruptions at Yugama crater lake that commenced in 1882 (Tsuya 1933; Minakami et al. 1943; Ossaka et al. 1980, 1997). These eruptions were probably caused by enhanced heating of the hydrothermal system beneath Yugama crater lake in response to magma degassing at depth.

In 2014, microearthquake swarms were accompanied by ground deformation, increased water temperature, and changes in the chemical concentrations of the water in Yugama crater lake (including the detection of Cl and SO_4 ions), but no eruption occurred at Yugama crater lake. Unusual seismic activity and inflation at shallow depths within Yugama crater lake ceased in 2015, and water temperatures stabilized and returned to normal in August 2016 (Kuwahara et al. 2017).

On January 23, 2018, a phreatic eruption occurred at the Kagami-ike-kita pyroclastic cone, which is located 1.7 km south of Yugama crater lake. Volcanic ejecta (including volcanic bombs) were erupted, resulting in the death of a skier. The water temperature and level of Yugama crater lake did not show any changes in response to the eruption.

Field operation

Drone

We used a drone to sample lake water from Yugama crater lake (Fig. 1) in this study. The drone was a six-rotor LAB645 (Enroutelab, Japan; Fig. 2a, b). The maximum flight duration is 40 min when the drone is powered by

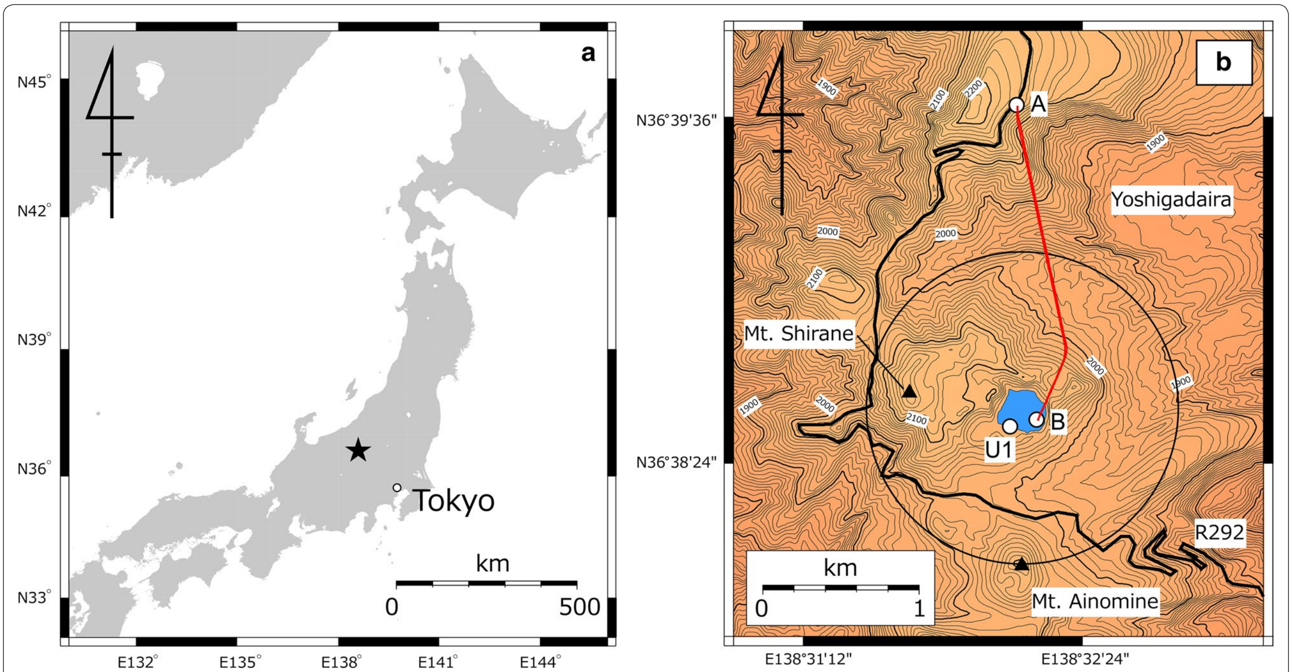

Fig. 1 Location and topography of Kusatsu-Shirane volcano. **a** Location map of Kusatsu-Shirane volcano within Japan (marked by a star). **b** Topographic map of Kusatsu-Shirane volcano. Solid lines are topographic contours at intervals of 10 m. "A" and "B" correspond to the takeoff/landing site and water sampling site, respectively. Regular sampling of lake water by hand has been carried out at site U1. Red line indicates the flight route for water sampling on October 18, 2017. The circle indicates a distance of 1 km from the center of Yugama crater lake

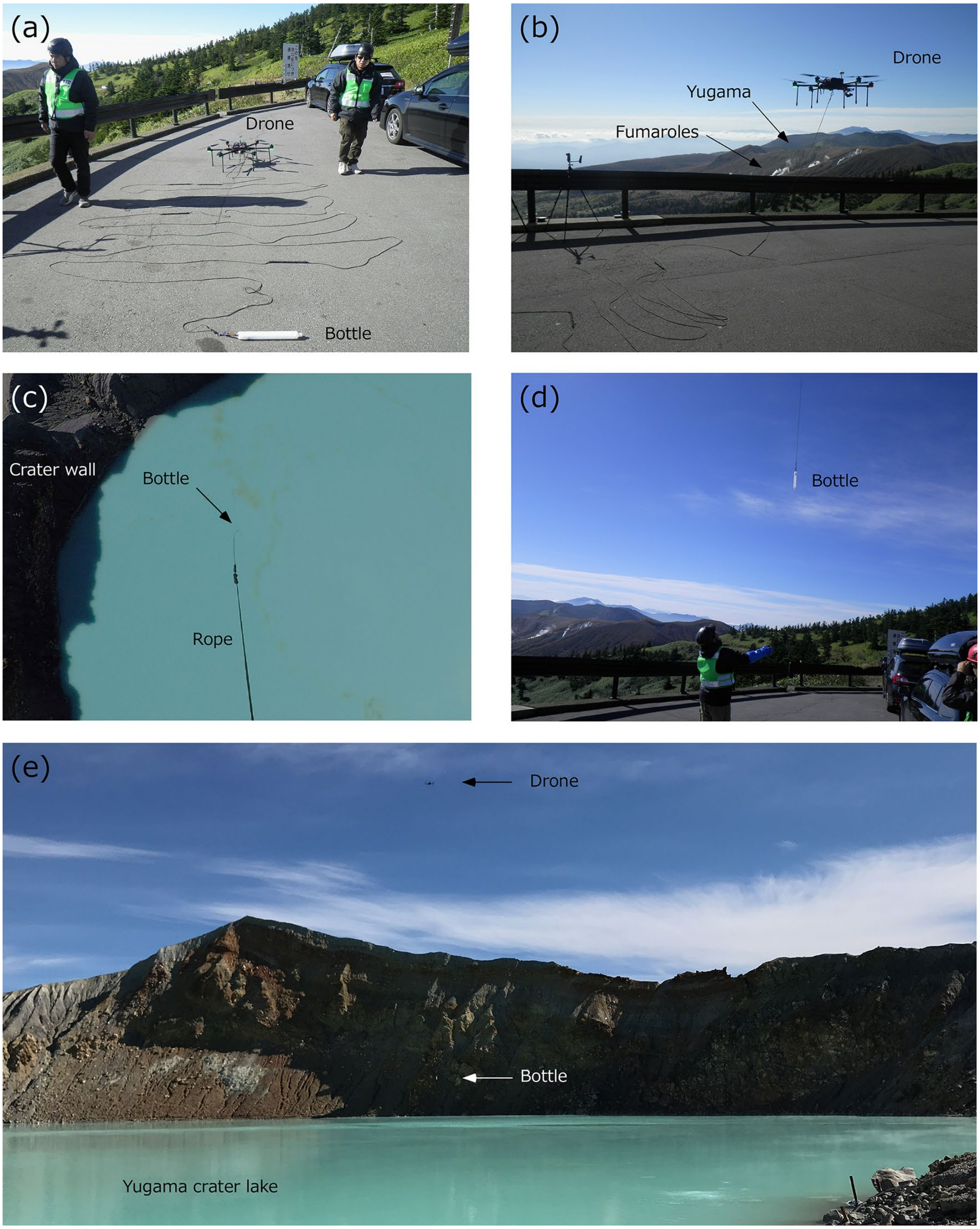

Fig. 2 Photographs of the drone operation on October 18, 2017. **a** Setup of the drone LAB645, with the rope and sampling bottle on the ground. **b** Taking off with the suspended sampling bottle. **c** Photograph above sampling point B shown in Fig. 1, taken by a camera on the drone. **d** Catching the bottle by hand just before landing. **e** Approach of the drone and sampling bottle to the surface of Yugama crater lake

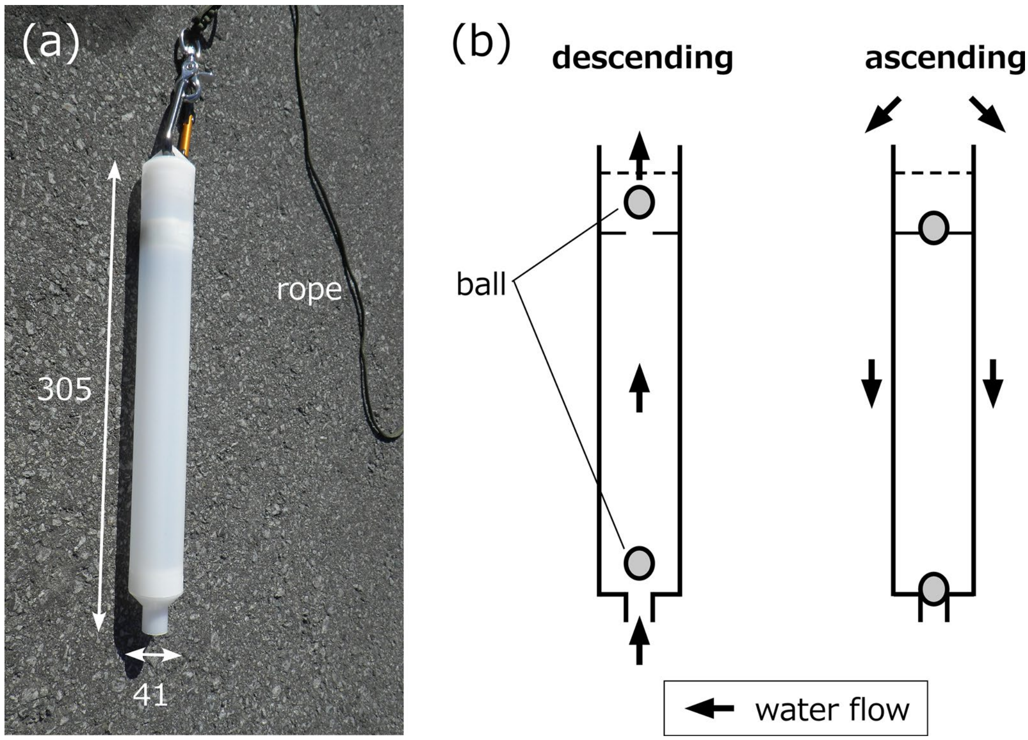

Fig. 3 Photograph and schematic illustrations of the water sampling bottle. **a** Photograph of the water sampling bottle, and **b** schematic illustrations of the bottle. Numbers in panel **a** represent dimensions in millimeters

two 350 Wh (22.5 V) batteries with a total weight of 4 kg. The drone can takeoff with a maximum load of 12 kg. It is controlled by an operator during takeoff and landing (Fig. 2b), but at other times it navigates automatically by GNSS between prefixed waypoints.

Sampling device

A metal-free bottle made of high-density polyethylene (Techno International Trading, Japan) was used for sampling. Figure 3 shows a photograph and schematic illustrations of the bottle, which was originally developed for sampling water from a well. The bottle has a hollow tube-like structure that allows water to freely flow through the tube when lowered into a lake. When the bottle is pulled upwards, two balls in the bottle shut the inlets to stop downward flow, resulting in the sampled water being instantly trapped. Thus, the bottle can sample lake water at an intended depth by simply lowering/raising the drone. The bottle used in this study (Fig. 3) is capable of sampling a maximum of 330 mL of water; the weight of the bottle itself is 0.115 kg.

The bottle is suspended from a 30 m length of rope. The rope length was determined based on topographic considerations to ensure that the bottle did not strike the ground on the way to Yugama crater lake (Fig. 2a, b). Weights (each 200 g) are attached to the rope to prevent it from being disturbed by ambient wind, at distances of 2, 15, and 25 m from the drone (based on the results of preliminary tests). The rope attaching the drone to the bottle (Fig. 2a) is gently lifted when the drone takes off (Fig. 2b).

Sampling procedures

As the drone is able to navigate automatically by GNSS, once optimal waypoints for sampling locations are programmed the drone can follow the intended route even during times of volcanic unrest.

There are some limitations to this approach. The camera view transmitted from the drone is unlikely to provide sufficient information for the operator to estimate an accurate relative height between the drone and the lake surface. Moreover, radio communications may be perturbed due to the presence of a crater wall between the drone and operation site. In these cases, adjusting the drone's location via remote control can be difficult. In addition, there are uncertainties in both GNSS and the topographic maps used.

To overcome these problems without requiring any additional special equipment, the sampling waypoint can be adjusted by an observer located on a crater wall or at the lakeshore during calm period. In the case of Kusatsu-Shirane volcano, volcanic activity is calm at the time of writing and therefore an observer can approach Yugama crater lake. The observer on the lakeshore measures the relative height between the lake surface and the drone using a laser range finder (TruPulse 360). The altitude of the sampling waypoint can then be adjusted on the basis of the observer's reports.

After water sampling, the drone returns to the takeoff site and gently lowers the bottle to the ground to be retrieved by gloved hands.

Results

Water sampling using a drone was carried out on October 18, 2017. Wind speed was ~1.5 m/s or less at 1 m above the ground at the takeoff/landing site ("A" in Fig. 1). Neither cloud nor fog was present during the flight, meaning that visibility was good between site A and Yugama crater lake. During the course of the first test flight between site A and Yugama, we encountered no problems in terms of wind or radio communications.

Water sampling

The height of the sampling waypoint was initially fixed to 108 m lower than the takeoff/landing site on the basis of a topographic map published by the Geospatial Information Authority of Japan (GSI). This waypoint corresponded to 30 m above the lake surface at site B (Fig. 1), and this distance is much larger than the altitude error of GNSS (equipped on the drone) and the uncertainties in the topographic map. Therefore, water sampling failed during the first experimental flight because the bottle did not reach the lake. From the camera view transmitted from the drone (Fig. 2c), it was difficult for the operator to monitor the clearance between the lake surface and the bottle in real time. Remote adjustments to the drone height were not carried out because of the risk of a loss of radio communications between the drone and the operator at site A due to topographic effects.

According to laser range finder observations undertaken by an observer on the lakeshore, the clearance was reported as 7–8 m above the lake surface (Fig. 2e). During the next flight, the target height was adjusted to −115 m from site A, and as a result, the sampling bottle was successfully immersed into the lake. The bottle reached 0.8 m below the lake surface, as indicated by the observation that the rope was wet at a range of 0.8 m from the bottle.

When the drone returned to site A, the sample bottle had been successfully filled with 250 mL of lake water (Fig. 2d). Although the suspended sampling bottle was swinging like a pendulum at an amplitude of a few meters, it was safely caught by hand.

Comparison of water properties between drone-based sampling and traditional techniques

To evaluate the potential effects on sample properties caused by differences in sampling procedures, we assessed the consistency between lake water sampled by the drone and that sampled by hand at site U1 (Fig. 1), where regular samplings had previously been carried out.

Table 1 and Fig. 4 show the water properties of the lake water sampled at the two sites. We found that electrical conductivity, pH, chemical concentrations, and stable isotope ratios were largely consistent between the two sites. For instance, the difference in Cl and SO_4 ion concentrations between the two sites was only 0.3%, which is less than the analytical uncertainty (Table 1). For comparison, differences in anion concentrations of 0.7–11% between sites U1 and B were reported in 1967 (sites I and V of Ossaka 1984). Thus, to monitor lake water chemistry, data from water sampled by a drone can be coupled with data from other samples that have been regularly sampled at site U1 (Fig. 1).

Discussion and conclusion

In our experiment, the drone successfully sampled >250 mL of water from Yugama crater lake during a calm period at Kusatsu-Shirane volcano. Site A (the takeoff/landing site) is located 2 km north of the lake center (Fig. 1), which means that water sampling can be safely carried out even if Kusatsu-Shirane volcano is in a period of unrest. Using programmed waypoints, the drone can repeatedly sample lake water at exactly the same location, even during periods of high probability of volcanic unrest (when approaching Yugama crater lake is prohibited by the local government). Sampling locations and depths can be easily altered by modifying the waypoints, and therefore, other features of interest can be sampled (e.g., fluid emissions from subaqueous fumaroles).

Drone flight operation

The procedure of water sampling presented here is robust and easy to achieve (except during high winds) and can therefore be carried out by volcanologists using just a drone without any special apparatus or techniques. If the drone can carry a load of multiple bottles, simultaneous water samplings from various depths may be possible. Even under conditions of high temperatures or hyperacidic lake water, the drone does not experience any mechanical problems because the bottle filled with lake water is suspended 30 m below the drone. It is not necessary for the drone to approach close to the lake surface, which reduces the risk of damage to the drone resulting from perturbations of the water surface, strong upward air currents, and acidic gases.

Table 1 Water chemistry in Yugama crater lake

	Ec (S/m)	pH	Cl (mg/L)	SO_4 (mg/L)	Al (mg/L)	Ca (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Na (mg/L)	SiO_2 (mg/L)	δD (‰)	$\delta^{18}O$ (‰)
Drone	4.98	1.01	4453	1834	205	120	93.4	16.7	28.4	1.31	37.5	160	−48.5	−3.64
U1	4.97	1.00	4438	1840	205	120	96.9	16.1	28.7	1.28	36.2	158	−48.6	−3.83

Chemical concentrations, pH, electrical conductivity (EC), and stable isotope ratios of hydrogen and oxygen in lake water sampled by drone, and in lake water sampled by hand at site U1 (i.e., the site of regular sampling; e.g., Ohba et al. 2008). The pH and EC were measured using a handheld pH/EC meter (HORIBA, D-74) equipped with a glass electrode (HORIBA, 9615S-10D) for measuring pH and a two-electrode instrument (HORIBA, 3552-10D) for measuring EC. Both pH and EC values are converted to the reference temperature of 25 °C. The concentrations of Cl and SO_4 ions were determined with an ion chromatograph (Thermo Scientific, Integrion). The concentrations of cations were measured by a microwave plasma–atomic emission spectrometer (Agilent Technologies, 4210 MP–AES). The δD and $\delta^{18}O$ values were determined by cavity ringdown spectroscopy (Picarro, L2120-i). The analytical precisions of the EC, pH, anion concentration, cation concentration, $\delta^{18}O$, and δD values are ± 0.11 S/m, ± 0.02, ± 0.2%, ± 5%, ± 0.7‰, and ± 0.07‰, respectively

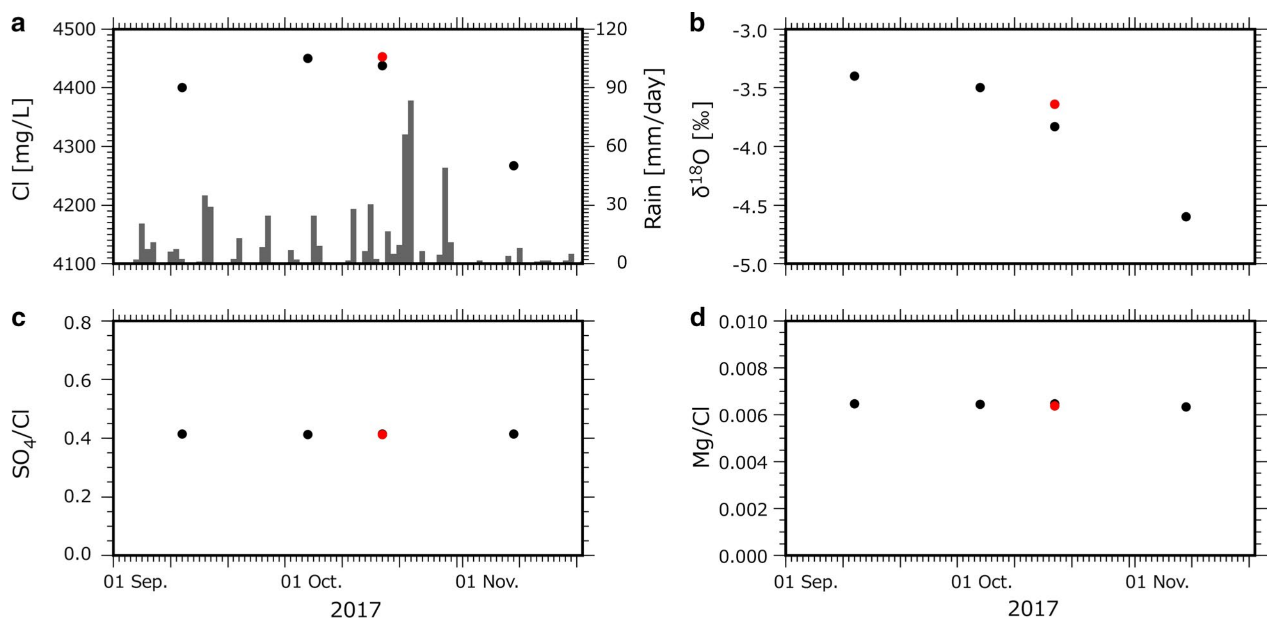

Fig. 4 Temporal changes in water chemistry in Yugama crater lake. Temporal changes in the chemical concentrations and stable isotope ratios of Yugama lake water sampled by drone at site B on October 18, 2017 (red closed circles), and regularly sampled by hand at site U1 from September to November in 2017 (black circles). **a** Cl ions and daily precipitation observed at Yugama crater, **b** $\delta^{18}O$, **c** SO_4/Cl, and **d** Mg/Cl

However, multiple flights were necessary to adjust the waypoints used in this study. Drone locations should not be remotely adjusted, given the risk of loss of radio communications. Furthermore, the method presented here requires an observer at the crater lake during periods of volcanic quiescence. Even in cases that an observer or surveillance camera is not available, we expect that sampling of lake water would be feasible if the height of the sampling waypoint is lowered little by little at each flight.

Atmospheric conditions (e.g., wind speed) are the prime cause of difficulties in flight operations. The criteria for safe drone deployment depend on the rotor power of the drone, the load weight, and the length of the rope carrying the sampler. Preliminary test flights are therefore essential. In addition, at crater lakes located at high altitudes, such as Yugama crater lake (2000 m a.s.l.), the duration of a single flight is shorter than at crater lakes located at low altitudes because of the lower density of ambient air (e.g., Mori et al. 2016). It is noted that rapid acceleration and deceleration of the drone may cause the suspended sampling bottle to swing like a pendulum. To avoid these problems, the final waypoint is set to just above the landing site. After maintaining the position of the final waypoint for a period of time, the drone should descend slowly (<0.5 m/s) to the ground from almost directly below.

Lake water properties

We compared the properties of lake water sampled by the drone with that sampled by hand at site U1. As a result, we found that lake water sampled by drone is useful for comparison with lake waters sampled at the lakeshore (site U1 in Fig. 1), because both have similar chemistry (Table 1). Analyses of our sampled lake water show that electrical conductivity and concentrations of Cl and SO_4 ions on 10 November decreased from the previous data, while SO_4/Cl remained constant (Fig. 4), probably due to dilution by the input of precipitation. Such fluctuations in lake water chemistry are much larger than the differences between sites U1 and B (Figs. 1, 4).

Minor spatial inhomogeneities in water properties are observed at some crater lakes (e.g., Kawah Ijen in Indonesia; Delmelle et al. 2000), probably due to fluid emissions from subaqueous fumaroles. Although anion concentrations in the surface water of Yugama crater lake show perturbations of 10% (Ossaka 1984), larger spatial inhomogeneities may be attributed to enhanced activity of subaqueous fumaroles during eruptive periods. Such inhomogeneities can be easily assessed by sampling water from multiple sites using drones.

Previous studies have reported that crater lake water chemistry changes in response to volcanic activity (e.g., Giggenbach and Glover 1975; Rowe et al. 1992;

Christenson 2000; Rouwet et al. 2014). Such changes may be correlated with phreatic eruptions and earthquake swarms and have also been identified at Yugama (Takano and Watanuki 1990; Ossaka et al. 1997; Ohba et al. 2008; Takano et al. 2008). For instance, the Mg/Cl ratio is a good indicator of microearthquake swarms beneath Yugama crater lake (Ohba et al. 2008). In 2014, microearthquakes accompanied by ground deformation were detected at Yugama crater lake. A Mg/Cl value of 0.006 was obtained by a drone on October 18, 2017 (Table 1), corresponding to values measured prior to the microearthquake swarms in 2014, meaning these earthquake swarms in 2014 were not accompanied by an increase in the Mg/Cl ratio of the lake water. This is similar to the case of the 1989–1992 earthquake swarms and was most likely caused by the invasion of groundwater through the breached sealed zone beneath Yugama crater lake (Ohba et al. 2008).

At Yugama crater lake, interaction between groundwater and degassing magma is a possible mechanism of temporal change in the SO_4/Cl ratio of lake water. This process is controlled by the breaching of a self-sealed zone (Fournier 1999) surrounding the magma body (Ohba et al. 1994, 2008). During periods of volcanic unrest (including explosive activity), continuous sampling by hand at the lakeshore is difficult or impossible, in contrast to data collection by seismometer and GNSS. Water sampling using a drone, coupled with geophysical observations, is essential to understand the hydrothermal system underlying the crater lake.

Authors' contributions
AT designed the flight plans and drafted the manuscript. YM led the overall study. TH, TM, and WK prepared and improved the apparatus on the drone and supported flight operations. TO and MY analyzed the water chemistry. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
Flight logs are available on request from the corresponding author.

Consent for publication
Not applicable.

Ethics approval and consent to participate
Not applicable.

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