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資　料

Can volcanic activation be identified from the geochemistry of surface discolored water in the active crater lake Yugama at Kusatsu-Shirane volcano, Japan? ―Example from July 2025

Muga Yaguchi[1)]*, Akihiko Terada[2)] and Takeshi Ohba[3)]

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草津白根山の活動的火口湖“湯釜”における変色湖水表層の地球化学的特徴から火山活動の活発化は読み取れるか？ ―2025年7月の例―

谷口無我[1)]*，寺田暁彦[2)]，大場　武[3)]

要　旨

草津白根山の湯釜火口湖は水蒸気噴火の発生場であり，しばしば地震や微動に伴う湖面変色が発生する．私たちは2025年7月に地震や地殻変動に伴う湖面変色を発見し，この変色水を分析することで火山活動の活発化を読み取れるかどうかを調査するためにドローンを用いて白濁した変色域および通常色域の表層湖水を採取し，主要な溶存成分と水の安定同位体比（δD, $\delta^{18}O$）を分析した．結果として変色域と通常色域の湖水の水質に明瞭な差は見当たらず，変色水に特有の，火山活動の活発化を示唆するような特徴を読み取ることはできなかった．

キーワード：火口湖，火山活動，湖水変色，採水，化学分析

[1)] Department of Volcanology Research, Meteorological Research Institute, Japan Meteorological Agency, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan. [1)] 気象庁気象研究所火山研究部　〒305-0052　茨城県つくば市長峰1-1. *Corresponding author：E-mail myaguchi@mri-jma.go.jp

[2)] Volcano and Earthquake Research Division, Multidisciplinary Resilience Research Center, Institute of Integrated Research, Institute of Science Tokyo, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan. [2)] 東京科学大学 総合研究院 多元レジリエンス研究センター 火山・地震研究部門　〒152-8551 東京都目黒区大岡山2-12-1.

[3)] Department of Chemistry, School of Science, Tokai University, 4-1-1 Kitakaname, Hiratsuka, Kanagawa 259-1291, Japan. [3)] 東海大学理学部化学科　〒259-1292　神奈川県平塚市北金目4-1-1.

Abstract

Yugama crater lake at Kusatsu-Shirane volcano, Japan, is a site of phreatic eruptions, where water discoloration occasionally occurs in association with abnormal activities such as seismicity and volcanic tremors. In July 2025, we observed lake surface discoloration associated with increased seismicity and crustal deformation. To investigate whether the geochemical properties of such discolored water contain information regarding increased volcanic activity, we collected surface lake water from both the discolored area with whitish turbidity and the normal colored areas using a drone, and analyzed major dissolved components and stable isotopic ratios of hydrogen and oxygen. As a result, no significant difference in water quality was observed between the discolored and normal areas, and no distinctive features uniquely associated with the discolored water that would suggest increased volcanic activity were identified.

Key words : crater lake, volcanic activity, water discoloration, water sampling, chemical analysis

1. Introduction

Kusatsu-Shirane volcano, in central Japan, is an active volcano composed of three pyroclastic cones : Shirane, Ainomine, and Motoshirane, with the Yugama crater on Mt. Shirane being a known site of phreatic eruptions (e.g., Ohba and Yaguchi, 2025 ; Terada and Kuwahara, 2025) (Fig. 1). The Yugama crater hosts an active crater lake due to the injection of volcanic fluids from the bottom, with water characterized by strong acidity (about pH 1) and an emerald green color. Since at least the 1940s, its water has been analyzed for dissolved chemical components and used to understand volcanic activity (Minami et al., 1952 ; Ohba et al., 2008 ; Yaguchi et al., 2021). Although the last eruption at the Yugama crater occurred between 1982 and 1983, abnormal activities such as water ejection from the lake surface and discoloration accompanied by earthquakes and volcanic tremors have occasionally been observed since then (Tokyo Institute of Technology (TIT), 1996 and 2004 ; Japan Meteorological Agency (JMA), 2013). In particular, lake water discoloration has continued to be observed at the Yugama crater lake in recent years.

The milky emerald green of the Yugama crater lake arises from sunlight absorption and scattering : green from Fe^{2+} absorption, blue from Rayleigh scattering by sulfur colloids (0.1–0.45 μm), and white turbidity from Mie scattering by larger sulfur particles (>1.2 μm), as shown by Onda et al. (2003). Although a milky emerald green color is commonly seen in active crater lakes (e.g., Christenson et al, 2015) and water discoloration has been reported in several cases (e.g., Christenson and Wood, 1993 ; Pasternack and Varekamp 1994 ; Trunk and Bernard, 2008), the link between discoloration, water chemistry, and volcanic activity remains unclear (Ohsawa et al., 2010). However, recent advances in drone-based techniques have increasingly enabled water sampling even during active periods, which was previously particularly difficult (Terada et al., 2018). The Yugama crater lake serves as a representative site where drone-based techniques have been successfully applied, and discolored water sampling and analysis are being progressively implemented. For example, in June–July 2018, black to grayish-white discoloration appeared days after volcanic tremors, and similar discoloration occurred in July 2019 (Terada

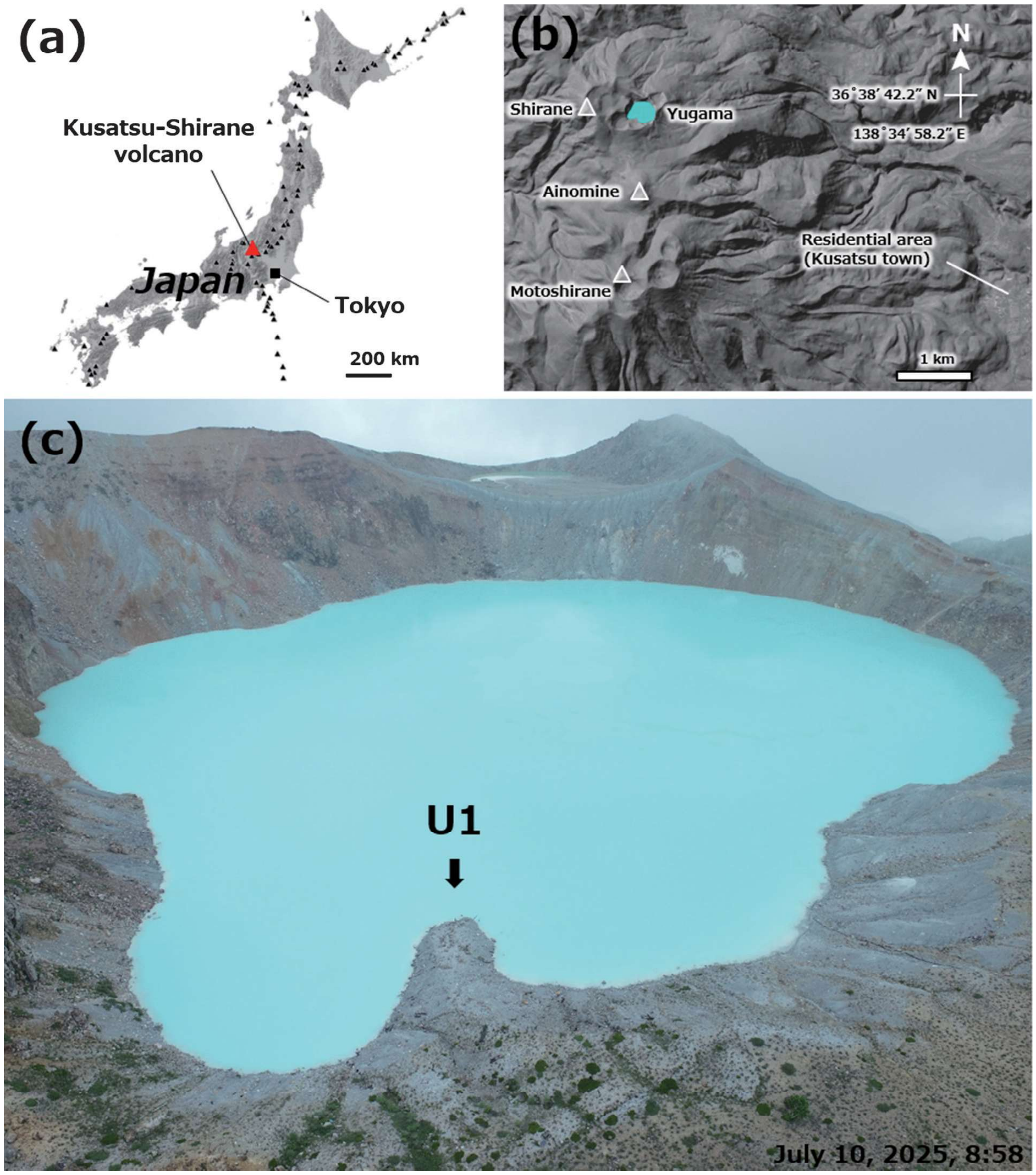

Fig. 1　Location map of the Yugama crater lake of Kusatsu-Shirane volcano in central Japan.
(a) Index map of Kusatsu-Shirane volcano. Solid triangles indicate active volcanoes. The base map is sourced from the Geographical Survey Institute of Japan (GSI). (b) Shaded-relief image overlaid with an aerial photograph, based on data from GSI. (c) Aerial photograph of the Yugama crater lake captured using a drone.

and Kuwahara, 2025). With the expectation that lake water from the discolored area might provide insights into increased volcanic activity, because the lake surface discoloration observed in 2018 and 2019 was associated with volcanic tremors, water samples were collected by drone in July 2019 from both a shoreline site without discoloration at the time and the discolored center of the Yugama crater lake. However, chemical and isotopic analyses showed no significant differences (TIT, 2020 ; Yaguchi et al., 2021).

In the latest case, seismic activity increased and tilt changes suggesting underground inflation were observed near the Yugama crater beginning on June 26, 2025 ; subsequently, on the afternoon of July 9, a camera located within the crater captured yellowish discoloration on the western side of the Yugama crater lake, followed by drone observations in the morning of July 10 that revealed whitish discoloration near the center of the lake. Unlike the discoloration events in 2018 and 2019, no blackish coloration was observed in July 2025. In the days that followed, volcanic earthquakes around Yugama increased significantly from the afternoon of August 3, and the volcanic alert level was upgraded from 1 to 2 on August 4 (JMA, 2025).

This study aims to investigate whether analyzing discolored lake water can reveal information about volcanic activity that cannot be obtained from analyzing normally colored water. To this end, on July 10, 2025, we collected samples of discolored water using a drone and analyzed their major chemical components, as well as the stable isotope ratios of hydrogen and oxygen.

2. Concise overview of the Yugama crater lake and surface discoloration in July 2025

The Yugama crater lake, approximately 300 meters in diameter and averaging 15 meters in depth, occasionally exhibits volcanic gas bubbling and floating sulfur at its surface. Molten sulfur at 116℃ exists at the lake bottom, where contact with lake water causes surface solidification. However, volcanic fluids occasionally breach the sulfur layer, allowing gas bubbles to rise to the lake surface (Ossaka et al., 1984). Sonar surveys have revealed bubble discharge from at least three lake-bottom locations (Ossaka et al., 1984), and water quality surveys at multiple underwa-

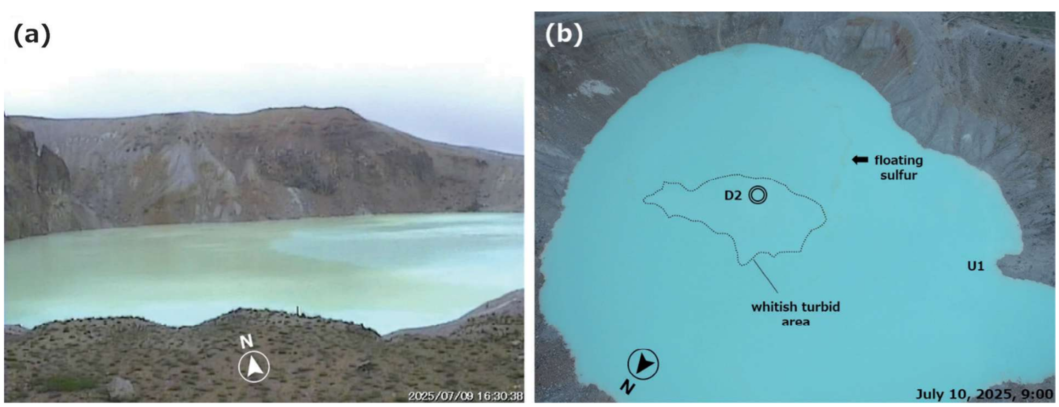

Fig. 2　Surface discoloration observed at the Yugama crater lake in July 2025.
(a) Image captured by a camera in the southern part of the crater at 16:30 on July 9, showing yellowish turbidity in the western part of the lake surface. (b) Drone photograph taken at 09:00 on July 10, showing a whitish turbid area and sulfur floating on the lake surface. Water samples were collected approximately at sites D2 and U1 (listed as U1-D in Table 1 due to drone-based sampling). The north arrows are approximate.

ter points revealed spatial heterogeneity in chemical composition (Ossaka, 1984), with particularly high-concentration zones of anions such as Cl and SO_4 shaped like eruption plumes (Minami et al., 1969).

The discoloration of the lake surface in July 2025 was observed as follows :

- Around 14:30 on July 9, 2025, a camera located within the crater captured yellowish turbidity on the western side of the Yugama crater lake (Fig. 2a). However, the origin of the discoloration remains uncertain as to whether it was caused by inflow of surface water, rocks and sediment from the lakeshore, or upwelling from the lake bottom.
- Aerial observation of the lake surface using a drone between 9:00 and 10:00 on the following day, July 10, revealed no yellowish discoloration on the western side, but instead showed whitish turbidity in the central part of the lake (Fig. 2b), which appeared to result from subaqueous upwelling. Similar discoloration has previously been observed at the Yugama crater lake during past active periods, but its link to lake water properties remains unclear due to offshore sampling difficulties.

3. Sample and analysis

Lake water samples were collected between 09:00 and 10:00 on July 10 using a drone from two locations : an offshore point near site U1 (in this paper, U1-D for drone sampling) and site D2, as shown in Fig. 2b. Site U1 is a regular sampling site where surface water is typically collected manually using a ladle, and no discoloration was observed during water sampling conducted in this study. In contrast, site D2 exhibited whitish turbidity at the time of sampling. Although the lake water color at the sampling sites is difficult to clearly discern visually in Fig. 2b, the RGB values reveal subtle differences : approximately (118, 208, 226) in and around U1, and (128, 209, 221) for the area surrounding D2, indicating slightly greater whiteness near D2. The water sampling by drone followed Terada et al. (2018), with sampling depths of several tens of centimeters below the lake surface.

The pH and electrical conductivity were measured using a handheld pH/EC meter (Horiba, D-74), equipped with a glass electrode (Horiba, 9615S-10D) calibrated with pH 1.68 and 4.00 buffer solutions, and a platinum–platinum black electrode (Horiba, 3552-10D), respectively. Water samples were filtered through a 0.45 μm membrane filter and appropriately diluted prior to analysis, with Cl and SO_4 analyzed by ion chromatography (Thermo Scientific, Dionex Integrion HPIC), and Na, K, Ca, Mg, Fe, Al, Mn, and Si analyzed using a microwave plasma atomic emission spectrometer (Agilent, 4210 MP-AES). Stable isotope ratios of water samples (δD and $\delta^{18}O$) were analyzed by using a cavity ring-down spectrometer (Picarro, L2140-i) and reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW). The relative standard deviations (RSDs) of IC, MP-AES, and isotope analyses were tested using standard materials and are listed in Table 1 along with the analytical results.

Incidentally, manual sampling was conducted at site U1 on July 8, the day before lake water discoloration occurred, and the lake water was analyzed using the same methods as above, with the results included in Table 1 for reference.

Table 1　Analytical results of water samples from the Yugama crater lake

Location	Sampling date	Temp. °C	pH	EC S/m	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	$\delta^{18}O$ ‰	δD ‰
(Analytical precisions[a] :		–	–	–	*0.64%*	*0.71%*	*0.46%*	*1.15%*	*1.20%*	*0.72%*	*0.68%*	*1.92%*	*1.23%*	*1.63%*	*0.04‰*	*0.5‰)*
Manual sampling using a ladle																
U1	**July 8, 2025**	**28.8**	**1.13**	**3.66**	**4002**	**943**	**198**	**114**	**75.3**	**14.0**	**27.2**	**1.04**	**31.9**	**166**	**-3.77**	**-49.7**
Drone sampling																
U1-D	**July 10, 2025**	**ND**	**1.15**	**3.64**	**3942**	**939**	**196**	**110**	**74.7**	**13.6**	**26.8**	**1.02**	**31.4**	**162**	**-3.74**	**-49.4**
D2	**July 10, 2025**	**ND**	**1.15**	**3.64**	**3952**	**945**	**193**	**109**	**74.2**	**13.6**	**26.5**	**1.00**	**30.9**	**158**	**-3.78**	**-49.4**
ΔD2 (%) relative to U1-D		–	–	–	*0.25%*	*0.64%*	*-1.53%*	*-0.91%*	*-0.67%*	*0.00%*	*-1.12%*	*-1.96%*	*-1.59%*	*-2.47%*	*(-0.04‰)[b]*	*(-0.0‰)[b]*

[a] Analytical precision for Cl to SiO_2 was expressed as RSD (%), and for δD and $\delta^{18}O$ as repeatability (‰), both based on repeated tests using standard materials.
[b] δD and $\delta^{18}O$ are expressed as absolute differences between D2 and U1-D.

4. Results and brief interpretation

Based on the analytical results shown in Table 1, the chemical compositions of the normally colored and discolored lake water on July 10 can be reasonably regarded as essentially similar, although some components (e.g., Al, Mg, Na) slightly exceed the analytical RSDs. In addition, compared to the water quality on July 8, the day before the discoloration, the concentrations of dissolved constituents on July 10 were generally similar, or, if anything, slightly lower. Accordingly, no changes in concentration were observed that would suggest increased volcanic activity.

Regarding δD and $\delta^{18}O$, these values are expected to become heavier if volcanic activity increases, due to increased contributions from magmatic vapor or enhanced evaporation. However, water samples collected on July 10 showed no significant difference between the discolored and normal areas, with variation within the range of analytical repeatability. Consistent with the chemical composition, the δD and $\delta^{18}O$ values also exhibited no appreciable variation when compared to the lake water sampled on July 8.

As previously noted, the whitish turbidity observed in the Yugama crater lake is mainly attributed to the scattering of sunlight by sulfur colloids (particle size $>1.2\,\mu m$) (Onda et al., 2003 ; Ohsawa et al., 2010). The colloidal sulfur here was rapidly formed through the reaction between SO_2 and H_2S released from subaqueous fumaroles, as follows :

$$SO_2 + 2H_2S \rightarrow 3S + 2H_2O \quad (1)$$

Therefore, the whitish turbidity on the lake surface may result from either the progression of the reaction in Equation (1), triggered by subaqueous fumarolic gas injection, or the resuspension of sulfur precipitates from the lake bottom due to fumarolic activity. Given the plume-like distribution of high-concentration dissolved components in the Yugama crater lake (Minami et al., 1969), chemical and stable isotopic traces of subaqueous fumarolic activity (i.e., a sign of volcanic unrest) preceding the surface turbidity were expected. Nevertheless, at least in this particular case, even surface samples from the discolored area suggested that such identification was likely difficult.

5. Conclusion and remarks

The water quality of the discolored water observed at Yugama crater lake in July 2025, including major dissolved components and stable isotope ratios (δD and $\delta^{18}O$), was essentially identical to that of the nearby normally colored water, with no geochemically distinctive features uniquely associated with the discolored surface water that would suggest increased volcanic activity.

With regard to future perspectives, tracking future changes related to the current event remains important. Given the diverse discoloration patterns observed at the Yugama crater lake, the findings of this study are considered to represent only a single case among many, and the continued accumulation of observational and analytical data is also considered important. On the other hand, more prompt detection of volcanic activity through lake water analysis may be facilitated by techniques such as underwater sampling (Suzuki et al., 2020) and the estimation of the chemical composition of fluids discharged from the lake bottom based on surface water analysis (Terada et al., 2022), which may be worth exploring as potential approaches. In addition, although in this study we used RGB values only as a supplementary means to check differences in lake water color at the sampling sites, incorporating indicators such as RGB values derived from photographs or videos may be worth considering to enhance the objectivity of surface condition assessments, particularly in evaluating lake surface discoloration.

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