Triggering mechanism of the recent eruptions at Yugama crater at Kusatsu-Shirane volcano since 1982 insighted by lake water chemistry

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Introduction

Yugama crater lake at Shirane pyroclastic cone of Kusatsu-Shirane volcano is the site of frequent phreatic eruptions with the recent eruptive events (including small events) in 1982–83, 1989, and 1996 (e.g., KSVO, 1996; Terada, 2018). Although geomagnetic observations observed the cooling of the hydrothermal system from 1996 to 2012 (Takahashi and Fujii, 2014), earthquake swarms occurred in 2014 and 2018, with crustal deformation and thermal demagnetization just below the Yugama crater (Terada et al., 2021; JMA, 2021). In this study, we investigate the magma–hydrothermal interaction beneath Yugama crater lake and propose a key mechanism for the recent eruptions at this crater, based on the lake water using the chemical composition of the lake water until November 2021.

Results and discussions

Kusatsu-Shirane volcano releases a large amount of heat for an active volcano in the non-eruption period, about 20 MW from Yugama crater lake in the summit area and the surrounding fumarolic area, and about 110 MW from the hot spring water at the foot of the volcanic edifice (Ohba et al., 1994; Ueki and Terada, 2012; Kagiyama, 1981). In this study, however, we assume a crystallizing magma with a self-sealing zone at the margin of about 400˚C (Giggenbach, 1992; Fournier, 1999) as the driving source of the Yugama crater lake in the context of the following points: the last magmatic eruption at Shirane pyroclastic cone, which hosts the Yugama crater lake, was about 1,400 years ago (Kametani et al., 2021); no clear signs of magma intrusion in the shallow beneath Yugama crater have been detected since at least the 1990s (Munekane, 2021; Terada et al., 2021); concentrations of SO_2 in fumarolic gas, as a representative of magmatic gas derived from fresh magma at shallow depth, are low (Ohba et al., 2019). The self-sealing zone corresponds to brittle to plastic transition. Dominantly meteoric water circulates in the brittle rock region, while the region below the self-sealing has a temperature of about >400˚C with low permeability. In addition, we focused on Ca, Al, and Si concentrations as representatives of the breach and dissolution of minerals (e.g., silica, gypsum/anhydrite, and alunite) comprising the self-sealing zone and the Mg/Cl ratio as an indicator for enhanced interaction between groundwater and hot rock inside the self-sealing zone (Giggenbach and Glover, 1975).

From 2005 to 2012, Cl and SO_4 concentrations decreased slowly, suggesting the development of a self-sealing zone surrounding the crystallizing magma. On the other hand, the Si, Ca, and Al concentrations and the Mg/Cl ratio increased in 2006–2007. Following the above assumptions, the breach (dissolution) of the self-sealing zone and the contact between groundwater and the hot rock region inside the self-sealing zone occurred in 2006. However, no Cl and SO_4 increase during this period suggests the self-sealing zone was leached by deep circulating groundwater enabled by long-term cooling after 1996, rather than by magmatic fluids injection.

After the 2014 earthquakes, Si, Ca, and Al increased again but was associated with a significant Cl increase and a pH decrease; hence we believe that the HCl-rich magmatic fluids breached the self-sealing zone, leading to fluids injection from the crystallizing magma to the Yugama crater. During this period, the Mg/Cl ratio did not increase, meaning that magmatic fluids ascending from the breached area of the

self-sealing zone inhibited the deep intrusion of groundwater into the hot rock region. The increase in dissolved components after the 2014 earthquake continued until 2016.

After the 2018 earthquakes, an increase in Cl concentration (or stagnation of concentration decrease) and a slight increase in the Mg/Cl ratio were observed, suggesting the less intense ascend of magmatic fluid, allowing deep groundwater intrusion to the hot rock region.

One of the implications withdrawn from our observations is that there are at least two modes of breach of the self-sealing at the margin of the crystallizing magma, which is assumed to be the driving source of the Yugama crater lake: by leaching by deep circulating groundwater and by magmatic fluids injection. In addition, all eruptions since 1982 have been accompanied by a Mg/Cl ratio increase and a Cl decrease, whereas, when a significant HCl input occurs, as in 2014, no eruptions and no Mg/Cl ratio increase occurred. This demonstrates that the groundwater–hot rock interaction, rather than the magmatic fluids input, played an essential role in triggering phreatic eruptions; i.e., eruptions at Yugama crater can potentially occur without clear signs of fresh magma intrusions or actively degassing.

Keywords: Kusatsu-Shirane volcano, Yugama crater lake, crystallizing magma, self-sealing zone, Mg/Cl ratio

