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Effects of subvolcanic hydrothermal systems on edifice collapses and phreatic eruptions at Tokachidake volcano, Japan

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ABSTRACT

Subvolcanic hydrothermal alteration often leads to volcanic hazards, such as edifice collapse and phreatic eruption. The 1926 eruption of Tokachidake volcano caused a pyroclastic cone to collapse, and phreatic eruptions have occurred repeatedly. Here, we investigate the hydrothermal system of Tokachidake volcano by examining the characteristics of hydrothermally altered rocks and discuss the effects of the hydrothermal system on volcanic hazards. Beneath the crater area, the dense Tairagadake lavas (Ta lava) at the basement of Tokachidake volcano form piles that are >500 m thick. The Ta lava constrains the flows of volcanic gases and thermal water in the subsurface, and strong hydrothermal alteration occurs in both the underlying and overlying deposits that are more permeable. Above the Ta lava, Tokachidake ejecta are altered in low-temperature acidic environments (<100 °C). The sulfur isotopic composition of sulfate minerals suggests that alteration occurred in magmatic steam and steam-heated environments. However, in some samples, alunite has a high-δ^{34}S value (~17.5‰) and a Ca-rich composition, suggesting a high-temperature magmatic-hydrothermal environment (about 300 °C). Percolated meteoric water flows along the upper surface of the Ta lava and volcanic gas influx to that water produces sulfuric, acidic thermal water. This acidic mixture weakened the edifice rocks at the boundary with the Tokachidake ejecta. This weakened zone acted as a slip surface in the 1926 eruption. Beneath the Ta lava, a hydrothermal alteration zone with an alunite + kaolinite + pyrophyllite + quartz assemblage formed within the large-scale pyroclastic flow deposits. The alunite in this zone has a high-δ^{34}S value (up to 19.7‰). Thus, we can conclude that the permeation and subsequent condensation of magmatic vapor selectively occurred in the permeable pyroclastic flow deposits, and that condensed vapors produced a high-temperature magmatic-hydrothermal environment (200–300 °C). Phreatic eruptions were rooted in this zone, and thermal water was released from the uppermost part of this zone associated with the 1926 edifice collapse.

1. Introduction

In active volcanoes, volcanic heat and gases are continuously supplied from the deep magma to the shallow subsurface of the volcanic edifice, even during quiescent periods. This results in the formation of hydrothermal systems and associated hydrothermal processes in the edifice (Rye et al., 1992; Rye, 2005). These processes include dissolution, mineral precipitation and secondary mineralization, and lead to significant changes in physical properties of rocks such as density, porosity and permeability (Pola et al., 2012; Julia et al., 2014; Wyering et al., 2014; Heap et al., 2015). Weakening of the edifice due to alteration is likely to be an important factor in edifice collapses, which are one of the most catastrophic volcanic hazards (Carrasco-Núñez et al., 1993; Lopez and Williams, 1993; Reid et al., 2001; Reid, 2004; John et al., 2008; Ball et al., 2013; Rosas-Carbajal et al., 2016). Furthermore, phreatic eruptions are often associated with hydrothermal systems, and thus their ejecta contain alteration minerals (Ohba and Kitade, 2005; Ohba et al., 2007; Mazot et al., 2008; Minami et al., 2016). Mineral precipitation tends to reduce the porosity of deposits (hydrothermal sealing) (Edmonds et al., 2003; Christenson et al., 2010; Mayer et al., 2015), resulting in decreased permeability (Heap et al., 2017). Decreases in permeability can lead to the pressurization of hydrothermal systems, causing phreatic eruptions. In contrast, increased permeability due to acid-leaching can reduce the risk of pressurization (Mayer et al., 2016). Recent experimental studies have attempted to reveal phreatic eruption processes in hydrothermal areas, such as trigger mechanism, and fragmentation and ejection processes (Mayer et al., 2015; Montanaro et al., 2016a, 2016b, 2016c; Mayer et al., 2017).

Volcanic hazards related to hydrothermal systems are usually bereft of precursory signals, and hence are nearly unpredictable (Barberi et al., 1992;Hurst et al., 2014). Therefore, it is important to identify the possible hazards posed by a volcano in advance, based on an understanding of the subvolcanic hydrothermal systems. However, in the case of active

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volcanoes, it is difficult to investigate hydrothermally altered zones in edifice interiors because these are generally unexposed. Thus, the number of active volcanoes whose subvolcanic hydrothermal systems have been investigated in detail is limited (e.g., Mount Rainier: Frank, 1995; Moran et al., 2000; Finn et al., 2001; Reid et al., 2001; John et al., 2008). To understand the subvolcanic hydrothermal systems of active volcanoes, it is crucial to investigate debris avalanche deposits, phreatic ejecta and altered accessory fragments, all of which record subsurface environments.

Tokachidake volcano, one of the most active volcanoes in Japan, is part of the Tokachidake volcano group (Fig. 1). Vigorous fumarolic activity is observed in the summit crater area, and many thermal springs discharge on the flanks (Takahashi et al., 2015, 2017). Adjacent hydrothermally altered zones suggest that subvolcanic hydrothermal systems have developed. Edifice collapses in Tokachidake volcano occurred as a result of the 1926 eruption, and Uesawa (2008, 2014) proposed that these collapses caused large volumes of thermal water to be ejected from the edifice interior. Moreover, phreatic eruptions occurred repeatedly. In order to mitigate such volcanic hazards in the future, there is a need to study the characteristics of hydrothermal alteration and the extent of subvolcanic hydrothermal systems.

The distribution of hydrothermally altered minerals is mainly constrained by variations in pH and temperature (Meyer and Hemley, 1967; Hemley et al., 1980). Thus, if the precipitation sequence of altered minerals can be revealed, we can understand the development of the alteration environment. Sulfur isotopic and chemical compositions of altered minerals can often be effectively used to estimate their precipitation environments. The disproportionation of SO_2, oxidation of H_2S, and oxidation of pyrite occur in distinct hydrothermal environments (magmatic-hydrothermal, steam-heated and supergene) and cause differences in the sulfur isotopic composition of sulfate minerals (Rye et al., 1992; Rye, 2005). Moreover, the chemical composition of alunite varies depending on its precipitation temperature (Stoffregen and Cygan, 1990; Stoffregen and Alpers, 1992; Chang et al., 2011). Using

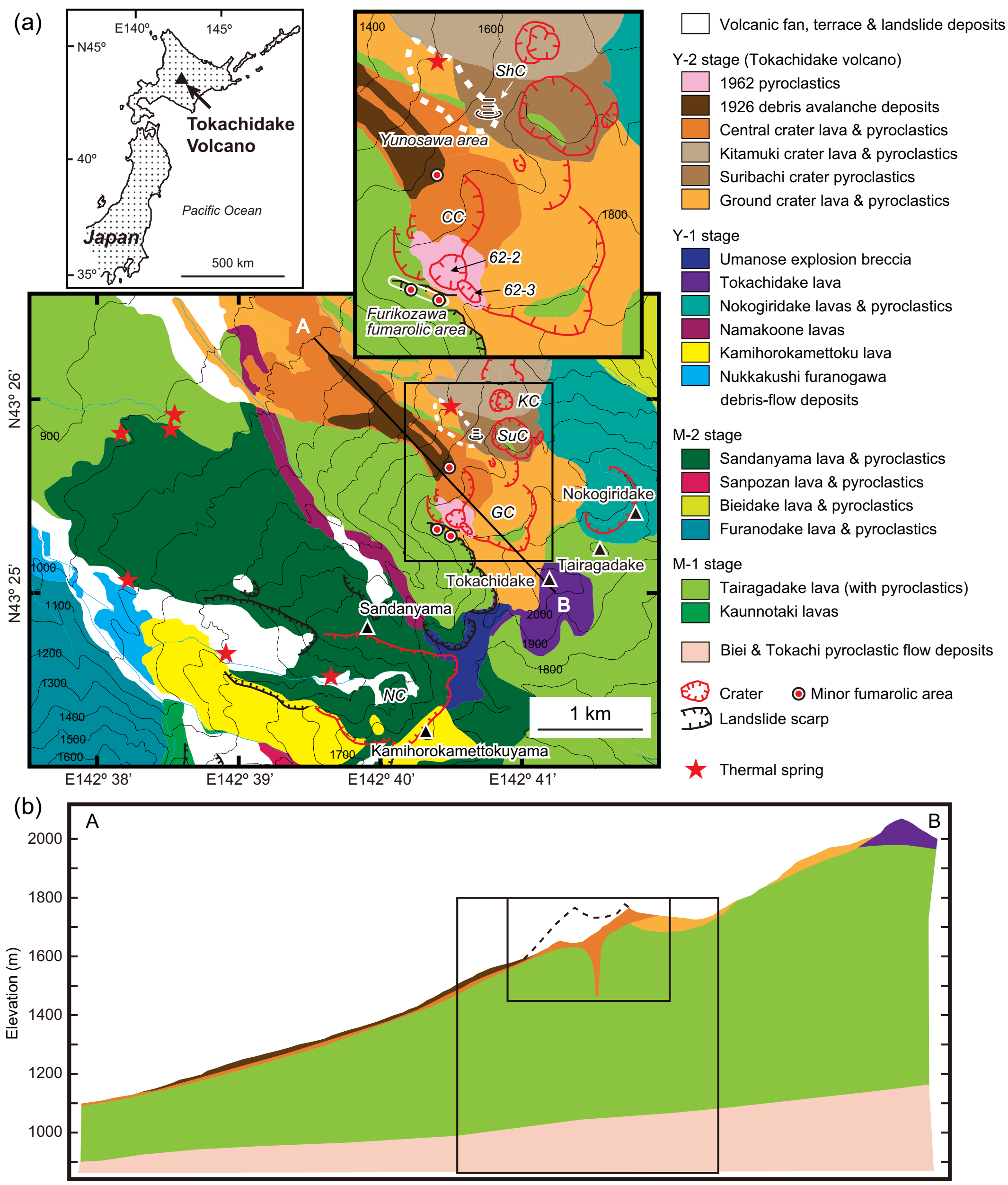

Fig. 1. (a) Regional and geological maps of Tokachidake volcano. The white broken circle indicates the Yunosawa area. The geological map is modified from Ishizuka et al. (2010). KC: Kitamuki crater, SuC: Suribachi crater, ShC: Showa crater, CC: Central crater, GC: Ground crater, 62-2: 62-2 crater, 62-3: 62-3 crater, NC: Nukkakushi crater. (b) Geological cross section. A–B cross section line is shown in (a). Large and small boxes indicate ranges of Fig. 9 and Fig. 11, respectively.