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Evolution of the 120 ka caldera-forming eruption of Kutcharo volcano, eastern Hokkaido, Japan: Geologic and petrologic evidence for multiple vent systems and rapid generation of pyroclastic flow

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ABSTRACT

We investigated the eruptive sequence and temporal evolution of juvenile materials during the 120 ka Kutcharo pumice flow IV (Kp IV) eruption, which was the most voluminous (175 km^3: bulk volume) caldera-forming eruption of Kutcharo volcano. The eruptive deposits are divided into four units in ascending order. Unit 1 is widely dispersed and consists of silt-sized, cohesive ash. Unit 2 is a thin, moderately sorted pumice fall deposit with a restricted distribution and small volume (<0.2 km^3). Unit 3, consisting of widely distributed ignimbrite, is the most voluminous. Unit 4 is also composed of pyroclastic flow deposits, but its distribution is limited to the northwest side of the caldera. Juvenile materials consist mainly of rhyolite pumice (74%–78% SiO_2) associated with a minor amount of scoria (52%–73% SiO_2) that are found only northwest of the caldera in Unit 3 and Unit 4. These scoriae can be classified on the basis of the P_2O_5 contents of their matrix glass into low-P, medium-P, and high-P types, which are almost entirely restricted to the lower part of Unit 3, Unit 4, and the upper part of Unit 3, respectively. These three types display distinct mixing trends with the rhyolitic compositions in SiO_2–P_2O_5 variation diagrams. This evidence indicates that three distinct mafic magmas were independently and intermittently injected into the main body of silicic magma to erupt from the northwestern part of the magma system. Mafic injections did not occur in the southern part of the magma system. This petrologic evidence implies that the northwestern and southeastern flows of Unit 3 are heterotopic, contemporaneous products derived from multiple vent systems. Although Unit 2 was derived from an eruptive column, its volume is very small compared to Plinian fall deposits of typical caldera-forming eruptions. In our interpretation, the activity of the Kp IV eruption reached its climax rapidly, depositing Unit 3, without first producing a stable Plinian column. The presence of multiple vent systems could have allowed the system to bypass an initial eruptive stage with a stable Plinian column and begin its climactic stage, represented by Unit 3, rapidly. Multiple vents could have been the result of sequential injections of mafic magma in the early stages of the Kp IV eruption.

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1. Introduction

The sequence of caldera-forming eruptions that produce large volumes (>100 km^3) of pyroclastic ejecta is poorly understood owing to the absence of observations and historical records. Although several studies have revealed the detailed sequence of such eruptions based on studies of the pyroclastic deposits (e.g., Oruanui ignimbrite by Wilson, 1993, 2001; Koya ignimbrite by Maeno and Taniguchi, 2007; Bishop Tuff by Hildreth and Wilson, 2007), cases are few because large-scale pyroclastic flow deposits (ignimbrites) are typically massive, monotonous bodies with silicic composition. In addition, there are few flow unit boundaries (Smith, 1960) in typical ignimbrites, such as the Ito (Aramaki, 1984), Campanian (Fisher et al., 1993), and Kos ignimbrites (Allen and Cas, 1998), that make it hard to reconstruct the sequence and timing of events during the emplacement of these deposits. However, clarifying the sequence and styles of caldera-forming eruptions is essential for understanding these hazardous events. Here we present a case study from Kutcharo volcano in Japan.

Previous tephrostratigraphic studies have shown that Kutcharo volcano, including the largest Quaternary caldera in Japan, has undergone eight caldera-forming eruptions (Katsui and Satoh, 1963; Okumura, 1991). The 120 ka eruption that produced Kutcharo pumice flow IV (Kp IV: Katsui and Satoh, 1963) is the largest silicic eruption of Kutcharo volcano. However, eruption sequence of the Kp IV deposits that are distributed around the caldera has not been clearly revealed. In addition, although geochemical studies have shown that two end-member magmas were mixed in the Kp IV eruption (Miyagi et al., 2012), the temporal and spatial variations of the eruption's juvenile materials are unclear.

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This study investigated the sequence and lithology of the Kp IV eruption products at many exposures around the caldera. The systematic survey for medial to proximal successions of the ignimbrites enabled us to establish the detailed stratigraphy that would reflect the main characteristics of the depositional units, and found that the eruption's climactic stage, producing an ignimbrite, occurred soon after the formation of a Plinian column. To clarify the relationship between the eruption sequence and magmatic processes, we quantified the proportions of the juvenile materials and studied their petrography, glass chemistry, and whole-rock chemistry, guided by our stratigraphic correlations. Particularly, this paper focuses on the petrologic variations of juvenile mafic scoria that are found in parts of the felsic ignimbrite.

2. Geologic setting

Kutcharo volcano forms a caldera cluster along with Akan and Mashu volcanoes in eastern Hokkaido, at the NE–SW Akan-Shiretoko volcanic chain, south end of the Kurile arc. Beneath which the Pacific plate is obliquely subducting (Kimura, 1986). The basement to these volcanoes consists of Miocene to Pliocene sedimentary and volcanic rocks (e.g., Katsui, 1958) (Fig. 1). Kutcharo volcano consists of a 26 × 20 km caldera and post-caldera volcanoes, such as Nakajima and Atosanupuri (Fig. 1). The somma of the caldera is composed of early Pleistocene stratovolcanoes, including Mokoto (1000 m) and Samakkarinupuri (974 m). These pre-caldera volcanoes were active from ca. 4 Ma until 870 ka (Hirose and Nakagawa, 1995; Goto et al., 2000).

Eight explosive eruptions associated with the formation of the Kutcharo caldera occurred during middle and late Pleistocene time. The first eruption produced the welded ignimbrite named as Furuume Welded Tuff (FWT; Katsui, 1962) at 400 ± 100 ka (Hasegawa et al., 2011) (Fig. 2). Subsequent eruptions, producing Kutcharo pumice flows VIII to I (Kp VIII to Kp I in ascending order), occurred from 210 ± 180 to 40 ± 1 ka with intervening dormant periods lasting 20 to 40 kyr (Katsui and Satoh, 1963). After that, Okumura (1991) showed that the Kp III and the Kp II deposits represent the same eruption (Kp II/III). The pyroclastic deposits of these Quaternary eruptions amount to more than 500 km^3 (it should be noted volumes in this paper are not corrected to dense rock equivalent) (Fig. 2).

The Kp IV eruption produced the largest deposits (175 km^3) of the eight caldera-forming eruptions (Hasegawa et al., 2012; Hasegawa and Nakagawa, 2016). Pyroclastic flows from this eruption traveled over 50 km from source in all directions, reaching the Okhotsk Sea and Pacific Ocean (Fig. 3). The eruption age was determined as approximately 120 ka from the stratigraphic relationship of its deposits with overlying widespread tephra from the Toya caldera (112–115 ka) in southwestern Hokkaido (e.g., Machida and Arai, 2003). Younger eruptive products, such as Kp I, are bounded by the inner caldera wall (Sumita, 2003). In addition to this description, extremely large volume of Kp IV among the eight eruptions suggests that the shape of the

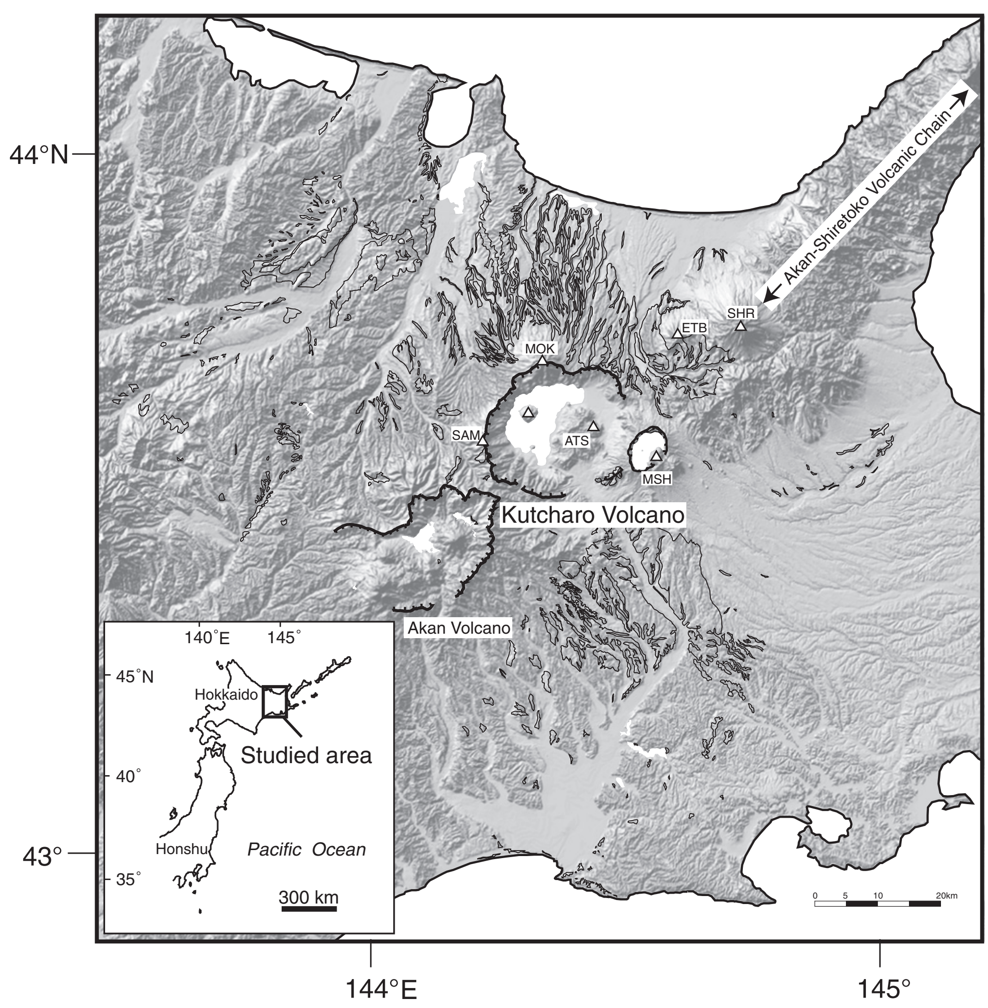

Fig. 1. Shaded digital relief map showing topography of eastern Hokkaido illuminated from the NW; Kp IV ignimbrite appears outline, water appear white. The rims of Akan, Kutcharo, and Mashu calderas are also shown. Triangles are the summits of notable volcanoes. SHR, Mt. Shari; ETB, Mt. Etombi; MOK, Mt. Mokoto; SAM, Mt. Samakkarinupuri; NKJ, Nakajima volcano; ATS, Atosanupuri volcano; MSH, Mashu volcano. NKJ, ATS, and MSH are post-caldera volcanoes of Kutcharo caldera.

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