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Magma systems of the Kutcharo and Mashu volcanoes (NE Hokkaido, Japan): Petrogenesis of the medium-K trend and the excess volatile problem

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ABSTRACT

Despite the existence of a growing database of the amount of H_2O in melt inclusions, it is difficult to calculate the bulk H_2O content for vapor-saturated magma because the observable H_2O concentration in melt is limited by its solubility. To overcome this problem, we focus on K_2O, which shows similar geochemical behavior to H_2O but is largely retained within melt in the case of volatile saturation and magma degassing. As an initial trial of this approach, we document the evolution of K_2O content for the Kutcharo and Mashu volcanoes in northeastern Hokkaido, Japan, which are located close to each other and have similar timing of eruptive activity, but are chemically distinct, with Kutcharo being medium-K in composition and Mashu being low-K. Despite the contrasting bulk-rock compositions of the two volcanoes, the melt inclusions show a smooth compositional trend that is continuous from low-K basalt to andesite, rhyolite, medium-K rhyolite, and finally high-K rhyolitic melt. The observed medium-K series probably is made by mixing of low-K basalt and medium-K rhyolite which derive from solidified low-K basalt. Thermodynamic computations using MELTS show that the observed chemical variation in melt inclusions can be explained by fractional crystallization and subsequent re-melting of low-K basalt. In addition, the similar Sr, Nd, and Pb isotopic compositions of the basalt and rhyolite, combined with the progressive enrichment of trace elements from basalt to rhyolite, support the interpretation that the two rock types are genetically related. The observed evolution of K_2O contents suggests that the total volume of basalt supplied intermittently beneath the volcanoes was approximately 10 times the volume of erupted rhyolite magma. The solidified basalt, which contains $H_2O \leq 5$ wt.%, $S \leq 0.3$ wt.%, and $Cl = -0.01$ wt.%, supplied a much larger amount of magmatic volatiles to the overlying felsic magma than could be dissolved.

1. Introduction

The amount of H_2O in magma is an important research topic in petrology and volcanology because H_2O plays a key role in magma genesis (e.g., Gill, 1981; Tatsumi, 1989), in the chemical evolution of magma (e.g., Bowen and Tuttle, 1950; Tuttle and Bowen, 1958; Wyllie, 1978), and in the triggering of volcanic eruptions (e.g., Eichelberger et al., 1986; Tait et al., 1989; Jaupart and Allégre, 1991; Woods and Koyaguchi, 1994; Sparks, 2003; Melnik et al., 2005). As an aid in estimating the amount of H_2O in magma, a large database has been compiled on the H_2O concentrations in melt inclusions (MIs) in phenocrysts (e.g., Lowenstern and Mahood, 1991; Bacon et al., 1992; Dunbar and Hervig, 1992; Devine et al., 1995; Miyagi and Yurimoto, 1995; Wallace et al., 1995; Roggensack et al., 1997; Saito et al., 2001; Hauri et al., 2002; King et al., 2002; Borisova et al., 2005). However, the concentrations of volatiles in MIs do not always reflect the bulk H_2O concentration in magma because of the H_2O solubility in silicate melt (e.g., Burnham and Jahns, 1962; Miyagi et al., 1997; Newman and Lowenstern, 2002).

K and H are incompatible elements in rock-forming minerals such as plagioclases and pyroxenes. Because of the similar geochemical behavior as incompatible elements, the concentration of K_2O in volcanic rock is used as a proxy of magmatic H_2O content (e.g., Aoki et al., 1981; Kovalenko et al., 2006; Portnyagin et al., 2008). The advantage of K_2O in this regard is that it is largely retained by melt by saturation and magma degassing during an eruption. In addition, it is easy to measure the K_2O content by electron micro-probe analyzer (EPMA). However, our understanding of the geochemical relationship between K_2O and H_2O is inadequate. In particular, geochemical interpretations of K_2O concentrations are complicated in the case that two volcanoes with different K_2O contents are closely linked in space and time. A good example in this regard is the Kutcharo (medium-K) and Mashu (low-K) calderas in NE Hokkaido, Japan. In this study, we analyzed samples from these calderas for major, trace, and volatile element contents in bulk rock, phenocrysts, and minerals and MIs in phenocrysts. The data are used to construct a model of the magma plumbing system in order to explain the observed chemical variations at the Kutcharo and Mashu volcanoes and to estimate the bulk H_2O content of the magmas.

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2. Geological and petrological outline

During the late Oligocene to middle Miocene, the opening of the Sea of Okhotsk to the west of the Kurile arc was accompanied by southwestward movement of the arc to its present position (Kimura and Tamaki, 1986). Following widespread Neogene intraplate volcanism in the Kitami area, within the back-arc region of the Kurile arc system (Goto et al., 1995), a group of calderas, including Kutcharo and Mashu, developed near the volcanic front, approximately 150 km west of the Kurile trench (Fig. 1, Table 1). Kutcharo is the largest group of calderas (20 by 26 km in size), and is one of the largest calderas in Japan (Katsui and Sato, 1963).

Volcanic activity at Kutcharo occurred in nine stages within three main eruptive phases (Katsui and Sato, 1963; Sumita-Sone, 1990; Okumura, 1991; Hasegawa et al., 2009). According to Sumita-Sone (1993), the early eruptive phases were marked by the Furuume Welded Tuff (FWT rhyolite) stage at 340 ka, which produced about 40 km^3 of dense rock equivalent (DRE), and ended with KP IV (Kutcharo pumice flow deposit IV) (Koshimizu and Ikushima, 1989; Sumita-Sone, 1993). The caldera-forming stage started at 120 ka, marked by the KP IV, which produced approximately 48 km^3 of DRE, and ended with KP II/III (Sumita-Sone, 1993). The current post-caldera era started at 70 ka and included the KP I stage at 35 ka, which produced 20 km^3 of DRE (Sumita-Sone, 1993; Machida and Arai, 2003; Itoh et al., 2007; Yamamoto et al., 2010). After the KP I stage, a group of lava domes (rhyolite, andesite, and minor low-K tholeiitic basalt) formed within the Kutcharo caldera (Atosanupuri volcano) at about 10 ka (Katsui, 1962; Katsui et al., 1986).

Mashu is a stratovolcano with a summit caldera of 7.5 by 5.5 km in size, located east of Kutcharo caldera. The volcano became active after the KP I stage of Kutcharo (i.e., 35 ka). The oldest activity at Mashu, known as the "stratified volcano era," produced basaltic to andesitic lava flows and scoria falls over a period of at least several thousand years (Katsui et al., 1986; Kishimoto et al., 2009). The subsequent "caldera era" started at about 12 ka and produced 27 km^3 DRE of tephra (termed Ma-l, Ma-k, and with the main eruption occurring at around 7 ka). The last stage, the "central cone volcano era", followed a 3000-year period of dormancy. The most recent large eruption of Mashu (Ma-b) younger than 3660 ± 40 yBP Ma-d (Yamamoto et al., 2010) produced 4.6 km^3 of DRE (Katsui et al., 1986; Kishimoto et al., 2009).

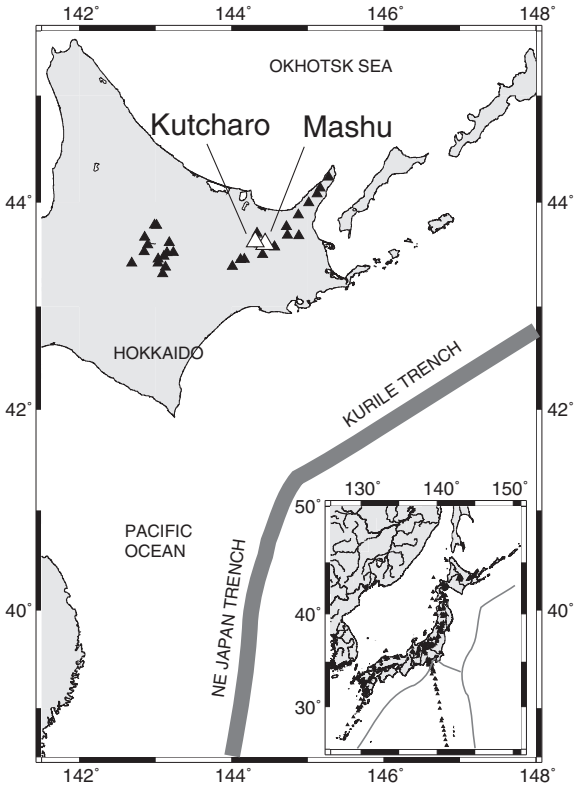

Fig. 1. Location map of Kutcharo and Mashu volcanoes.

Table 1
Locations and periods of activity of volcanoes in NE Hokkaido.

Name of Volcano	Activity	Location (N, E)
Samakkenupuri	1.1-0.8 Ma	43°41' 01", 144°43' 54"
Musadake	0.9-0.5 Ma	43°40' 40", 144°52' 55"
Unabetsudake	0.9-0.5 Ma	43°52' 36", 144°52' 35"
Shiretokodake	0.6-0.2 Ma	44°14' 09", 145°16' 26"
Onnebetsudake	0.4-0.1 Ma	43°59' 36", 145°00' 47"
Kutcharo	0.34 Ma -	43°42' 15", 144°19' 51"
Mashu	40 ka -	43°34' 20", 144°33' 39"
Sharidake	0.3 Ma -	43°45' 56", 144°43' 03"
Rausu	0.1 Ma -	44°04' 32", 145°07' 20"
Shiretokodake	0.25 Ma -	44°14' 09", 145°16' 26"
Meakan	50 ka -	43°23' 11", 144°00' 32"
Oakan	13 ka -	43°27' 14", 144°09' 53"

Data from the "Database of Japanese Active Volcanoes", Geological Survey of Japan.

It is relatively simple to discriminate between the eruptive products of Kutcharo (medium-K) and Mashu (low-K): the typical matrix-glass produced by Kutcharo contains 75.0–79.5 wt.% SiO_2 and 3.3–3.8 wt.% K_2O (Hasegawa and Nakagawa, 2007), while the equivalent figures for Mashu are 55–75 wt.% and 0.4–0.7 wt.%, respectively (Hasegawa et al., 2009). Similarly, bulk-rock samples of Kutcharo pumice contain 62–75 wt.% SiO_2 and 1–2 wt.% K_2O, whereas the equivalent values for Mashu are 55–70 wt.% and 0.4–0.7 wt.%, respectively (Sumita-Sone, 1993).

The pumices from Kutcharo and Mashu contain phenocrysts of plagioclase (PL), orthopyroxene (OPX), clinopyroxene (CPX), magnetite, and trace amounts of ilmenite (FETI) and olivine (OL). Scoria and pumice from Mashu contain fewer phenocrysts than those from Kutcharo, typically less than 10 wt.% (Hasegawa et al., 2009). Olivine is abundant at Mashu (Sumita-Sone, 1993; Hasegawa et al., 2009) relative to Kutcharo. The existence of non-equilibrium phenocrysts (e.g., forsterite-rich OL and anorthite-rich PL) in post-caldera felsic eruptive products indicates the occurrence of magma mixing immediately prior to eruption (Sumita-Sone, 1993). All of the known tephras from Kutcharo and Mashu for the period 35–12 ka lack phenocrysts of hornblende (HB) or quartz (QZ) (Sumita-Sone, 1993; Hasegawa and Nakagawa, 2007; Hasegawa et al., 2009).

3. Sampling and analytical procedures

Table 2 lists the sample locations and provides a brief description of the samples. We used an improved sample selection procedure (Miyagi and Matsubaya, 2003) to avoid collecting samples that may have lost volatile elements from MIs as a result of degassing during

Table 2
Description of samples analyzed in the present study.

ID	Volcano	Horison	Occurrence	Sampling Location (N, E)
h-E	Mashu	Ma-b	A	43°33′05.6″, 145°00′19.3″
h-F	Mashu	Ma-b	A	43°33′05.6″, 145°00′19.3″
h-D	Mashu	Ma-b	A	43°33′05.6″, 145°00′19.3″
h-C	Mashu	Ma-b	A	43°33′05.6″, 145°00′19.3″
i-B	Kutcharo	KP I	B	43°46′35.3″, 144°25′57.9″
e-A	Kutcharo	KP I	C	43°51′09.1″, 144°38′28.7″
e-D	Kutcharo	KP I	B	43°51′09.1″, 144°38′28.7″
i-D	Kutcharo	KP IV	C	43°46′35.3″, 144°25′57.9″

Brief description of occurrence: A: Phreatomagmatic fall, B: Ash fall with pisolite, C: Bottom of pyroclastic flow deposit.