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Temporal variations in volumetric magma eruption rates of Quaternary volcanoes in Japan

Takahiro Yamamoto[*], Takashi Kudo and Osamu Isizuka

Abstract

Long-term evaluations of hazard and risk related to volcanoes rely on extrapolations from volcano histories, including the uniformity of their eruption rates. We calculated volumetric magma eruption rates, compiled from quantitative eruption histories of 29 Japanese Quaternary volcanoes, and analyzed them with respect to durations spanning 10^1–10^5 years. Calculated eruption rates vary greatly (10^1–10^{-4} km³ dense-rock equivalent/1000 years) between individual volcanoes. Although large basaltic stratovolcanoes tend to have high eruption rates and relatively constant repose intervals, these cases are not representative of the various types of volcanoes in Japan. At many Japanese volcanoes, eruption rates are not constant through time, but increase, decrease, or fluctuate. Therefore, it is important to predict whether eruption rates will increase or decrease for long-term risk assessment. Several temporal co-variations of eruption rate and magmatic evolution suggest that there are connections between them. In some cases, magma supply rates increased in response to changing magma-generation processes. On the other hand, stable plumbing systems without marked changes in magma composition show decreasing eruption rates through time.

Keywords: Eruption rate, Magma-discharge step diagram, Quaternary volcano, Japan

Introduction

Quantitative evaluation of eruptive histories is key to our understanding of volcanism and attempts to predict volcanic activity. Especially important are rates of magma generation and eruption, which are key factors affecting the petrological and geochemical evolution of magma bodies and eruptive styles due to the intrinsic coupling between magma recharge, fractional crystallization, melting of crustal rocks, and volatile saturation in the melt (Spera et al. 1982; Shaw 1985; Annen et al. 2006). Although global compilations of time-averaged volumetric eruption rates reveal long-term patterns of magmatism and volcanism (Crisp 1984; Wadge 1984; White et al. 2006), eruption rates at individual volcanoes vary widely. Some active volcanoes erupt repeatedly at intervals of 10^1–10^3 years, such that the cumulative erupted volume increases linearly with time (Nakamura 1964;

Wadge 1982; King 1989). However, most composite volcanoes are characterized by brief periods of intense activity followed by repose periods that span significant portions of their lifetimes (Davidson and de Silva 2000; Hora et al. 2007; Klemetti and Grunder 2007).

External hazards (including volcanic eruptions) and their associated risks are increasingly recognized as important for nuclear power plant safety. After the 2011 Fukushima Daiichi Nuclear Power Plant accident, the Nuclear Regulation Authority of Japan revised its regulatory requirements and developed the Evaluation Guide for Volcanic Hazards in 2013. This guide requires the evaluation of volcanic risks over several decades, corresponding to the typical operational period of nuclear power plants. It is possible to extrapolate from the quantitative eruption histories of nearby volcanoes, based on geological records, and forecast likely volcanic events. However, the guide provides no explicit criteria for extrapolation. Additionally, our knowledge of complex volcanic processes is insufficient for long-term eruption forecasting at individual volcanoes. Therefore, we must

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accumulate quantitative eruption histories, analyze their patterns, and set criteria for evaluation of volcanic hazards likely to affect nuclear power plants.

According to the Nuclear Regulation Authority guide, an application for the Sendai nuclear power plant by the electric company showed a cyclic recurrence of caldera-forming eruptions since 0.6 Ma, using a compound diagram of cumulative eruption volumes versus time for some caldera volcanoes of southern Kyushu Island. However, Koyama (2015) claimed that the evaluation method is arbitrary, because the eruption cycles cannot be extrapolated uniformly across the different volcanoes. Similar diagrams since 2 Ma for Yellowstone caldera (Christiansen 1984) and the Taupo Volcanic Zone (Houghton et al. 1995) did not demonstrate such cyclicity for those caldera-forming eruptions, whereas flare-ups of caldera-forming eruptions have occurred at intervals of several million years in other volcanic fields (Salisbury et al. 2011; Yamamoto 2011). Eruption rates averaged over a volcano's lifetime (Crisp 1984; Tomiya 1991; White et al. 2006) do not necessarily permit the forecasting of volcanic activity by simple extrapolation of these mean values. It is important to better understand the evolution of eruption rates through time and their controlling factors.

Eruption rates of Quaternary volcanoes

Yamamoto (2015) compiled quantitative eruption histories of 56 major Japanese volcanoes over the last several hundred thousand years, plotting cumulative eruption volume versus time (magma-discharge step diagram; Koyama and Yoshida 1994); dense-rock equivalent (DRE) volumes were calculated from erupted volumes, and eruptive ages were recalibrated to calendar dates. Furthermore, Yamamoto (2015) analyzed and reported data quality and dataset reliability. In this study, we calculated volumetric magma eruption rates using 29 well-documented examples (Fig. 1) from Yamamoto (2015). Except for the Izu-Tobu monogenetic volcanoes, the others are composite volcanoes from basalt to rhyolite in composition; some volcanoes include caldera-forming events.

For long-term evaluation, it is necessary to examine the uniformity of eruption rates, as that is the premise of extrapolation based on eruption histories. Thus, we compared eruption rates at different time scales. Because uncertainties in eruption ages and volumes increase with age of the eruptive products, it is difficult to compare the eruption rates of poorly preserved, older eruptions to recent eruptions occurring over a similar time interval. Therefore, we defined the duration as the time when it dated back to from last eruption event, and plotted it on a logarithmic scale to indicate average magma eruption rates as a function of the duration spanning 10^1–10^5 years

(Fig. 2). The maximum durations of the volcanoes are almost equivalent to their lifetimes, such that their average eruption rates are nearly the same values estimated by Tomiya (1991). On the other hand, the minimum durations of the volcanoes include at least two recent magmatic eruption events. Thus, there is a tendency for volcanoes characterized by short minimum durations to show high eruption rates, and those with the long minimum durations to show low eruption rates.
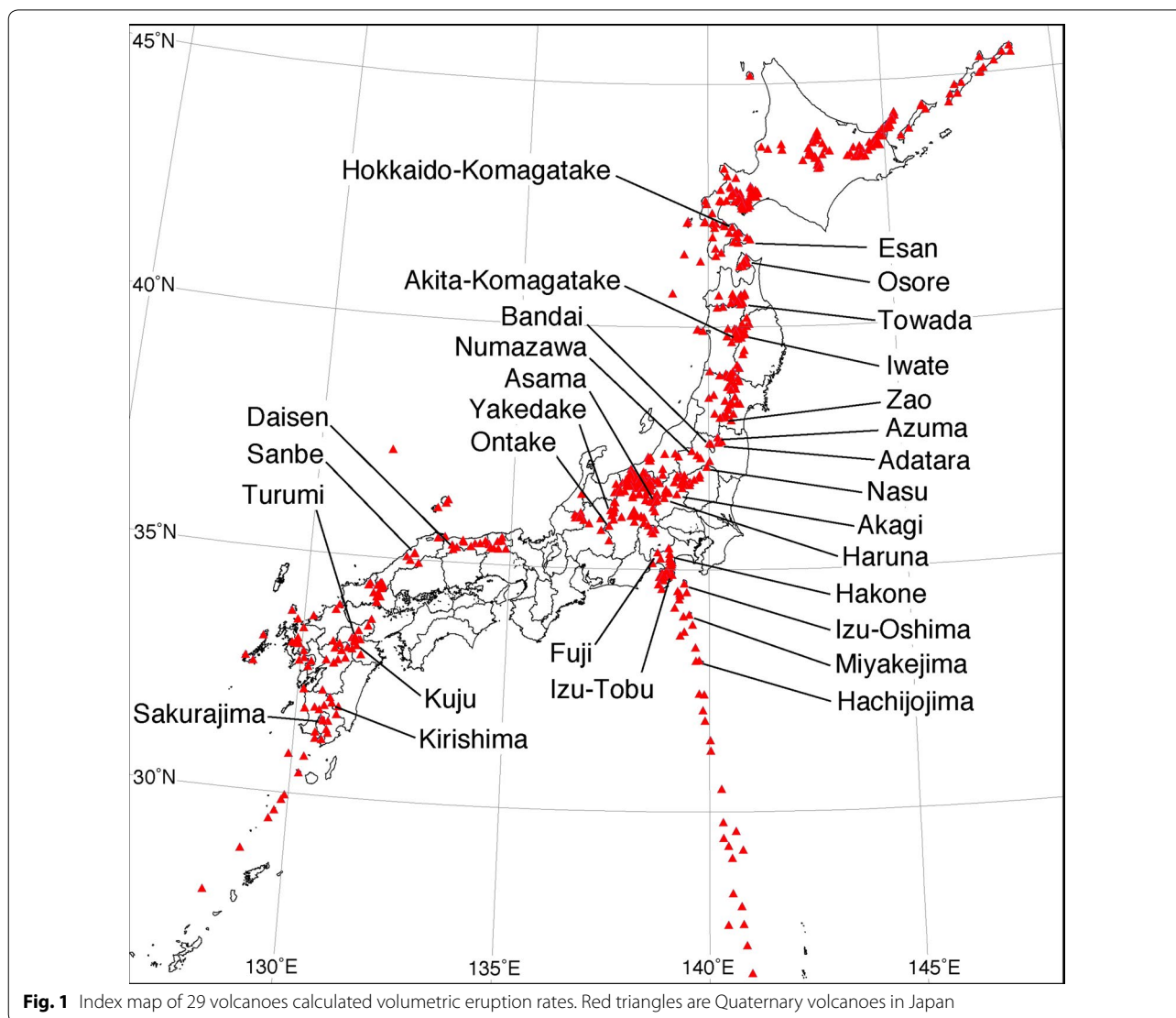
Calculated magma eruption rates show various patterns, and they differ widely between volcanoes and durations. The eruption rate of Sakurajima, the most active volcano in Japan, is 1–10 km^3 DRE/1000 years, a typical value for long-term eruptions of basaltic to andesitic volcanoes in the world (White et al. 2006). On the other hand, at certain durations its eruption rates are as small as 10^{-4} km^3 DRE/1000 years. In terms of temporal variations, Fuji, Izu-Oshima, and Miyake, all large basaltic stratovolcanoes of the Izu-Mariana-Bonin arc, are characterized by high eruption rates that do not strongly depend on durations. At other volcanoes, eruption rates are not constant at different durations, with rates, rising, dropping, or repeating both by at least an order of magnitude. Although Nakamura (1964) showed that constant eruption rates are typical at Izu-Oshima volcano, this is an uncommon case in Japanese arcs. Such changes of eruption rates are important for the evaluation of future volcanic activity, because it is necessary to forecast the change in eruption rate. In other words, the likelihood that the eruption rate will increase or decrease in the future must be reflected in the long-term evaluation.

Relationship between eruption rate and magmatic evolution

In general, magma composition changes with volcano growth, as does eruption rate. It is therefore necessary to understand how magmatic processes differ during increasing and decreasing rates of eruption. We present several well-documented examples of temporal changes in magma composition for cases of both decreasing and increasing eruption rate.

Increasing case 1: Sakurajima Volcano

Sakurajima (Fig. 1) is a post-caldera composite volcano of Aira caldera, formed by the 30 ka catastrophic Ito pyroclastic flow eruption (Aramaki 1984). Sakurajima average eruption rates increased dramatically at repose intervals of 100–10,000 years (Fig. 2). Eruptive products are medium-K andesite to dacite and consist of the Older and Younger Kitadake and Older and Younger Minamidake stages. The Older and Younger Kitadake stages are separated by a quiescence of about 11,000 years (Kobayashi et al. 2013). The dipping pattern of the eruption

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Fig. 1 Index map of 29 volcanoes calculated volumetric eruption rates. Red triangles are Quaternary volcanoes in Japan
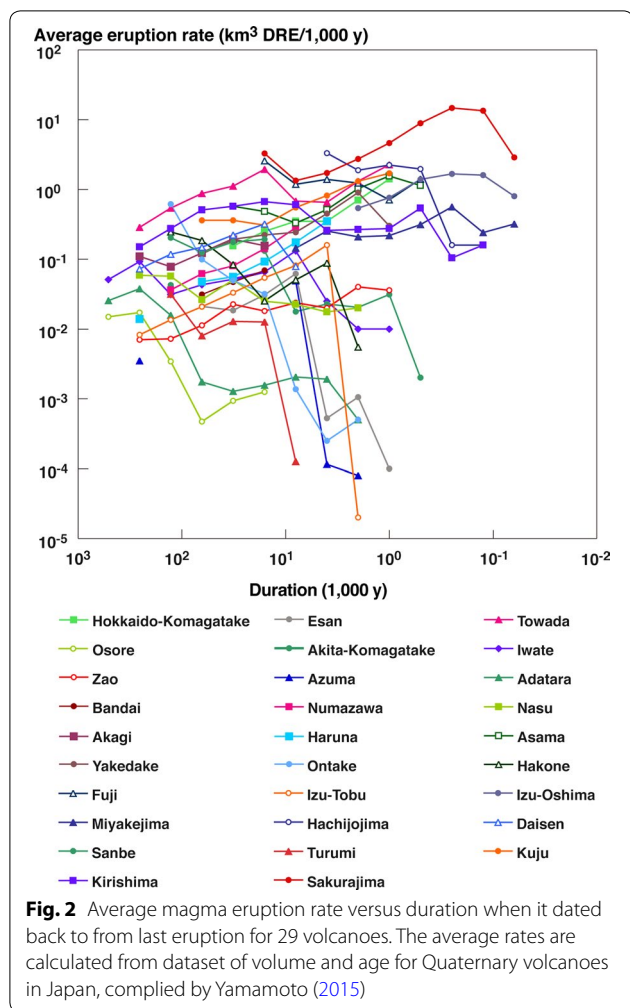
rate around 10,000 years in duration (Fig. 2) is corresponding to this quiescence. After the largest eruption (P14) occurred at 12.8 ka (the beginning of the Younger Kitadake stage), the cumulative eruption volume rapidly increased during the Older and Younger Minamidake stages (Fig. 3). During each eruptive stage, the chemical composition of the eruptive products has changed (Uto et al. 2005; Takahashi et al. 2011, 2013). For example, Zr/Th ratios have increased since about 4.5 ka, and $^{87}Sr/^{86}Sr$ ratios have decreased gradually since the Ito eruption (Fig. 4; Uto et al. 2005). These trends, and high Zr/Th and low $^{87}Sr/^{86}Sr$ in mafic inclusions, suggest mafic magma recharge to the Aira caldera magma chamber and mixing with crustal-derived felsic magma. The marked increase in eruption rate and the change of magmatic compositions have simultaneously occurred during the present

Younger Minamidake stage (Figs. 3, 4). This relationship may present that the supply of mafic magma from the mantle has increased with time.

**Increasing case 2: Numazawa Volcano**

Numazawa (Fig. 1) is a small caldera volcano in the Northeast Japan back-arc. Eruptions at Numazawa began at 110 ka, and increased in eruption rate until the caldera-forming eruption at 4.6 ka (Fig. 5; Yamamoto 2003). Eruptive products decrease in SiO_2 content from rhyolite to dacite and show homogeneous Sr isotopic ratios (Fig. 6). Based on trace-element abundances, this trend is plausibly caused by increasing degrees of batch partial melting at a constant bulk distribution coefficient (Yamamoto 2011). Thus, the compositional variation through time indicates that the increase in eruption rate directly

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Fig. 2 Average magma eruption rate versus duration when it dated back to from last eruption for 29 volcanoes. The average rates are calculated from dataset of volume and age for Quaternary volcanoes in Japan, complied by Yamamoto (2015)

Fig. 3 Cumulative magma volume erupted from Sakurajima Volcano. A red solid line represents an eruption event. A pink square shows the ranges of volume and age for a volcanic edifice which is undivided into separate eruption events. P14 is the Sakurajima-Satsuma tephra, which occurred at the beginning of Younger Kitadake stage after a long repose (Kobayashi et al. 2013). The eruption rate is apparently increasing in the recent Younger Minamidake stage

reflects the magma production rate. Furthermore, increasingly depletion of middle and heavy rare earth elements (REEs) with time suggest progressive amphibole fractionation during partial melting of lower-crustal materials (Fig. 7); it is thus likely that repeated intrusions of mantle-derived melts have gradually increased the temperature of the cooled lower crust since 110 ka.

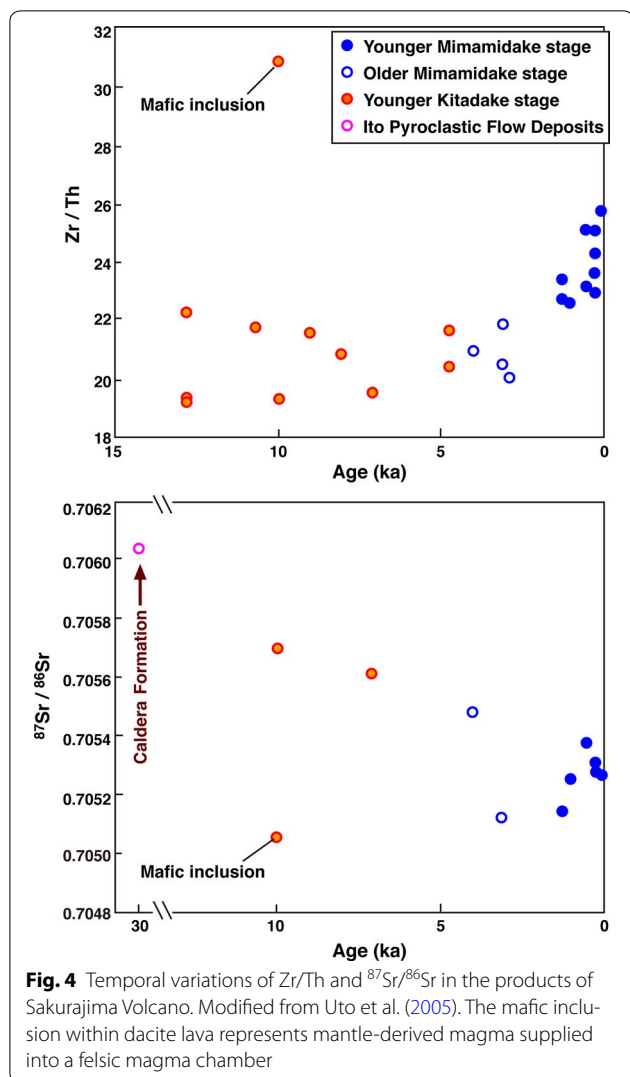### Increasing case 3: Akagi Volcano

Akagi is a large composite volcano in the volcanic front of the Northeast Japan arc (Fig. 1). The eruptive history of Akagi comprises the volcanic cone-building stage (ca. 220–150 ka) that erupted voluminous low- to medium-K basaltic andesite to andesite lava flows, the pumice-eruption stage (ca. 150–44 ka) that produced many medium-K andesite to dacite pumice falls and pumice flows, and the post-caldera stage (44–30 ka) that effused medium-K rhyolite lava domes (Moriya 1970; Takahashi et al. 2012). After the volcanic cone-building stage at a high magma-discharge rate, the eruption rate declined until the
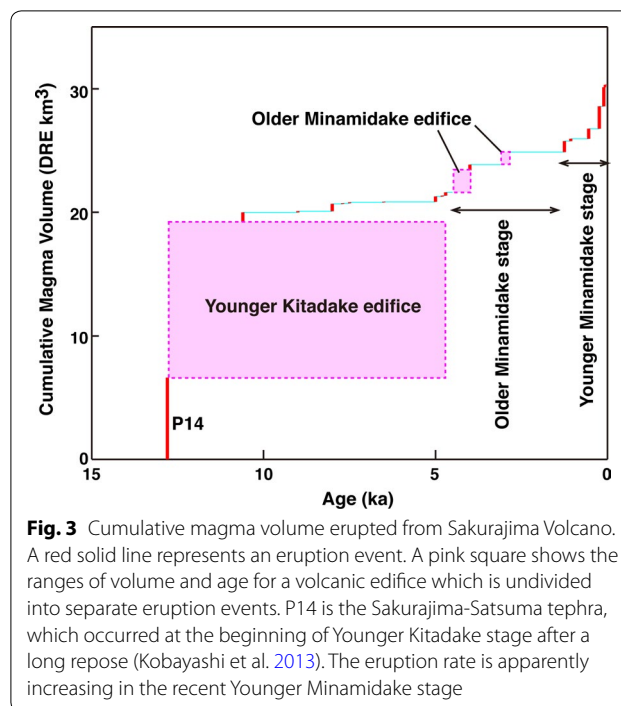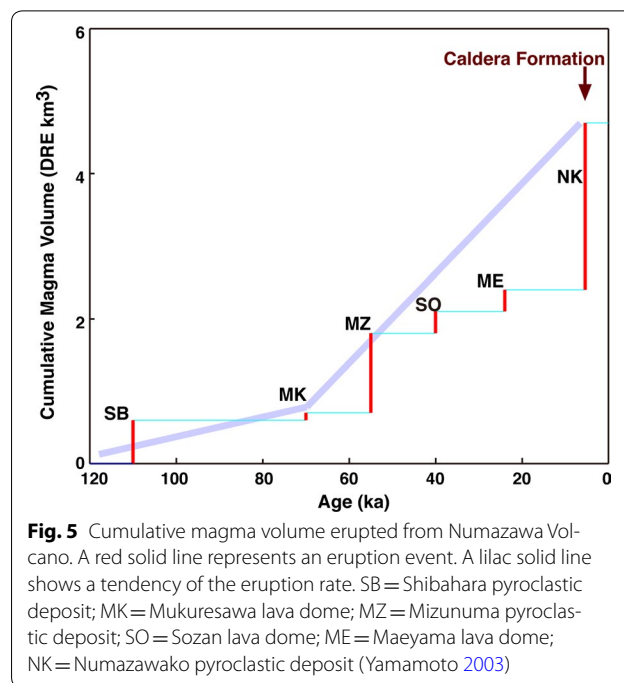
vigorous pumice-eruption sub-stage (P3 in Fig. 8; Yamamoto 2016). Trace-element abundances and Sr–Nd–Pb isotopes suggest that Akagi magmatism is characterized by interactions between mantle-derived magma and lower-crustal materials (with amphibole fractionation; Kobayashi and Nakamura 2001). Felsic magmas erupted during the pumice-eruption stage are more depleted in middle to heavy REEs than magmas erupted during the cone-building stage, suggesting amphibole fractionation and/or a greater crustal melt contribution during the pumice-eruption stage (Fig. 9). Decreases in the K contents of magmas erupted at the beginning of sub-stages P1, P2, and P3 indicate the repeated injection of voluminous mantle-derived magma into the lower crust (Fig. 10, Yamamoto 2016) and correspond to increased eruption rates (Fig. 8). Post-caldera lava domes, the most recent eruptive products of Akagi, are the most felsic but the most isotopically depleted (Kobayashi and Nakamura 2001), suggesting that production of mantle-derived magmas decreased, and they no longer interacted with crustal materials.

Increasing case 4: Towada Volcano

Towada is an active caldera volcano in the northern part of the Northeast Japan arc. Eruptive products are low-K basaltic andesite, andesite, dacite, and rhyolite (Hunter and Blake 1995). Hunter and Blake (1995) attributed the compositional evolution of Towada magmas to combined assimilation and fractional crystallization. The eruptive

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Fig. 4 Temporal variations of Zr/Th and $^{87}Sr/^{86}Sr$ in the products of Sakurajima Volcano. Modified from Uto et al. (2005). The mafic inclusion within dacite lava represents mantle-derived magma supplied into a felsic magma chamber

Fig. 5 Cumulative magma volume erupted from Numazawa Volcano. A red solid line represents an eruption event. A lilac solid line shows a tendency of the eruption rate. SB = Shibahara pyroclastic deposit; MK = Mukuresawa lava dome; MZ = Mizunuma pyroclastic deposit; SO = Sozan lava dome; ME = Maeyama lava dome; NK = Numazawako pyroclastic deposit (Yamamoto 2003)

Numazawa and Akagi volcanoes (Fig. 13). The increased eruption rate of Towada is also linked to crustal assimilation and fractional crystallization crystallization relating to amphibole.

Decreasing case 1: Nasu-Chausudake Volcano

Chausudake, the youngest edifice of the Nasu Volcano group, is on the volcanic front of the NE Japan arc (Fig. 1). Six magmatic units (CH1–6) of medium-K andesite have been emplaced as Vulcanian fallouts, block-and-ash flows, and lava flows: CH1 (19 ka) is the first and largest unit, and subsequent units decrease in volume (Fig. 14; Yamamoto 1997). Whole-rock compositions of CH1–6 increase linearly in SiO_2 content from 56.1 to 61.2 wt%, suggesting that the rocks derive from mixing between mafic and felsic end members; the mixing lines appear to be fixed throughout the entire eruptive history of Chausudake (Ban and Yamamoto 2002). The $^{87}Sr/^{86}Sr$ and Zr/Th ratios of the felsic rocks are constant in all units (Fig. 15), suggesting that the felsic end-member magma was produced through melting of lower-crustal materials at the time of formation of the magma-plumbing system. The mafic end-member magmas, represented by mafic inclusions of constant composition since 19 ka, might have repeatedly ascended from a large, homogeneous lower-crustal magma chamber (Ban and Yamamoto 2002). To summarize, no major change has occurred in the magma-plumbing system since eruptions began (unit CH1); the decreasing eruption rate at Chausudake may be a result of this stable system.
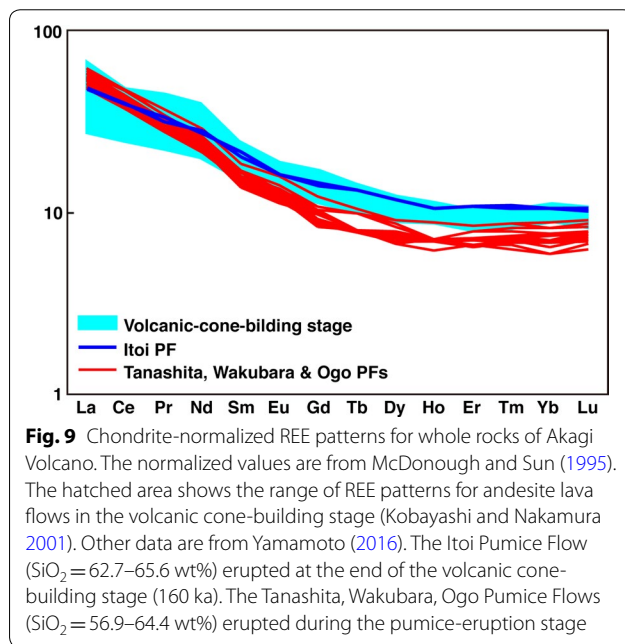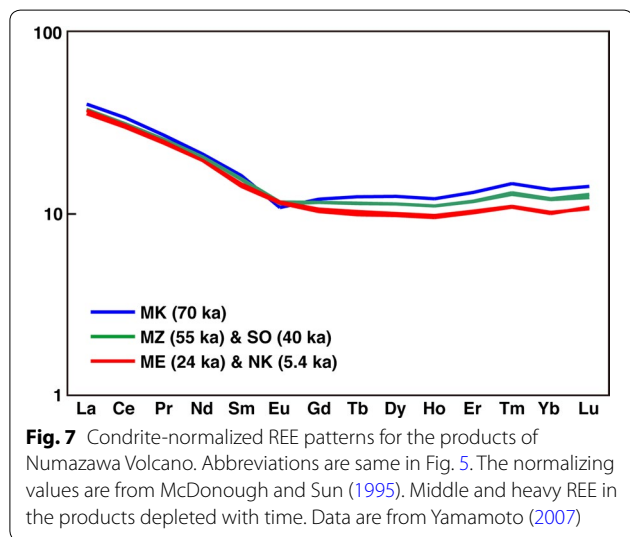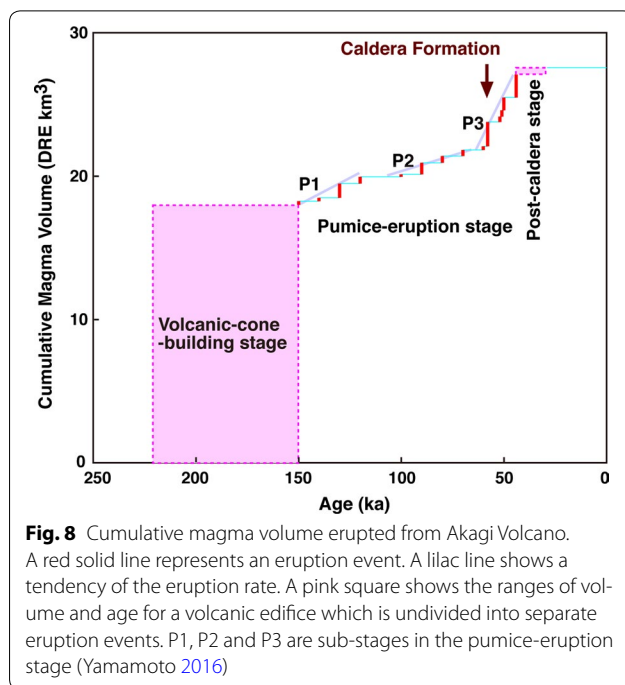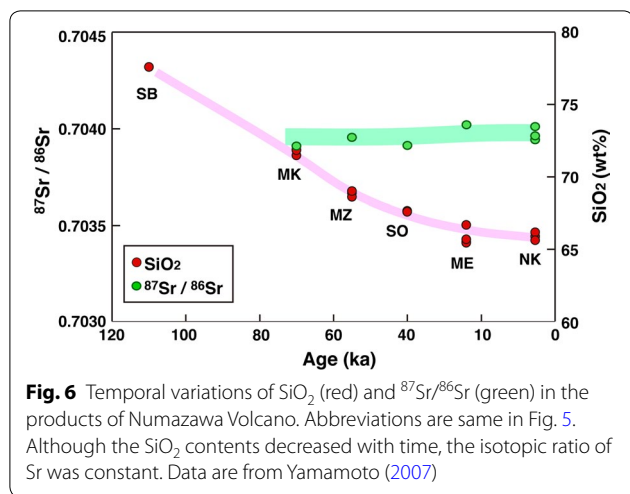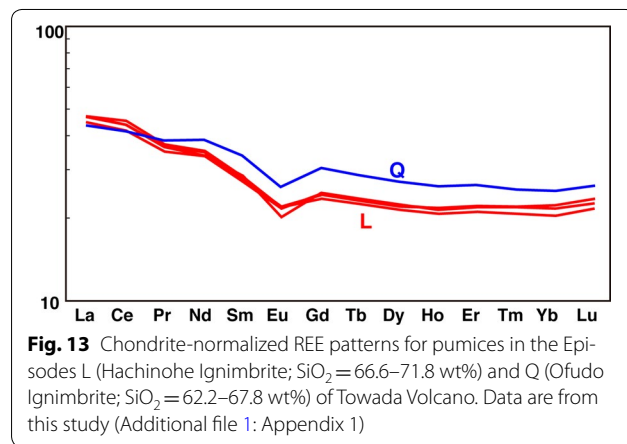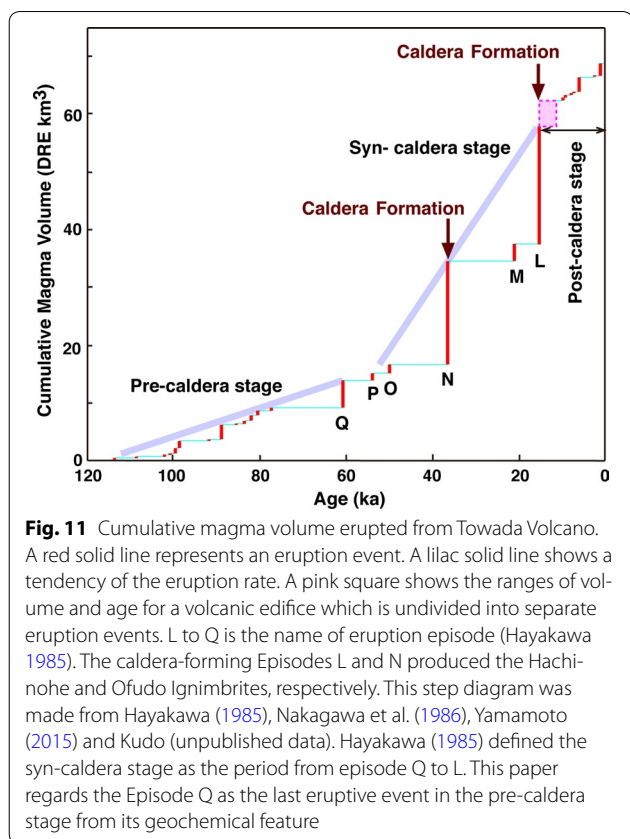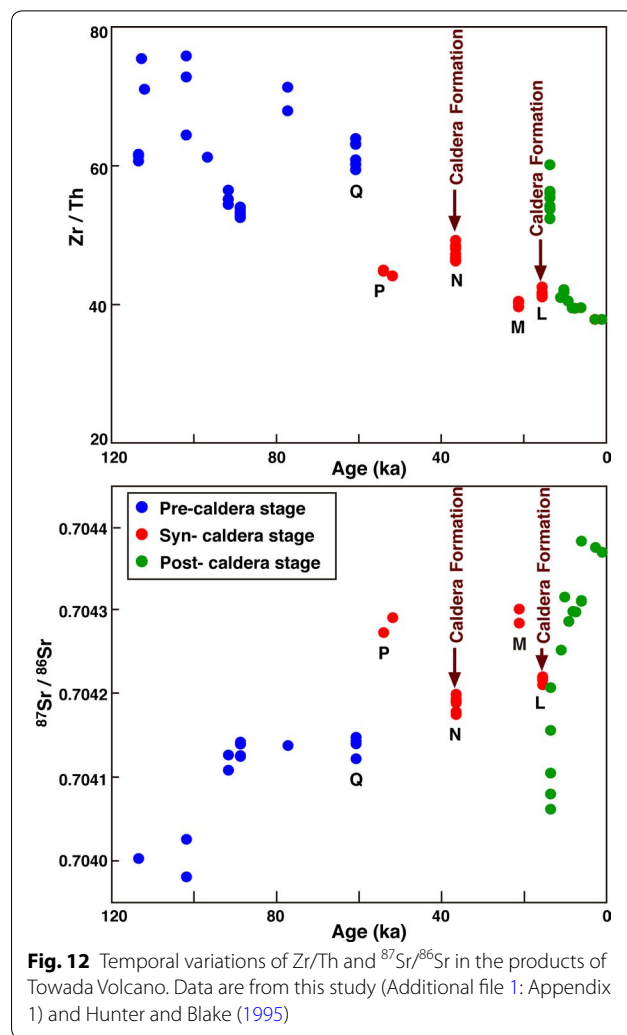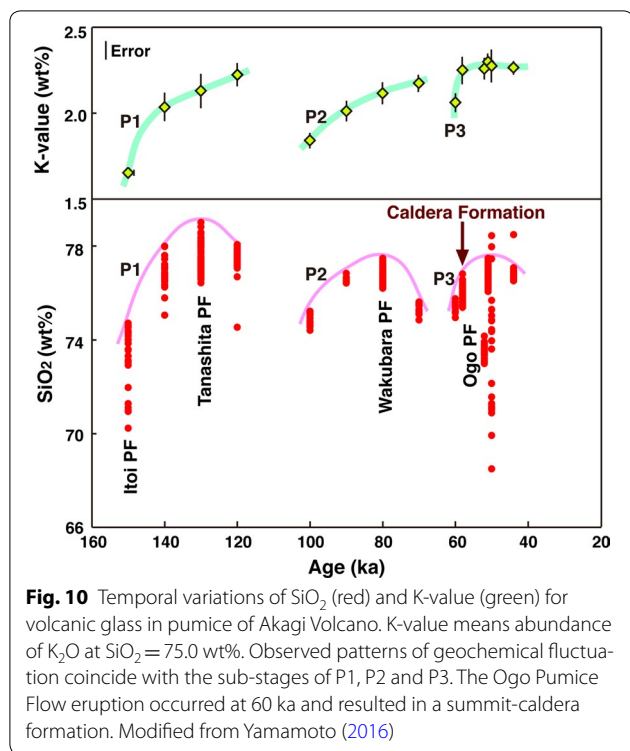
history of Towada is divided into pre-, syn-, and post-caldera stages (Hayakawa 1985); the large caldera-forming eruptions occurred during Episodes N (36 ka) and L (15.5 ka), which emplaced the Ofudo and Hachinohe Ignimbrites, respectively. Magma eruption rates increased during the syn-caldera stage (Fig. 11), associated with compositional changes of the eruptive products; Zr/Th decreased and $^{87}Sr/^{86}Sr$ increased from the pre- to syn-caldera stages (Fig. 12). We note that these compositional changes preceded the caldera-forming Episode N by tens of thousands of years. Zr/Th increased and $^{87}Sr/^{86}Sr$ decreased temporarily at the onset of post-caldera volcanism, recording transient eruptions of basaltic andesite and andesite magmas that experienced less crustal assimilation (Hunter and Blake, 1995). The caldera-forming felsic magmas are more depleted in middle and heavy REEs than pre-caldera felsic magmas, similar to the cases of

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Fig. 6 Temporal variations of SiO_2 (red) and $^{87}Sr/^{86}Sr$ (green) in the products of Numazawa Volcano. Abbreviations are same in Fig. 5. Although the SiO_2 contents decreased with time, the isotopic ratio of Sr was constant. Data are from Yamamoto (2007)

Fig. 8 Cumulative magma volume erupted from Akagi Volcano. A red solid line represents an eruption event. A lilac line shows a tendency of the eruption rate. A pink square shows the ranges of volume and age for a volcanic edifice which is undivided into separate eruption events. P1, P2 and P3 are sub-stages in the pumice-eruption stage (Yamamoto 2016)

Fig. 7 Condrite-normalized REE patterns for the products of Numazawa Volcano. Abbreviations are same in Fig. 5. The normalizing values are from McDonough and Sun (1995). Middle and heavy REE in the products depleted with time. Data are from Yamamoto (2007)

Fig. 9 Chondrite-normalized REE patterns for whole rocks of Akagi Volcano. The normalized values are from McDonough and Sun (1995). The hatched area shows the range of REE patterns for andesite lava flows in the volcanic cone-building stage (Kobayashi and Nakamura 2001). Other data are from Yamamoto (2016). The Itoi Pumice Flow ($SiO_2 = 62.7–65.6$ wt%) erupted at the end of the volcanic cone-building stage (160 ka). The Tanashita, Wakubara, Ogo Pumice Flows ($SiO_2 = 56.9–64.4$ wt%) erupted during the pumice-eruption stage
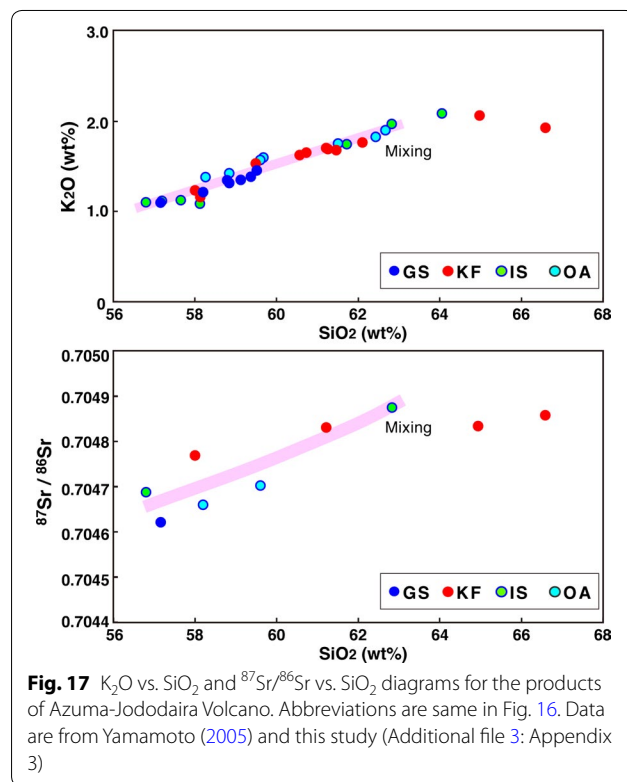
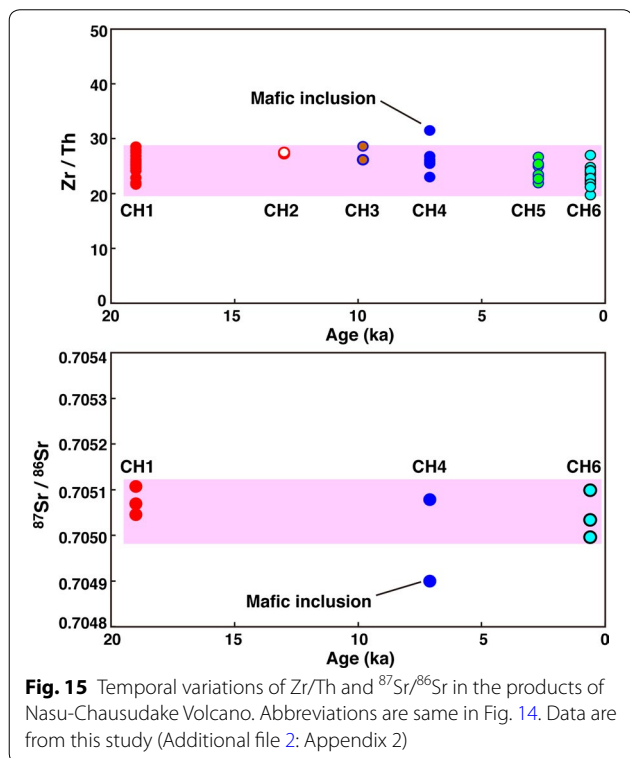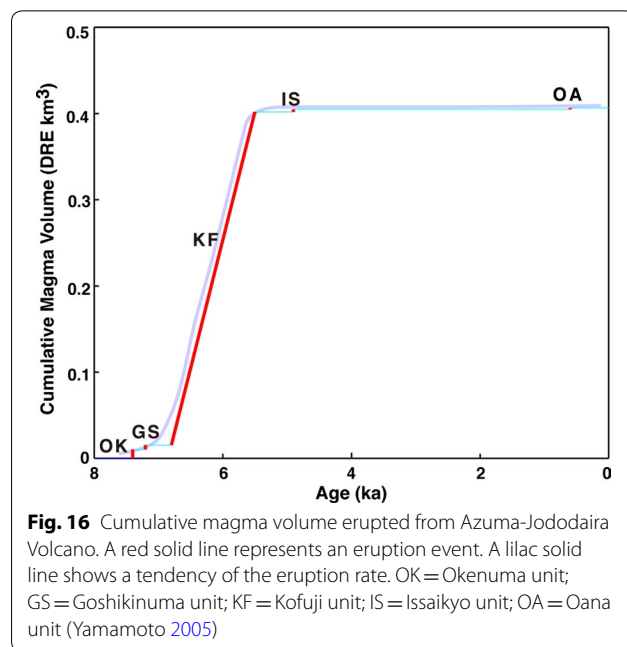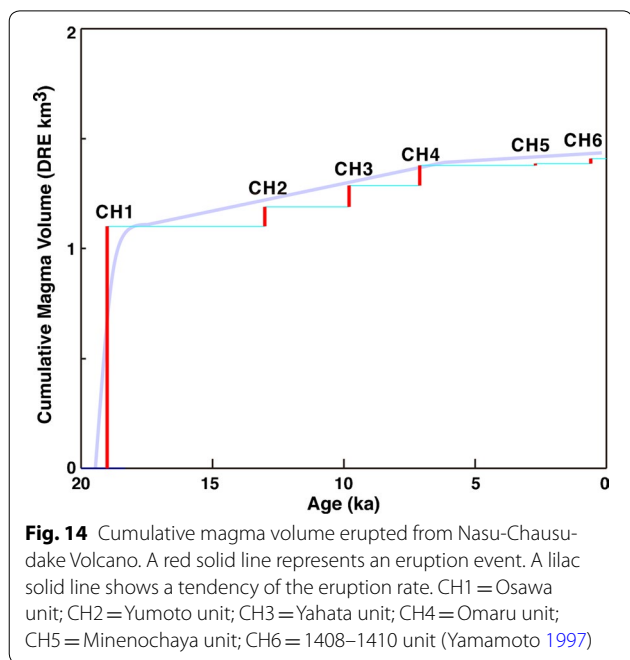## Decreasing case 2: Azuma-Jododaira Volcano

Jododaira is the youngest volcano of the Azuma Volcano group, on the volcanic front of the Northeast Japan arc (Fig. 1). Since eruptions began at 7.6 ka, Jododaira has produced five magmatic units comprising Vulcanian fallouts and lava flows (Fig. 16; Yamamoto 2005). The largest volume eruption was of the Kofuji unit between 6.8 and 5.5 ka, which produced a large pyroclastic cone (Azuma-Kofuji) and many associated lava flows; more than 95% of the total 0.4 km^3 DRE was erupted during this period. After the climactic Kofuji eruption, the eruption rate decreased greatly. Jododaira magmas are mainly medium-K andesites (56.8–61.5 wt% SiO_2), with some minor medium-K dacites (62.7–66.6 wt% SiO_2; Yamamoto 2005). Whole-rock compositions and $^{87}Sr/^{86}Sr$ ratios of andesite magmas of all units show a linear trend

in variation diagrams, suggesting that magmas derive from repeated mixing of the same mafic and felsic end members; dacitic magmas, however, are varied (Fig. 17). Overall, erupted magma compositions do not change drastically over the lifetime of the volcano.
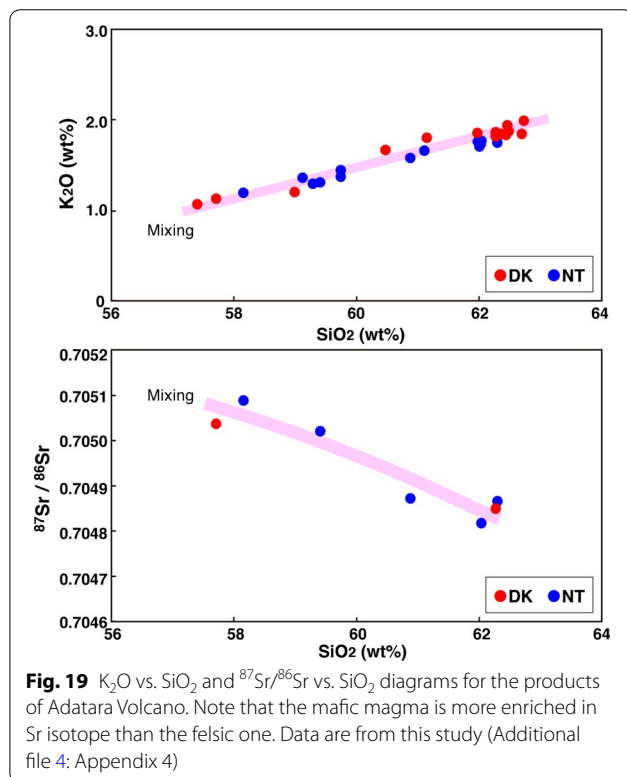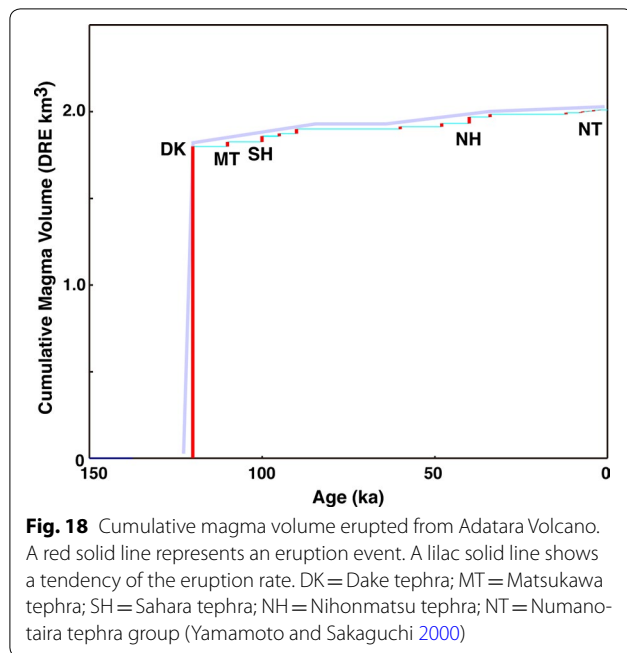
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Fig. 10 Temporal variations of SiO_2 (red) and K-value (green) for volcanic glass in pumice of Akagi Volcano. K-value means abundance of K_2O at $SiO_2 = 75.0$ wt%. Observed patterns of geochemical fluctuation coincide with the sub-stages of P1, P2 and P3. The Ogo Pumice Flow eruption occurred at 60 ka and resulted in a summit-caldera formation. Modified from Yamamoto (2016)

Fig. 11 Cumulative magma volume erupted from Towada Volcano. A red solid line represents an eruption event. A lilac solid line shows a tendency of the eruption rate. A pink square shows the ranges of volume and age for a volcanic edifice which is undivided into separate eruption events. L to Q is the name of eruption episode (Hayakawa 1985). The caldera-forming Episodes L and N produced the Hachinohe and Ofudo Ignimbrites, respectively. This step diagram was made from Hayakawa (1985), Nakagawa et al. (1986), Yamamoto (2015) and Kudo (unpublished data). Hayakawa (1985) defined the syn-caldera stage as the period from episode Q to L. This paper regards the Episode Q as the last eruptive event in the pre-caldera stage from its geochemical feature

Fig. 12 Temporal variations of Zr/Th and $^{87}Sr/^{86}Sr$ in the products of Towada Volcano. Data are from this study (Additional file 1: Appendix 1) and Hunter and Blake (1995)

Fig. 13 Chondrite-normalized REE patterns for pumices in the Episodes L (Hachinohe Ignimbrite; $SiO_2 = 66.6$–71.8 wt%) and Q (Ofudo Ignimbrite; $SiO_2 = 62.2$–67.8 wt%) of Towada Volcano. Data are from this study (Additional file 1: Appendix 1)

Decreasing case 3: Adatara Volcano

Adatara is a large composite volcano on the volcanic front of the Northeast Japan arc (Fig. 1). Most eruptive

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Fig. 14 Cumulative magma volume erupted from Nasu-Chausu-dake Volcano. A red solid line represents an eruption event. A lilac solid line shows a tendency of the eruption rate. CH1 = Osawa unit; CH2 = Yumoto unit; CH3 = Yahata unit; CH4 = Omaru unit; CH5 = Minenochaya unit; CH6 = 1408–1410 unit (Yamamoto 1997)

Fig. 16 Cumulative magma volume erupted from Azuma-Jododaira Volcano. A red solid line represents an eruption event. A lilac solid line shows a tendency of the eruption rate. OK = Okenuma unit; GS = Goshikinuma unit; KF = Kofuji unit; IS = Issaikyo unit; OA = Oana unit (Yamamoto 2005)

Fig. 15 Temporal variations of Zr/Th and $^{87}Sr/^{86}Sr$ in the products of Nasu-Chausudake Volcano. Abbreviations are same in Fig. 14. Data are from this study (Additional file 2: Appendix 2)

Fig. 17 K_2O vs. SiO_2 and $^{87}Sr/^{86}Sr$ vs. SiO_2 diagrams for the products of Azuma-Jododaira Volcano. Abbreviations are same in Fig. 16. Data are from Yamamoto (2005) and this study (Additional file 3: Appendix 3)

products are medium-K basaltic andesite to andesite (Fujinawa 1991). The young stage of activity began at 120 ka (after a long repose of ca. 80,000 years) with the eruption of the Dake tephra, which produced Plinian fall and pyroclastic flow deposits totaling 1.8 km^3 DRE (Fig. 18; Yamamoto and Sakaguchi 2000). After earlier eruptions of high-silica andesites (60.5–62.7 wt% SiO_2), the Dake and later eruptions produced intermediate-silica andesites (57.4–59.0 wt% SiO_2), reflecting renewal

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Fig. 18 Cumulative magma volume erupted from Adatara Volcano. A red solid line represents an eruption event. A lilac solid line shows a tendency of the eruption rate. DK = Dake tephra; MT = Matsukawa tephra; SH = Sahara tephra; NH = Nihonmatsu tephra; NT = Numanotaira tephra group (Yamamoto and Sakaguchi 2000)

Fig. 19 K_2O vs. SiO_2 and $^{87}Sr/^{86}Sr$ vs. SiO_2 diagrams for the products of Adatara Volcano. Note that the mafic magma is more enriched in Sr isotope than the felsic one. Data are from this study (Additional file 4: Appendix 4)

of the magma-plumbing system (Fujinawa and Kamata 2005). After the largest Dake eruption, sub-Plinian or Vulcanian eruptions produced pyroclastic units of 10^{-2}–10^{-1} km^3 DRE every 10,000–20,000 years. Since

10 ka, six Vulcanian eruptions, producing pyroclastic units of 10^{-3}–10^{-2} km^3 DRE (Numanotaira tephra group), occurred at intervals of 500–2000 years, recording a decreasing eruption rate since the Dake eruption (Fig. 18). Most ejecta of the Numanotaira tephra group comprise mingled andesite and dacite magmas showing the same linear compositional trends as the mafic and felsic magmas of the Dake eruption; the $^{87}Sr/^{86}Sr$ ratios of both end members are also almost the same as those of the Dake tephra (Fig. 19). Although there are no geochemical data on ejecta erupted between the Dake and Numanotaira tephra group due to heavy weathering, their petrographic features are similar to the Dake tephra (Yamamoto and Sakaguchi 2000). The decreasing eruption rate at Adatara is marked after the largest eruption, and the magma-plumbing system has established a long-term stability.

Discussion

Step diagrams of cumulative eruption volume versus time are useful tools for evaluating magma-discharge rates. Koyama and Yoshida (1994) classified step diagrams into four types: time-predictable, volume-predictable, strictly periodic, and non-predictable. Time- and volume-predictable cases, characterized by constant eruption rates, have been reported for active basaltic volcanoes with high eruption frequency such as Izu-Oshima (Nakamura 1964; Koyama and Hayakawa 1996), Kilauea and Mauna Loa (King 1989), and Etna (Wadge and Guest 1981; Hughes et al. 1990). In such cases, a uniform magma supply is maintained over a significant duration. However, the eruption rates of most Japanese arc volcanoes have fluctuated over their eruptive histories (Fig. 2). Thus, their eruption rates are sufficiently variable to preclude simple extrapolation from their eruptive histories. Such eruption rate fluctuations are significant for hazards evaluation since it is necessary to forecast changes to the eruption rate. It is thus necessary to understand how magmatic processes differ between volcanoes with increasing and decreasing eruption rates.

Several temporal correlations of eruption rate and magmatic evolution suggest that there exists some connection between them. Most notably, in many cases, the magma supply rate increased in response to changing magma dynamics. At Sakurajima, increased mafic magma supply during the Younger Minamidake stage is directly linked to the increased eruption rate (Figs. 3, 4). At Numazawa, Akagi, and Towada, increased crustal melting, caused by repeated intrusions of mafic magma, resulted in an increased eruption rate (and caldera formation); REE patterns in felsic magmas from these volcanoes (Figs. 7, 9, 13) suggest amphibole fractionation during crustal melting. This is consistent with the amphibolite or hornblende

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gabbro lower crust of northeast Honshu inferred by laboratory measurements of P-wave velocity and the seismic velocity structure (Nishimoto et al. 2005). Depletion of middle and heavy REEs in felsic magmas is common in island arc settings (Bachmann and Bergantz 2008) and suggests water-saturated melting of amphibolite in the lower crust (Beard and Lofgren 1991). Although amphibolite-sourced felsic magmas characterize volcanism in northeast Japan, different sources are dominant in other arcs; upper continental crust-like granitoids are the most plausible sources of the caldera-forming felsic magmas in Kyushu, including the Ito pyroclastic flow from Aira caldera (Kimura et al. 2015). Furthermore, Daisen volcano in southwest Japan (Fig. 1) produces slab-derived felsic (adakitic) products having peculiar geochemical features (Kimura et al. 2014). Eruption rates seem to reflect the complex interplay of magmatic processes at each volcano. It is therefore necessary to examine the different systems individually to understand geochemical changes with eruption rate increase.

Cases of decreasing eruption rates occur after periods of intense activity. At Nasu, Azuma, and Adatara, the largest eruptions were either the initial eruptions or those occurring after an extended period of repose, and subsequent erupted volumes decreased drastically (Figs. 14, 16, 18). In general, eruptions occur when an overpressure in the magma chamber reaches the fracture criterion of the chamber wall (Tait et al. 1989), except for huge magma chamber (Gregg et al. 2013; de Silva and Gregg 2014). After the establishment of a new eruptive conduit, the overpressure necessary for eruption becomes smaller for subsequent eruptions; major decreases in eruption volume are likely related to the lowered failure criterion. Despite repeated subsequent eruptions, the eruption rate decreased gradually in these cases (Figs. 14, 16, 18). Common to all cases of decreasing eruption rate is a well-established magma-plumbing system (stable for 10^3–10^5 years) that does not show significant compositional variations (Figs. 15, 17, 19). In the case of constant eruption rate volcanoes (Izu-Oshima and Miyakejima), magma compositions differed over 10–100 year intervals (Nakano and Yamamoto 1991; Amma-Miyasaka and Nakagawa 2003). We speculate that these high eruption rates are probably maintained by frequent replenishment by variably differentiated magmas from a parental source. Furthermore, magma recharge may also have sustained eruption rates at Nasu, Azuma, and Adatara, although the injection frequency and volume were probably too small to replace the initial magma chamber. As a result, the long-lived magma-plumbing system was preserved without any major changes to the erupted magma compositions.

Conclusion

We examined volumetric magma eruption rates compiled from 29 datasets of well-documented Japanese Quaternary volcanoes over the past 10^1–10^5 years. Average eruption rates are very different at each volcano and tend to change with evolving compositional or magma genesis parameters. Therefore, it is important to determine likely changes in eruption rate for long-term evaluation. Several temporal co-variations of eruption rate and magmatic evolution suggest that there are connections between them. Notably, magma supply rates at some volcanoes increased in response to changing magma-generation processes, including new/renewed supply of voluminous mafic magma batches and crustal melting. On the other hand, the long-term stability of a plumbing system (characterized by little change in erupted magma compositions) relates to decreasing eruption rates. However, the examination in this report is not sufficiently quantitative to determine evaluation criteria for volcanic risk assessments, and further work is necessary to quantify the geochemical evolution of the various magma systems reported herein.

Additional files

Additional file 1: Appendix 1. Geochemical data for Towada Volcano.

Additional file 2: Appendix 2. Geochemical data for Nasu Volcano.

Additional file 3: Appendix 3. Geochemical data for Azuma Volcano.

Additional file 4: Appendix 4. Geochemical data for Adatara Volcano.

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