Geochemistry of caldera-forming and resurgent magmas in the Pliocene Hiwada caldera, northeast Japan: An example of a monotonous intermediate system

Takahiro Yamamoto

Abstract

The 2.9-Ma Hotokezawa Ignimbrite, which was ejected from the Aizu caldera cluster in the northeast Japan arc, is a typical monotonous intermediate ignimbrite, with 40–50 vol% crystals and an eruptive volume of >140 km³ dense-rock equivalent. This ignimbrite filled Hiwada caldera and was deformed by post-caldera plutonic intrusions that formed a resurgent dome. The Hotokezawa Ignimbrite is a calc-alkaline, medium-K dacite to rhyolite with SiO₂ contents of 67.9–71.3 wt%, and has homogeneous trace-element abundances and Sr–Nd isotopic ratios. These geochemical features suggest that the Hotokezawa magma was formed by partial melting of amphibolitic crustal rocks. This crystal-rich magma did not appear during the post-caldera stage. Therefore, it is plausible that the chamber of eruptible magma was emptied by the caldera-forming eruption. In contrast, post-caldera plutonic rocks exhibit a variety of compositions and have a clear SiO₂ gap corresponding to the caldera-forming magma: the early pluton (tonalite) and later ones (quartz porphyry, granite porphyries, and granite) contain 62.0–66.6 and 71.2–76.5 wt% SiO₂, respectively. The tonalite and the Hotokezawa Ignimbrite form a continuous trend in their major-element variations. The Sr–Nd isotopic ratios of the ignimbrite and tonalite overlap, but those of the porphyries and granite are more enriched. The early tonalite represents the more basic part of the Hiwada caldera system that was held in small pockets separate from the main magma chamber, because its trace-element abundances are varied and distinct from those of the Hotokezawa Ignimbrite. The distinct compositional change from the Hotokezawa Ignimbrite to the late porphyries and granite indicates that the partial melting crust generating felsic magma was renewed by the subsequent intrusion of the mantle melts. The new felsic magma ascended through subsidence-related faults into the shallow caldera system and emplaced as laccoliths forming the resurgent dome.

KEYWORDS
arc magmatism, caldera, caldera resurgence, geochemistry, ignimbrite, northeast Japan
INTRODUCTION

Caldera-forming ignimbrite eruptions are the largest (by volume) eruptions and pose a serious threat to human livelihoods, as they can significantly affect the environment, both locally and globally (e.g., Self, 2015). As volcanoes and their eruptions are merely the surface manifestations of large-scale magmatic processes operating in the Earth’s interior, calderas provide key insights into the generation and evolution of large-volume magma bodies (Hildreth, 1981; Lipman, 1984; Smith, 1979). Volcanic processes are the culmination of a complex interaction of geological processes at regional, and local scales, and the study of volcanoes, including calderas, provides useful information on lithospheric dynamics. Among the various caldera-forming eruptions, the eruptions of large, homogeneous, crystal-rich dacitic ignimbrites such as the Fish Canyon Tuff, USA (Bachmann et al., 2002; Whitney & Stormer Jr., 1985) unambiguously document the presence of large, homogeneous zones of crystal-rich magmas in the upper crust. Such “monotonous intermediates” (Hildreth, 1981) are common in large felsic magma provinces in the Western USA (Best et al., 2016; Lipman, 2007; Lipman & Bachmann, 2015), and the Central Andes (de Silva et al., 2006; de Silva & Kay, 2018).

In the present-day Northeast Japan arc, caldera-forming felsic volcanism has flared up since the late Miocene (Ito et al., 1989; Sato, 1994; Yamamoto, 1992; Yoshida, 2001; Yoshida et al., 2014). This arc is located approximately 500 km west of the Japan Trench, where the Pacific plate is being subducted at a rate of approximately 10 cm per year; the arc crust there is 30–35 km thick. The main part of this arc became submerged as a result of thermal subsidence after the cessation of the Japan Sea opening during the middle Miocene (Sato & Amano, 1991), and uplift of the arc, accompanied by caldera formation, began at about 10 Ma (Sato, 1994; Yamamoto, 2009). The tectonic evolution of the arc since the Miocene flare-up has been documented by Acocella et al. (2008). Late Miocene to Quaternary caldera volcanoes are distributed along the arc in clusters 40–80 km apart (Figure 1). There are seven main caldera clusters: the Hakkoda (Kudo et al., 2007), Sengan (Suto, 1987), Kurikoma (Yamada, 1988), Akiu, Inawashiro (Yamamoto, 1994), Aizu (Yamamoto, 1992, 2011), and Minami–Aizu clusters (Yamaguchi, 1991) from north to south. Each cluster contains three to more than ten calderas and some active stratovolcanoes. Most calderas are >10 km in diameter, but some clusters also include smaller ones. These clusters correspond to “hot-fingers” in the mantle wedge (Tamura et al., 2002). These calderas erupted abundant ignimbrites, some of which are typical homogeneous, crystal-rich ignimbrites with >40 vol% crystals (plagioclase + quartz + mafic minerals); they are, for example, the 7.3-Ma Kinugawa–Komadotoge Ignimbrite of Minami–Aizu (Yamaguchi, 1991), the 2.9-Ma Hotoketsawa Ignimbrite of Aizu (Yamamoto, 1992), and the 2.0-Ma Tamagawa-R4 Ignimbrite of Sengan (Suto, 1987; Suzuki et al., 2019).

In this paper, I focus on the geological and petrological evolution of the Pliocene Hiwada caldera that fed the Hotoketsawa Ignimbrite. This caldera is associated with various plutonic rocks that intruded into a resurgent dome and a contemporaneous basaltic stratovolcano, the geochemical variations of which provide crucial clues for understanding the magmatic processes that produced this monotonous intermediate ignimbrite. Resurgence is the structural uplift of a caldera floor and represents one of the most dynamic periods during a caldera’s life cycle (Kennedy et al., 2012; Smith & Bailey, 1968). Herein, I link the caldera-forming eruption with magma replenishment and caldera resurgence.

GEOLOGICAL SETTING

The Aizu caldera cluster includes Iriyamazawa (7.1 Ma), Takagawa (6.4 Ma), Jonoirisawa (5.6 Ma), Uwaigusa (4.1 Ma), Hiwada (2.9 Ma), Ono (1.4 Ma), Tonohtsuri (1.3 Ma), Narioka (1.1 Ma), and Sunagohara (0.29 Ma) calderas; each of these are filled with voluminous deposits of caldera-forming ignimbrite intercalated with breccia sheets generated during caldera collapse. This sequence is capped by caldera-lake sediments (Yamamoto, 1992, 1999). The calderas are concentrated approximately WNW–ESE from the volcanic front to the back-arc in a 60 × 30 km area, which is topographically high terrain (800–1200 m elevation) corresponding to a region with a positive gravity anomaly (Figure 2; Yamamoto, 2011). The calderas developed on lower to middle Miocene marine rocks as a result of subaerial ignimbrite eruptions. Extra-caldera...
ignimbrites are interstratified with fluvial sediments in the intra-arc Aizu Basin, corresponding to a negative gravity anomaly north of the caldera cluster (Yamamoto, 2009). The crystal contents of the ignimbrites are 10–50 vol% on essential materials; the Hotokezawa, Kumado, and Nishigo ignimbrites in particular contain abundant crystals (Figure 3).

The activity of the Aizu caldera cluster, which is characterized by ~100–300 km$^3$ dense-rock equivalent (DRE) ignimbrite eruptions every 1–2 my since 7 Ma (~10$^2$ km$^3$/my) from a 60 × 30 km area, is typical of the northeast Japan arc (Yamamoto, 1992). The Shirakawa Ignimbrites erupted five times from 1.4 to 1.0 Ma at intervals of ~0.1 Myr; their short-term eruption rate is ~6 × 10$^2$ km$^3$/Myr (Figure 3; Yamamoto, 2011). However, this caldera-forming activity is below the level of the ignimbrite flareup (>10$^3$ km$^3$/Myr) at the Western USA and the Central Andes (Best et al., 2016; de Silva & Kay, 2018). Best et al. (2016) have claimed that thicker crust played two significant roles in the flareups: (1) adjustment of the thermal gradient after orogenic thickening led to elevated temperatures in the lower to middle crust; (2) ample fertile source rock was available to create voluminous silicic magmas, and the compositional profile of the crust governed the details of ignimbrite composition. In contrast, the present crustal thickness of the northeast Japan arc is up to 35 km (Nishimoto et al., 2005), which is thinner than the continental margin. Moreover, the caldera-forming volcanism in this arc started after the crustal thinning by the Early to Middle Miocene back-arc extension (Yoshida, 2001; Yoshida et al., 2014). The low eruption rate of ignimbrites may reflect such a difference in the tectonic setting.

Hiwada caldera (Hw in Figure 2) is an elliptical large depression measuring 18 × 10 km in the center of the Aizu caldera cluster. This caldera was formed by the eruption of the Hotokezawa Ignimbrite at about 2.9 Ma (Figure 4). The caldera is surrounded by middle Miocene volcanic and sedimentary rocks and is filled by this voluminous ignimbrite, overlying caldera-lake sediments, and intruding plutonic rocks;
these intra-caldera rocks constitute the Hiwada Formation (Figure 4; Yamamoto, 1992, 1999). The subsiding caldera floors are concealed beneath the intra-caldera strata. Furthermore, this caldera is characterized by a horst-like resurgent dome with local positive gravity anomalies. This resurgence took the form of a hinged uplift, in which central blocks of the intra-caldera ignimbrite whose welding foliations dip at less than 25° are bounded by northwest–southeast-trending faults with displacements of approximately 1000 m (Figure 4). The southern part of the dome is complexly divided by many small faults. Plutonic rocks are exposed along incised valleys within the uplifted blocks, which hold up the resurgent dome as laccoliths.

2.1 Extra-caldera Hotokezawa Ignimbrite

The extra-caldera sheet of the Hotokezawa Ignimbrite (Ht in Figure 2) is preserved in the Aizu intra-arc basin and in the adjacent late Miocene Iriyamazawa caldera (Ir in Figure 2). This ignimbrite is 100–200 m thick and unconformably covers basement rocks around Hiwada caldera. The rock consists of massive, densely to moderately welded tuff breccia and lapilli tuff containing abundant large (>20 cm diameter) fiamme, and lacks vertical compositional zoning. The ignimbrite grades northward into non-welded pumice lapilli tuff and is interbedded with fluvial sediments of the Izumi Formation in the Aizu Basin (Yamamoto, 2009). The volume of the extra-caldera ignimbrite is estimated to be approximately 40 km³ DRE for the remaining portion north and west of the caldera (Figure 3). There is no alteration in the extra-caldera ignimbrite. The K–Ar age of fresh fiamme was determined as 2.94 Ma ± 0.15 Ma, consistent with the paleomagnetic stratigraphy of the Izumi Formation (Yamamoto, 1992).

2.2 Syn-caldera deposits of the Hiwada Formation

These deposits consist of the intra-caldera Hotokezawa Ignimbrite and intercalated caldera-collapse breccias (Figure 4; Yamamoto, 1992, 1999). The thickness of the syn-caldera deposits exceeds 1000 m in the resurgent dome (Figure 5); the base of these deposits is not exposed. The volume of the ignimbrite is estimated to be more than...
100 km$^3$ DRE. The lower part of the ignimbrite is homogeneous, densely welded pumice and crystal-rich ash with a minor amount of accidental materials (Figure 6(a)). The upper part of the ignimbrite consists of weakly welded tuff breccia and lapilli tuff that includes abundant lithic fragments, and is intercalated with caldera-collapse breccia, which comprises poorly sorted “middle Miocene mudstone and volcanic rocks” debris derived from the caldera wall (Figure 6(b)). The entire intra-caldera ignimbrite has been affected by hydrothermal alteration; the intra-caldera one contains many mafic crystals that have been altered to chlorite and epidote. The K–Ar age of its chlorite-bearing welded groundmass was determined as 2.64 Ma ± 0.20 Ma; this age is relatively younger than that of the extra-caldera ignimbrite, although the error ranges overlap slightly (Yamamoto, 1992). And it presumably indicates the alteration age caused by post-caldera plutonic activities.

2.3 | Post-caldera deposits of the Hiwada Formation

Post-caldera lacustrine sediments are distributed in two units along the northeastern and southwestern margins of the caldera, and are cut by faults and folded on both sides of the resurgent horst-like blocks (Figure 4). The dips of the sediments range from about 20°–85° along the faults. These sediments have a total thickness of 350 m and are composed mainly of 10-cm- to 2-m-thick normally, reverse-to-normally, or non-graded pebbly sandstone and conglomerate, and parallel-laminated siltstone and fine-grained sandstone containing plant fossils. The coarse-grained sedimentary rocks contain abundant lithic fragments of the basement rocks surrounding the caldera, and represent debris flows from the caldera wall. The upper part of the lacustrine sediments in the southwestern margin of the caldera is rich in pumice, accompanied by rhyolite intrusive bodies. The presence of these rock types suggests post-caldera volcanism within the caldera.

2.4 | Post-caldera plutonic rocks of the Hiwada Formation

Various plutonic rocks (fine-grained tonalite, quartz porphyry, granite porphyry, and medium-grained granite) intruded to form laccoliths that uplifted and distorted the overlying syn-caldera deposits. The fine-grained tonalite was emplaced early at the northern and southern ends of the resurgent dome. This rock is dark gray in color and characterized by the presence of acicular hornblende. The tonalite bodies at both ends of the dome are underlain by quartz and granite porphyries (Figure 5), and are often veined and brecciated by these porphyries (Figure 6(c)), which include disaggregated tonalite blocks from a few centimeters to meters across at their margins (Figure 6(d)). These porphyries form complexes of small intrusive bodies with various phenocryst assemblages, some of which were emplaced as dikes along the caldera margins. The medium-grained granite crops out in the center of the resurgent dome, and represents the deepest portion of the intra-caldera succession (Figure 5). The existence of a local positive gravity anomaly at the center of the caldera (Figure 2) indicates that a large plutonic mass is hidden beneath the resurgent dome. Most plutonic rocks have been hydrothermally altered to various degrees.

2.5 | Hakaseyama Volcanic Rocks

This volcanic unit is a dissected small stratovolcano comprising basalt and basaltic andesite lava flows and pyroclastic rocks 5 km northwest of Hiwada caldera (Hakaseyama Collaborative Research Group, 1990; Hk in Figures 2 and 5). The unit has a maximum thickness of 300 m and directly overlies the extra-caldera Hotokezawa Ignimbrite. The numerous (>20) lava flows are 1–12 m thick with ‘a’a clinkers. The pyroclastic rocks are composed of splatter bombs and highly vesicular scoria lapilli. Total volume of this volcanic unit is about 2 km$^3$. Because there is no major unconformity within this unit, this stratovolcano presumably formed in a short period of time. The K–Ar
3 | PETROGRAPHY

3.1 | Hotokezawa Ignimbrite

The extra-caldera ignimbrite is non- to densely welded vitric-crystal tuff breccia and lapilli tuff (Figure 7(a)), and contains crystals of plagioclase (21%–22% in modal proportion), quartz (10%–12%), hornblende (~3%), hypersthene (~2%), augite (~1%), and opaque minerals (~1%), and a vitric groundmass (59%–62%). This rock exhibits no vertical petrographic changes. In contrast, the intra-caldera ignimbrite is weakly to densely welded vitric-crystal tuff breccia and lapilli tuff, and contains crystals of plagioclase (23%–26%), quartz (12%–15%), hornblende (~4%), hypersthene (~3%), augite (~2%), and opaque minerals (~1%), and a devitrified eutaxitic groundmass (50%–55%). The intra-caldera ignimbrite obviously contains abundant crystals. The extra-caldera ignimbrite erupted at an early stage prior to caldera collapse, whereas the intra-caldera one ponded during the collapse. The maximum sizes of plagioclase, quartz, hornblende, orthopyroxene, and clinopyroxene in both are 2.0, 4.2, 3.2, 1.2, and 0.8 mm, respectively. Plagioclase are very clear, and do not exhibit sieve textures. Most quartz are euhedral.

3.2 | Fine-grained tonalite

The post-caldera tonalite is dark gray and fine-grained. The phenocryst assemblage of this rock consists mainly of plagioclase and hornblende (Figure 7(b)). Quartz, biotite, and opaque minerals are ubiquitously present as accessory minerals, but K-feldspar is totally absent. Plagioclase are euhedral to subhedral, have a maximum size of 3 mm, and exhibit distinct zoning. Hornblende are tabular and euhedral to subhedral; their major axis has a maximum length of 4 mm. Quartz are anhedral and smaller than 0.6 mm. Biotite are subhedral to anhedral with a maximum grain size of 0.6 mm. The southern tonalite is more hydrothermally altered than the northern one; the southern rocks contain abundant sericite in plagioclase, chloritized biotite, and secondary epidotes.
3.3 Quartz porphyry and granite porphyry

The granite porphyry contains large phenocrysts of plagioclase and quartz in a microgranitic groundmass (Figure 7(c)). Plagioclase phenocrysts are 8 mm in maximum size and sieve textured. Quartz phenocrysts are embayed, with a maximum grain size of 6 mm. Some rocks contain hornblende and/or biotite phenocrysts. The groundmass is composed of quartz, plagioclase, hornblende, biotite, K-feldspar, opaque minerals, and a small amount of zircon; these grains are all less than 0.6 mm in size. The quartz porphyry contains more abundant quartz phenocrysts than the granite porphyry and lacks mafic phenocrysts. Most rocks contain some secondary minerals (sericite, chlorite, and epidote).

3.4 Medium-grained granite

The post-caldera granite contains quartz, plagioclase, K-feldspar, biotite, and hornblende. Zircon, apatite, and opaque minerals are ubiquitously present as accessory minerals. Quartz are anhedral and smaller than 10 mm. Plagioclase are euhedral to subhedral with a maximum length of 8 mm. K-feldspar occurs as perthites and microclines. Plagioclase and K-feldspar are altered to sericite. Biotite and hornblende are subhedral to anhedral and smaller than 4 mm; both mafic minerals are mostly chloritized.

3.5 Hakaseyama Volcanic Rocks

The Hakaseyama Volcanic Rocks consist of basalt and basaltic andesite, which are plagioclase and 10%-20% mafic phenocrysts (olivine, augite, hypersthenite, and magnetite) in an intergranular groundmass (Figure 7(d)). Plagioclase phenocrysts are mostly smaller than 3 mm and sieve textured, though some rocks contain 10-mm-long plagioclase. Olivine phenocrysts are always surrounded by augite reaction rims. Augite and hypersthenite phenocrysts are clustered with plagioclase as glomerophyres.
4 | ANALYTICAL METHODS

The samples analyzed in this study were fiamme of the welded Hotokezawa Ignimbrite, post-caldera plutonic rocks of the Hiwada Formation, and lava of the Hakaseyama Volcanic Rocks. Sample localities are provided in the supplement (Table S1). Whole-rock major element contents were analyzed by X-ray fluorescence of glass beads prepared by fusing 1:10 mixtures of 0.5-g subsamples and lithium tetraborate. Trace-element concentrations (i.e., rare-earth elements [REEs], V, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Ta, Th, and U) of selected whole-rock samples were analyzed by inductively coupled plasma mass spectrometry on a VG Platform instrument. Approximately 100 mg of powder from each sample was dissolved in a 5:1 HNO₃–HF mixture. The samples were evaporated completely, then dissolved in 2 ml of 2.5 N HNO₃. Sr and Nd isotopic analysis was performed on a Finningan MAT 261 8-collector mass spectrometer. During the period of work, the weighted average of 15 SRM-987 Sr-standard runs and 10 La Jolla Nd-standard runs yielded values of 0.710256 ± 0.000010 (2σ) for \(^{87}\text{Sr}/^{86}\text{Sr}\) and 0.511860 for \(^{143}\text{Nd}/^{144}\text{Nd}\), respectively.

Analytical data are provided in the supplement (Table S2).

5 | RESULTS

5.1 | Major-element concentrations

The extra- and intra-caldera Hotokezawa Ignimbrites are calc-alkaline, medium-K dacite to rhyolite with SiO₂ contents of 68.7–70.1 and 67.9–71.3 wt%, respectively (Figure 8(e),(f)). Their SiO₂ contents overlap, but the fiamme of the intra-caldera ignimbrite, which contains
more abundant crystals, has a greater range of SiO2 values; high-SiO2 samples are especially rich in quartz. In contrast, the post-caldera plutonic rocks have various compositions and a clear SiO2 gap: the early pluton (tonalite) and the later ones (quartz porphyry, granite porphyries, and granite) contain 62.0–66.6 and 71.2–76.5 wt% SiO2, respectively (Figure 8). The magma emplaced during post-caldera plutonic activity differed from that of the caldera-forming ignimbrite. With increasing SiO2 content, the Hotokezawa Ignimbrite and the tonalite form a continuous trend of decreasing Al2O3, Fe2O3, MgO, CaO, Na2O, and TiO2 concentrations and constant K2O concentrations (Figure 8(a)–(e)). On the other hand, the porphyries and granite differ from this trend on the Na2O–SiO2 and Ti2O–SiO2 diagrams (Figure 8(c),(d)); in particular, the quartz porphyry (SiO2 = 76.1–76.5 wt%) is clearly distinct from the other rock types. This feature is common to see at the highest SiO2 plutonic rocks, because minimum melt components can be considerable scatter. The adjacent Hakaseyama Volcanic Rocks are tholeiitic basalt to basaltic andesite (SiO2 = 50.9–53.5 wt %), on the boundary between low- and medium-K series (K2O = 0.4–0.6 wt%; Figure 8(e),(f)). With increasing SiO2 content, the volcanics show increasing Na2O, K2O, and TiO2 concentrations, constant Al2O3, and Fe2O3 concentrations, and decreasing MgO, and CaO concentrations (Figure 8(a)–(e)). The basaltics contain >6.0 wt% MgO (Figure 8(b)).

5.2 Trace-element concentrations

Primitive mantle-normalized trace-element patterns of all samples show typical features of Quaternary volcanic rocks (island-arc products) in northeast Japan (Kimura & Yoshida, 2006; Pearce & Parkinson, 1993; Zheng, 2019); specifically, the studied rocks are enriched in large-ion lithophile elements (Rb, Ba, Th, U, K, and Pb) and light REEs, and are strongly depleted in high-field-strength elements (Nb and Ta; Figure 9). The basalts of the Hakaseyama Volcanic Rocks have the most depleted REE abundances, with a spike of Sr and minor depletion in Zr–Hf (Figure 9(d)). On the other hand, the felsic rocks of Hiwada caldera have negative anomalies in Sr and Eu, suggesting a control by plagioclase fractionation. The samples of the Hotokezawa Ignimbrite exhibit relatively homogeneous trace-element abundances (Figure 9(a)). In contrast, the post-caldera tonalite can be divided into two groups based on the Rb and Y contents (Figures 9(b) and 10(a),(b)); high-Rb tonalite is locally present and mingled with low-Rb tonalite at Loc. 3, although the K2O content does not differ between two groups. Most of the tonalitic rocks have been hydrothermally altered to form sericite, and it is thought that some of the samples used in the analysis were probably heavily affected by this alteration. This is because Rb and Y elements tend to be concentrated in sericite, and high-Rb samples clearly show greater loss of ignition than low-Rb
ones. The low-Rb tonalite with low degree of alteration shows a distinctly different trend from The Hotokezawa Ignimbrite in the K/Rb-Rb diagram (Figure 10(c)); the K/Rb of the ignimbrite is constant, whereas that of low-Rb tonalite decreases with increasing Rb. Although the major elements of the ignimbrite and the tonalite show a continuous trend, the differences in this trace element abundances cannot be explained by the same crystal differentiation process. The porphyries and granite include various rocks with different REE patterns (Figure 9(c)). The basalt and basaltic andesite of the Hakaseyama Volcanic Rocks show decreasing K/Rb values with increasing Rb content (Figure 10(c)); this observed relationship cannot be explained by fractionation of olivine, pyroxene, plagioclase, and/or magnetite, suggesting that these characteristics result from mixing or assimilation. In the Zr–Sm diagram (Figure 10(d)), the Hakaseyama Volcanic Rocks are aligned along the trend of mantle melts of Quaternary volcanic rocks in northeast Japan (Zr/Sm = ~20; Kimura & Yoshida, 2006). In contrast, felsic rocks from Hiwada caldera depart from this trend.

5.3 | Isotopes

The 87Sr/86Sr values of the Hotokezawa Ignimbrite, the post-caldera tonalite, the post-caldera porphyries and granite, and the Hakaseyama Volcanic Rocks are 0.70423–0.70433, 0.70425–0.70435, 0.70442–0.70462, and 0.70381–0.70403, respectively, and their 143Nd/144Nd values are 0.51275–0.5128, 0.51275–0.51278, 0.51272–0.51273, and 0.51282–0.51287, respectively. These rocks all plot within the field of Quaternary volcanic rocks in northeast Japan (Kersting et al., 1996; Kimura & Yoshida, 2006; Figure 11(a)). The Sr and Nd isotopic ratios of the Hotokezawa Ignimbrite and the tonalite overlap, but those of the porphyries and granite are more enriched and those of the Hakaseyama Volcanic Rocks are more depleted than both (Figure 11(b)). The isotopic ratios of the Hotokezawa Ignimbrite and the tonalite are not correlated with SiO₂ and Zr contents and Rb/Sr ratio (Figure 12). These constant trends are the same as those observed in the Shirakawa Ignimbrites (Yamamoto, 2011), although the Sr and Nd isotopic compositions are distinct among these ignimbrites. In contrast, the Hakaseyama Volcanic Rocks show positive and negative linear trends in the 87Sr/86Sr and 143Nd/144Nd diagrams, respectively, suggesting mixing or crustal assimilation (Figure 12). However, its trends are not consistent with the mixing lines between the mantle melt and the ignimbrite felsic magmas.

6 | DISCUSSION

6.1 | Origins of mafic and felsic magmas related to the formation of Hiwada caldera

Kersting et al. (1996) and Kimura and Yoshida (2006) concluded that the large isotopic variations observed in Quaternary volcanic rocks of the northeast Japan arc (Figure 11(a)) indicate mixing between various crustal melts and a common mantle-derived basalt. Because there is no significant difference in tectonic and magmatic settings caused by the subduction of the Pacific plate between Pliocene and Quaternary volcanism in this arc (Yoshida, 2001; Yoshida et al., 2014), the petrogenesis related to the formation of Hiwada caldera can be explained.
by this Quaternary magmatic model. Although the trends for the Hakaseyama Volcanic Rocks in the $^{87}$Sr/$^{86}$Sr–$^{143}$Nd/$^{144}$Nd–SiO$_2$ and K/Rb–Rb diagrams indicate crustal assimilation (Figures 10c and 12), the less-radiogenic basalts of these rocks preserve mantle characteristics, even after modification, because their Sr and Nd isotopic ratios are close to model values for mantle melts (Figure 12; Kimura & Yoshida, 2006). In addition, their Zr–Hf depletions relative to Sm and strong Ba enrichment relative to Th (Figure 9(d)) are common in mantle-derived arc basalts (e.g., Kimura & Yoshida, 2006; Tatsumi & Eggins, 1995). Therefore, the Hakaseyama mafic volcanism (2.8 Ma) implies that the underplating of mantle-derived melts was associated with the activity of Hiwada caldera. On the other hand, its assimilation trend cannot be explained by the mixing of the mantle melt and the ignimbrite felsic magmas but requires a more basic crustal material in the end component (Figure 12). Mixing of the crustal and mantle-derived melts have been reported from many Quaternary calc-alkaline andesitic lava and pyroclastic rocks in the northeast Japan arc (e.g., Takahashi et al., 2013; Tatsumi et al., 2008). However, there are no andesitic products around Hiwada caldera, which is characterized by bimodal volcanic activity (Figure 8). Although the mantle-derived melts were heat sources that melted the crust, the produced crustal melts accumulated in different locations and did not actively mix with each other.

The caldera-forming felsic magmas in the northeast Japan arc, including the Aizu caldera cluster, are thought to have been formed by partial melting of amphibolitic crustal materials based on their isotopic compositions and trace-element patterns (Kimura et al., 2015; Yamamoto, 2007, 2011). The Hotokezawa Ignimbrite and post-caldera plutonic rocks have been reported from many Quaternary calc-alkaline andesitic lava and pyroclastic rocks in the northeast Japan arc (e.g., Takahashi et al., 2013; Tatsumi et al., 2008). However, there are no andesitic products around Hiwada caldera, which is characterized by bimodal volcanic activity (Figure 8). Although the mantle-derived melts were heat sources that melted the crust, the produced crustal melts accumulated in different locations and did not actively mix with each other.

The flat trends for these felsic rocks in the isotopic ratios with SiO$_2$ and Zr contents and Rb/Sr ratio indicate simple fractionation without mixing, and the distinct isotopic compositions of the ignimbrites from the Aizu caldera cluster represent independent crustal melts (Figure 12). This result implies that the lower crust was isotopically heterogeneous, and the ignimbrite sources were renewed with every caldera-forming eruption (Yamamoto, 2011). Comparison of P-wave velocity measurements of xenoliths with observations of seismic velocity structure indicates that the lower crust the northeast Japan arc is composed of amphibolite and/or hornblende gabbro (Nishimoto et al., 2005). And, melting of amphibolite or hornblende gabbro can produce an intermediate to silicic magma (e.g., Beard & Lofgren, 1991; Takahashi, 1986) and this seems to be a more viable explanation for the origin of the Hiwada magmas. The trace-element patterns of the Hotokezawa Ignimbrite and post-caldera plutonic rocks (Figure 9(a)–(c)) can be explained by the melting model for the amphibolite source with standard high-alumina basalt composition (Table S4), that was used by Yamamoto (2007) to calculate the compositional changes of felsic magma from Numazawa Volcano (Nm in Figure 2). Although their heavy REE abundances are slightly higher than the modeled value, the contents of the other elements are in very good match. The model composition for the source (JB-3 in Table S4) is also like that of the Hakaseyama basalt.

### 6.2 The Hotokezawa ignimbrite as a monotonous intermediate

Igнimbrites tend to be either chemically zoned and crystal-poor (“zoned ignimbrites”) or chemically homogeneous and crystal-rich (“monotonous intermediates” with ~ 50 vol% crystals: Hildreth, 1981). According to this distinction, the Hotokezawa, Kumado, and Nishigo...
ignimbrites of the Aizu caldera cluster are monotonous intermediates (Figure 3), although the typical ones in the San Juan region, Western USA (Lipman, 2007) are several to more than 10 times more voluminous than the Hotokezawa Ignimbrite. In general, the rhyolitic composition and high crystallinity of the interstitial melt phase makes monotonous intermediate magmas significantly more viscous than crystal-poor rhyolites (Christiansen, 2005). However, this difference also makes the chemical homogeneity of the monotonous intermediate magma rather puzzling, as the efficiency of convective stirring and homogenization should be inversely proportional to viscosity (Dufek & Bachmann, 2010; Huber et al., 2012). These paradoxically homogeneous, crystal-rich magma systems require (1) the growth of
large silicic reservoirs by incremental additions of compositionally sim-
ilar magmas and (2) a mush-forming stage induced by latent heat buff-
ering, leading to rapid thermal equilibration (Huber et al., 2009).

Hydrothermal experiments on monotonous intermediate magmas
demonstrated that crystal-rich magma that reach around 55 vol% cr-
ystals tend to settle in a petrological trap, with their physical and
chemical properties changing little as a result of cooling or new
magma injections over time as the system grows (Caricchi &
Blundy, 2015). In larger reservoirs, second boiling and recharge
(including buoyancy effects) acting in concert or independently lead
to roof uplift and extension, and eruptions are finally triggered by
downward propagating faults from the extended and weakened roof
(de Silva & Gregg, 2014). Decompression experiments reveal contra-
sting interactions between growing gas bubbles and the crystal frame-
work in crystal-rich magmas, and suggest that caldera-forming eruptions
of crystal-rich magmas are induced by caldera collapse, resulting in the rapid decompression of a largely over-pressurized chamber (Okumura et al., 2019).

6.3 Caldera-forming and resurgent magmas in Hiwada caldera

In Hiwada caldera, the crystal-rich magma that formed the Hot-
okezawa Ignimbrite did not appear during the post-caldera stage. There-
fore, it is plausible that the chamber of eruptible magma was emptied by the caldera-forming eruption. Higher-crystallinity magma that was on the verge of solidification around the chamber should have remained, but the residue of this magma did not reappear as intrusions into the resurgent dome. Although crystal-rich felsic magma is unlikely to erupt due to its high viscosity (Marsh, 1981; Takeuchi, 2011), once an eruption starts, it is unlikely to be spontaneously interrupted. In the caldera-forming eruptions, subsidence and eruption may be coupled from the outset, and subsidence of the roof into the chamber maintains high excess pressure, promoting the ejection of crystal-rich magmas during almost the entire eruption (Gudmundsson, 2016; Okumura et al., 2019).

Although the post-caldera early tonalite has the continuous trend in major-element variations and the same Sr and Nd isotopic compositions as the caldera-forming magma (Figures 8 and 11), K/Rb variation suggests that the Hotokezawa Ignimbrite and the low-Rb tonalite cannot be explained by a same fractionation process from their parental crustal melts (Figure 10(c)). This finding suggests that the tonalite were isolated in the solidified reservoir and underwent different crystalline differentiation from the main part (Figure 13(a)). A variety of the crustal melts with different degrees of partial melting are thought to have been produced by the underplating of the mantle melt, but the homogenization process was efficient in the main magma reservoir, and the characteristics are unlikely to remain. Whereas, in the sub-chambers, such homogenization did not occur, and the diversity of the crustal melts was probably preserved. Disappearance of the main crystal-rich magma after the caldera collapse might lead to ascent of the tonalite magma along the newly formed caldera ring faults (Figure 13(b),(c)). Grocke et al. (2017) has revealed that a variety of styles of “monotonous intermediates” and found petrological het-

erogeneity caused by the continuum of the caldera-forming magma

system; such heterogeneity is quite consistent with the observed rela-
tionship between the Hotokezawa Ignimbrite and the post-caldera

tonalite.

The late porphyries and granite following the tonalite are differ-
ent from the caldera-forming magma in terms of their Sr and Nd iso-

topic compositions (Figures 11 and 12). However, their values are
within the compositional ranges of the Sirakawa Ignimbrites from the adjacent calderas, indicating the diversity of the lower crustal materials in this region (Yamamoto, 2011). This compositional change indicates that the partial melting crust generating felsic magma was renewed by the subsequent intrusion of the mantle melts (Figure 13(c)). The flow of new felsic magma into the shallow magmatic system as laccoliths was facilitated by subsidence-related faults that provide pathways for magma ascent. In addition, the mantle melts were assimilating with the lower crustal materials and producing new basaltic stratovolcanoes as the Hakaseyama Volcanic rocks outside Hiwada caldera.

6.4 | Comparison to other caldera systems

Although resurgence was classically defined by Smith and Bailey (1968) as structural uplift of the caldera floor by renewed buoyancy or intrusion of the viscous magma remaining in the post-caldera reservoir, the resurgence of Hiwada caldera was caused by replenishment of new magma at the late-intrusion stage (Figure 13(c)). Similar resurgent doming by intrusions of chemically distinct magmas have also occurred at Valles and Lake City calderas, USA (Kennedy et al., 2012). Furthermore, renewal of felsic magmas from caldera-forming to post-caldera activities has been reported at some caldera volcanoes. For example, new felsic magmas with incompatible element concentrations distinct from those of their preceding caldera-forming magmas accumulated in the chambers following the 7.3-ka Koya Ignimbrite eruption at Kikai caldera (Tatsumi et al., 2018) and the 30-ka Ito Ignimbrite eruption at Aira caldera (Geshi et al., 2020), southwest Japan, and were the sources of post-caldera eruptions. Remarkable changes in Sr isotopic compositions occurred between the 90-ka caldera-forming ignimbrite eruption and the emplacement of post-caldera felsic lavas at Aso caldera, southwest Japan (Miyoshi et al., 2012). In the Yellowstone Plateau volcanic field, USA, the Sr and Pb isotopic compositions of the felsic magmas fluctuated significantly during each of the three caldera-forming eruptions at 2.0, 1.3, and 0.6 Ma (Hildreth et al., 1984). Notwithstanding, there are also many cases in which caldera-forming magmas have continued to be active during post-caldera events. In Long Valley caldera, USA, voluminous post-caldera rhyolite lavas erupted after the 760-ka eruption of the Bishop Tuff, and exhibit compositions within the range of the zoned Bishop Tuff for most elements (Hildreth, 2004). In Toba caldera, Indonesia, rhyolite lava of the resurgent dome geochemically and mineralogically represents remnant magma that erupted shortly after the climactic 74-ka Youngest Toba Tuff eruption (Chesner et al., 2020; de Silva et al., 2015). At Campi Flegrei, Italy, the post-caldera products show interactions between mafic magmas of deeper origin and more evolved crystal-rich magmas recycling portions of the residual crystal mush (Forni et al., 2018). In short, there are various patterns of petrological cycles associated with caldera-forming events in long-lived felsic magmatic provinces. To better understand the magmagenic processes producing caldera-forming eruptions, it is important to accumulate further petrological examples of such eruptions.

7 | CONCLUSIONS

In this work, I focused on the geological and petrological evolution of Hiwada caldera during and after the 2.9-Ma Hotokezawa Ignimbrite eruption. The major conclusions of this study are as follows.

1. The caldera-forming Hotokezawa Ignimbrite (40–50 vol%, >140 km³ DRE), is a typical monotonous intermediate ignimbrite. This ignimbrite is a calc-alkaline, medium-K dacite to rhyolite with SiO₂ contents ranging from 67.9 to 71.3 wt%, and has homogeneous trace-element abundances and Sr–Nd isotopic ratios. These geochemical features suggest that the Hotokezawa Ignimbrite magma formed by partial melting of amphibolitic crustal materials. This crystal-rich magma did not appear during the post-caldera stage. Therefore, it is plausible that the chamber of eruptible magma was emptied by the caldera-forming eruption.

2. The post-caldera plutonic rocks intruded as laccoliths, uplifting and bending the overlying intra-caldera deposits. The plutonic rocks exhibit a variety of compositions and have a clear SiO₂ gap corresponding to the caldera-forming magma; the early pluton (tonalite) and the later ones (quartz porphyry, granite porphyries, and granite) contain 62.0–66.6 and 71.2–76.5 wt% SiO₂, respectively. The tonalite and the Hotokezawa Ignimbrite form a continuous trend in their major-element variations. The Sr–Nd isotopic ratios of the ignimbrite and tonalite overlap, but those of the porphyries and granite are more enriched.

3. The early tonalite represents the more basic part of the Hiwada caldera system that was held in small pockets separate from the main magma chamber, because its trace-element abundances are varied and distinct from those of the Hotokezawa Ignimbrite. In the main chamber, the homogenization process was efficient, and the diversity generated during partial crustal melting of the crust was lost, whereas in the sub-chamber, the original heterogeneity is thought to have been preserved.

4. The distinct compositional change from the Hotokezawa Ignimbrite to the late porphyries and granite indicates that the partial melting crust generating felsic magma was renewed by the subsequent intrusion of the mantle melts. The new felsic magma ascended through subsidence-related faults into the shallow caldera system and emplaced as laccoliths forming the resurgent dome.

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ORCID
Takahiro Yamamoto https://orcid.org/0000-0002-0652-1662

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