Chapter 3

Exploring the Base of the Volcano: A Case Study of an Active Stratovolcano, Mt. Zao, NE Japan

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Abstract

It is very important to explore the base of large volcanoes because older volcanoes with distinct petrological characteristics are sometimes hidden behind them. Such older volcanoes provide keys to investigate the change of magma genesis and tectonic setting during geological time. We newly found an older volcano in southern part of Zao volcano, located in Japan. We have investigated in detail the eruptive products outcropping in its southern part and found that some eruptive rocks with peculiar features form a new stratovolcano which is different from Zao volcano. We call this newly found volcano, the Hiyamizuyama volcano. We have performed K-Ar dating on the representative rocks, obtaining an old age of approximately 1.45 My. The rocks are calcalkaline andesites to dacites, having distinct chemical compositional features with respect to any other calcalkaline rock of the stages 2–6 of Zao volcano. Megacrystals and plutonic intrusions represent a distinct character of the eruptive rocks of the Hiyamizuyama volcano. The finding of this older volcano is also important in order to consider the long-term temporal variation of volcanism and magmatism in the northeastern sector of Japan.

Keywords: stratovolcano, eruptive history, K-Ar age dating, magmatic composition, crustal xenolith

1. Introduction

In the region where large volcanoes are present, sometimes older volcanoes are discovered even in well-investigated areas. It is because the newer large volcanoes sometimes cover the older volcanoes underneath. Such older volcanoes usually have distinct characters from the overlying younger volcano. Thus, the distinction and the characterization of such older volcanoes are very important not only in order to consider the characteristics of the volcanism and the magmatism in the area but also in order to examine the temporal change of the magma genesis in relationship with the tectonic setting. For example, the Hawaii shield volcanoes are composed of surface alkaline lavas. However, it has been revealed that the surface alkaline lavas are underlined by a huge amount of tholeiitic lavas [1, 2]. The change of the rock composition is explained by the variations of the mantle-derived primary magma composition. The melting conditions change during the volcanic evolution when the basal oceanic plate moves through the hotspot. Another example is represented by the Fuji volcano, which is the largest stratovolcano in Japan. An older volcano, named the Pre-Komitake volcano, was recently discovered beneath the Fuji volcano [3]. The rocks from this volcano have distinct characteristics as compared to those of the Fuji volcano. The rocks from the Pre-Komitake volcano are adakitic in composition, whereas those of the Fuji volcano are normal basaltic to dacitic compositions of the island arc setting [4]. The adakitic magma is formed by melting of downgoing slab. Thus, in the Fuji volcano area, the slab melting occurred in the older age but did not continue. This change would reflect the variation of distribution of downgoing slabs beneath this area [5].

In the northeastern Japan, one of the representative subduction zones in the world, many stratovolcanoes are arranged along the volcanic front (**Figure 1**), for example, see [6, 7]. The Zao volcano is one of the most representative among these stratovolcanoes. This volcano has a long eruptive history of about 1 million years. We found an older volcano underlying the eruption products of the Zao volcano. We named this newly found volcano the Hiyamizuyama volcano. We show the geologic and petrologic features and the K-Ar age of this volcano. Also, we consider the magma genesis for the rocks of the Hiyamizuyama volcano examining the

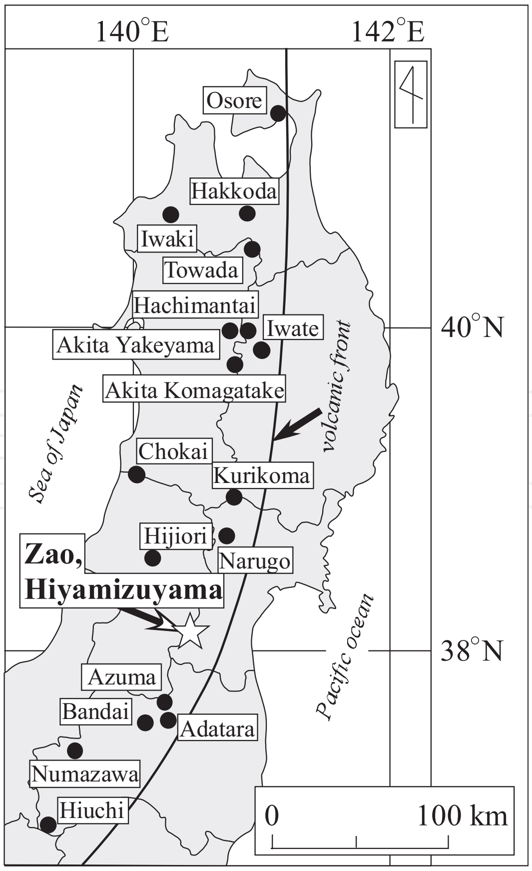

Figure 1. Locality map of Zao and Hiyamizuyama volcanoes. Eighteen active volcanoes, including Zao volcano, in NE Japan are plotted.

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time change in the rock compositions to a regional scale in relationship to the temporal change of the tectonic setting in the northeastern sector of Japan.

2. Geologic background

Zao volcano is an active stratovolcano in the volcanic front of the northeastern Japan (**Figure 1**). Its volcanic activity started approximately 1 Ma [8, 9] and comprised andesitic stratovolcano [10–14]. The volcanic activity is divided into six main stages based on the newest geologic study [14] (**Figure 2**). The first stage (ca. 1 Ma) is characterized by the subaqueous activity of

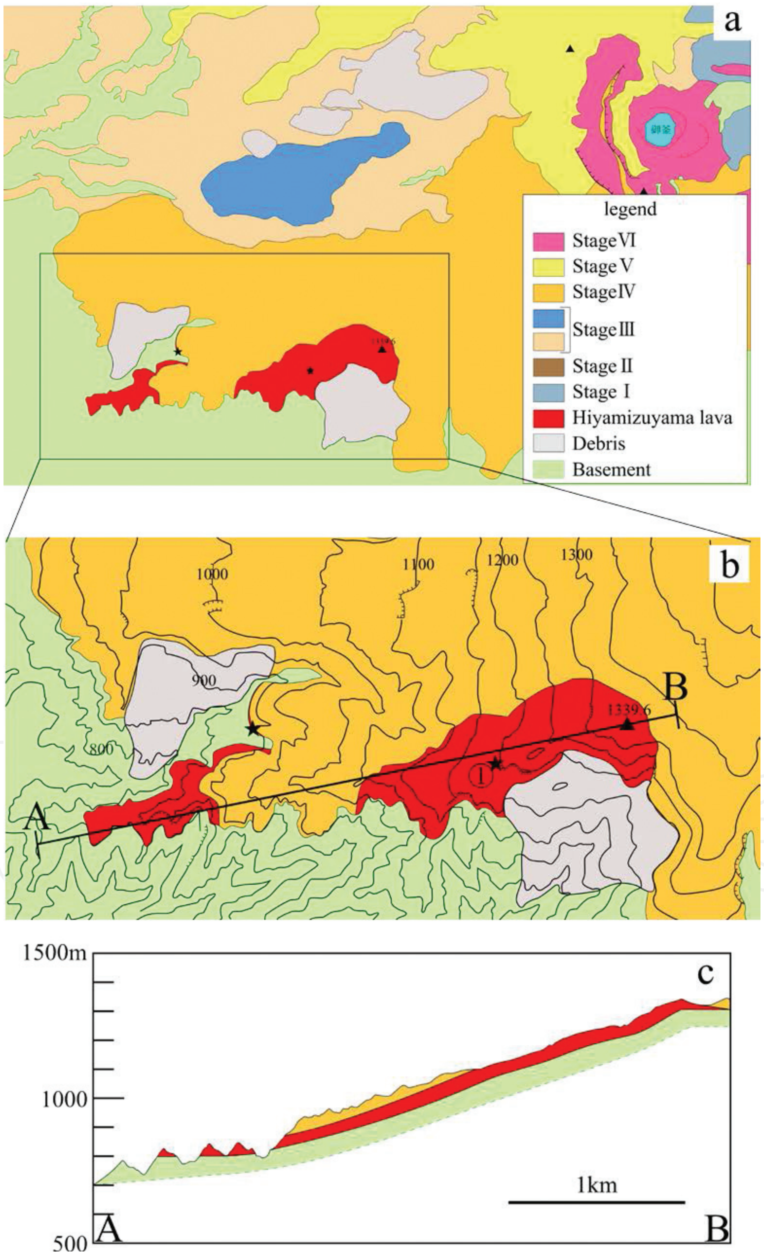

Figure 2. (a) and (b) Geological map of Zao volcano and the close-up view of Hiyamizuyama and the surrounding area (modified from Ref. [14]). (c) Geological cross-section of Hiyamizuyama volcano. Star mark represents well-exposed point.

low-K tholeiitic magma. Stages II–V (ca. 0.5–0.04 Ma) are characterized by the formation of middle-sized stratovolcanoes composed of medium-K calcalkaline basaltic andesite to dacite. Stage VI (ca. 35 ka to present) is characterized by explosive eruptions of medium-K calcalkaline series basaltic andesite to andesitic magmas [15–17].

3. Geologic feature of Hiyamizuyama volcano

The distribution of the eruptive rocks and the geologic section are presented in **Figure 2**. Hiyamizuyama eruptive rocks outcrop in the southern part of the Zao volcano. Previous studies [11, 12] pointed out that the eruptive rocks with peculiar petrologic features occur in the southern part of the Zao volcano, but the rocks were previously not well investigated and included in stage 3 of the Zao volcano.

The eruptive rocks consist of andesitic to dacitic massive lavas more than 10 m thick (**Figure 3**). The lavas are well exposed at the summit area of Hiyamizuyama volcano. In the outcrop of the summit area (star no.1 in **Figure 2**), the columnar joints can be well observed. The remarkable feature of these rocks is that the plagioclase megacrysts and plutonic inclusions as well as the mafic inclusions are characteristically identified by naked eyes. The mafic inclusions are ubiquitous in calcalkaline intermediate lavas, for example, see [18], but the plagioclase megacrysts and plutonic inclusions are not usually found in calcalkaline intermediate lavas. The details of the inclusions are described in the following section of petrologic features. Considering the distribution of this type rocks, the summit area to the western foot of Hiyamizuyama (**Figure 2a, b** would consist of this type of lavas. The lavas are covered by one of stage 3 lavas (Ichimaiishizawa lavas by [14]) of Zao volcano (**Figure 2c**). The estimated volume of the remaining lavas of Hiyamizuyama is about 0.075 km^3.

Figure 3. A photograph of the exposure (point of star no. 1 in **Figure 2**) of the lava at the summit area of Hiyamizuyama.

4. Analytical methods for petrologic analysis

More than 20 lava samples were collected from Hiyamizuyama volcano for petrologic analyses. Modal analysis is based on more than 2000 counts per thin section using optical microscope. The

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proportions of groundmass and phenocrystic minerals were calculated on a vesicle-free basis. Whole rock major and trace element (Ba, Sr., Cr, Ni, V, Rb, Zr, Nb, and Y) compositions were analyzed using an X-ray fluorescence analyzer (RIX2000; Rigaku Corp.) at Yamagata University. Analyses were undertaken at an accelerating voltage of 50 kV and 50 mA currents. Preparation methods of glass disks and calibration for major and trace elements followed the method of [19] using GSJ geochemical reference samples "igneous rock series." Analytical errors of trace elements are 5% (Sr, Rb, Zr, Nb, Y, and Ni), 10% (Cr and V), and 5–15% (Ba) [20].

5. Petrographic features of rocks from Hiyamizuyama volcano

The rocks are quartz-bearing clinopyroxene-orthopyroxene andesite to dacite. These are gray in color and poorly vesiculated dense rocks. The photographs of the rocks as well as the inclusions and plagioclase megacrysts are shown in **Figure 4**.

Total volumes of phenocrysts are approximately 15%, which is a low value if compared to those of the rocks from the Zao volcano, for example, see [21]. The rocks from Zao volcano usually have more than 20% phenocrystic modal compositions. Volumes of phenocrystic plagioclase, clinopyroxene, and orthopyroxene are 9–11, ~1.5, and ~2.0%, respectively

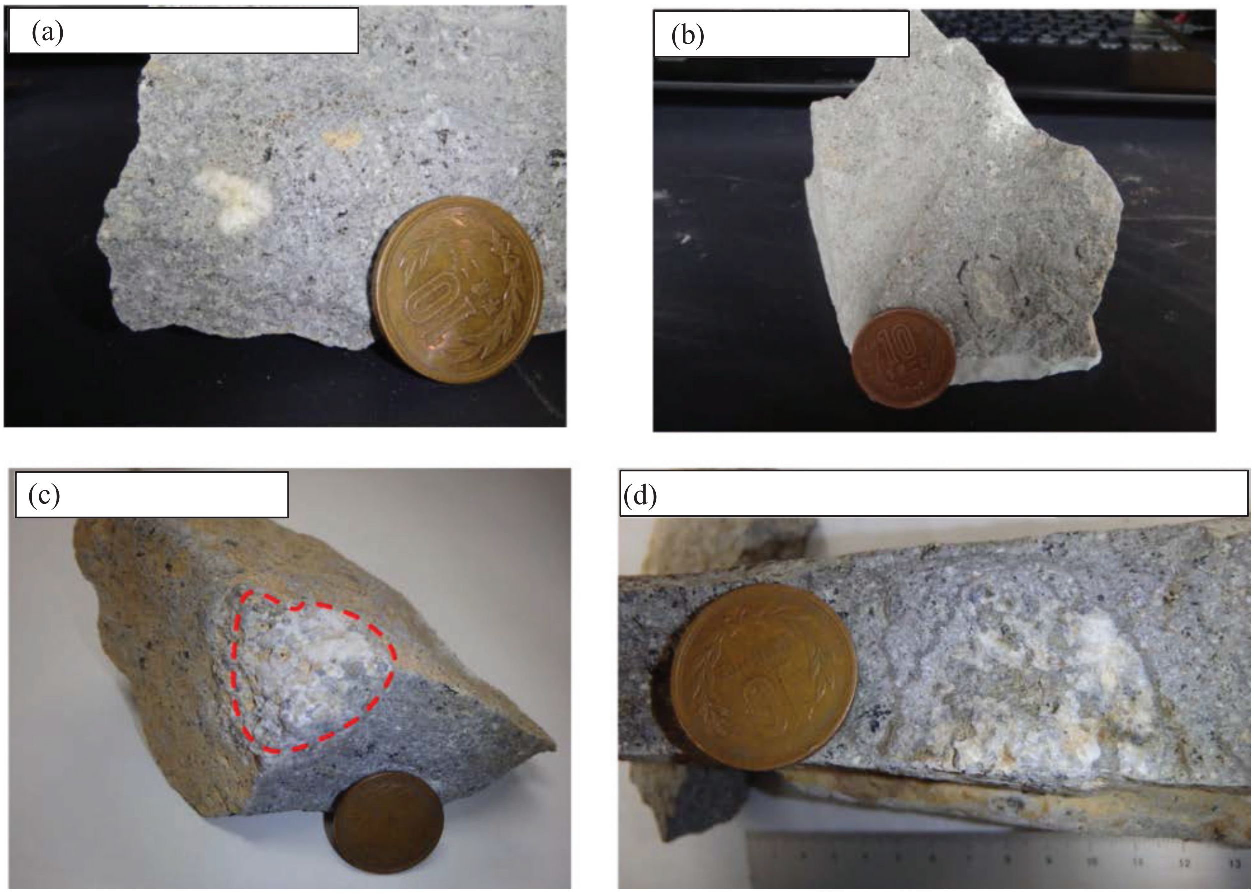

Figure 4. Photographs of the plagioclase megacrysts, the mafic inclusion, and the plutonic inclusion in the rocks from Hiyamizuyama volcano. (a) Plagioclase megacryst, (b) mafic inclusion, (c) plutonic inclusion (enclosed by the dotted red line), and (d) plutonic inclusion, which shows partial melting structure.

Sample no.	plg			Cpx	opx	ox	gm
vol.%	clear	dusty	patchy				
130,904–01-01	4.9	1.0	3.5	1.8	2.0	0.5	86.4
15,102,306–01	6.4	1.4	3.4	1.3	2.0	0.2	85.3

plg, plagioclase; clear, clear-type plagioclase; dusty, dusty zoned-type plagioclase; patchy, patchy zoned-type plagioclase; cpx, clinopyroxene; opx, orthopyroxene; and ox, oxide minerals.

Table 1. Modal compositions of representative rocks of Hiyamizuyama volcano.

(**Table 1**). Titanomagnetite phenocrysts are rarely observed in all samples and quartz phenocrysts occasionally present. Hyaloophitic-textured groundmass has microlites (up to 100 μm) of plagioclase, pyroxene, and rare titanomagnetite with interstitial glass. Photomicroscope images of representative phenocrystic minerals are displayed in **Figure 5**.

Plagioclase phenocrysts can be classified into three types. These are clear, dusty-zoned [22], and patchy-zoned [23] types. The clear type (**Figure 5a**) does not include glass inclusions and usually indicates euhedral in shape. Compositional zoning is sometimes observed. The dusty-zoned type (**Figure 5b**) has sieved-textured dusty zone in the rim part. The zone is composed of glasses, tiny grains of plagioclase, titanomagnetite, and mafic minerals. This zone is formed by resorption of the phenocrystic plagioclase, for example, see [22]. The patchy-zoned type (**Figure 5c**) is subhedral with oscillatory-zoned cores [18] having An-poor areas with rounded to irregularly shaped melt inclusions (ca. 300 μm), which constitute patches. The clear type is dominant among plagioclase phenocrysts. The second dominant

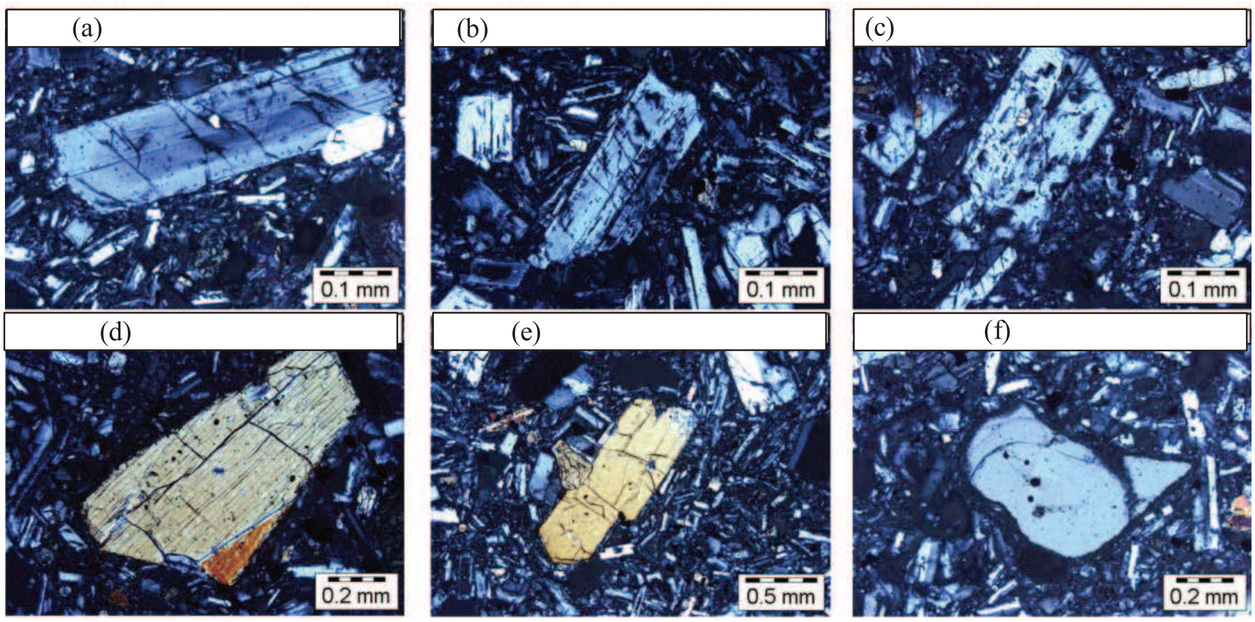

Figure 5. Photomicroscope images of the phenocrystic minerals. (a) Clear type plagioclase, (b) dusty-zoned type plagioclase, (c) patchy-zoned type plagioclase, (d) clinopyroxene, (e) orthopyroxene, and (f) quartz.

type is patchy-zoned type (**Table 1**). Most clinopyroxene (up to 0.4 cm) and orthopyroxene (ca. 0.9 cm) phenocrysts are euhedral to subhedral (**Figure 5d, e**). Quartz phenocrysts (up to 0.5 cm) show rounded form (**Figure 5f**). Crystal clots (up to 1 cm) composed of subhedral to anhedral plagioclase, orthopyroxene, clinopyroxene, and titanomagnetite are abundant.

The mafic inclusions are ubiquitously observed. These are light gray colored and usually less than 2.5 cm but sometimes up to several 10 cm in size. These are usually rounded form and sometimes show irregular shape. The texture is diktytaxitic, containing abundant interstitial glasses with bubbles between laths of the plagioclase and pyroxene (**Figure 6a**). The mafic inclusions are quenched products of mafic magmas which injected into intermediate to felsic magma chamber, for example, [18, 24]. The plagioclase megacrysts and the plutonic inclusions are less than the mafic inclusions in amount. The plagioclase megacrysts are up to 1.5 cm in size and belong to clear type. The corners are usually rounded. The plutonic inclusions are up to several cm in size. These consist of mostly plagioclase (up to 0.6 cm) and subordinately of quartz (up to 0.35 cm) with minor biotite (up to 0.5 cm). The fine grain veins invade into the inclusion along with the mineral boundaries **Figure 6b**. Sometimes, the veins can be observed by naked eyes (**Figure 4d**). These veins would be the mixture of host magma and the partial melt of the plutonic inclusion. The plagioclase grains are subhedral to anhedral and the quartz grains are anhedral. The biotites are mostly decomposed into finely grained plagioclases and titanomagnetites. The plutonic inclusions are classified into diorite according to the classification scheme of [25].

Among the petrographic features described earlier, the dissolution textures observed in the plagioclase phenocrysts (dusty zone and patchy zone) and the existence of mafic inclusion showing a quench texture indicate that the rocks of the Hiyamizuyama volcano were formed through magma mixing process as it happened in many calcalkaline rocks of the northeastern Japan [26–30]. On the other hand, the existence of partially melted plutonic inclusion, which is seldom reported from NE Japan active volcanoes, indicates the assimilation process. The texture suggesting partial melting and felsic nature of the plutonic inclusion indicate that the assimilation took place just before and during the eruption.

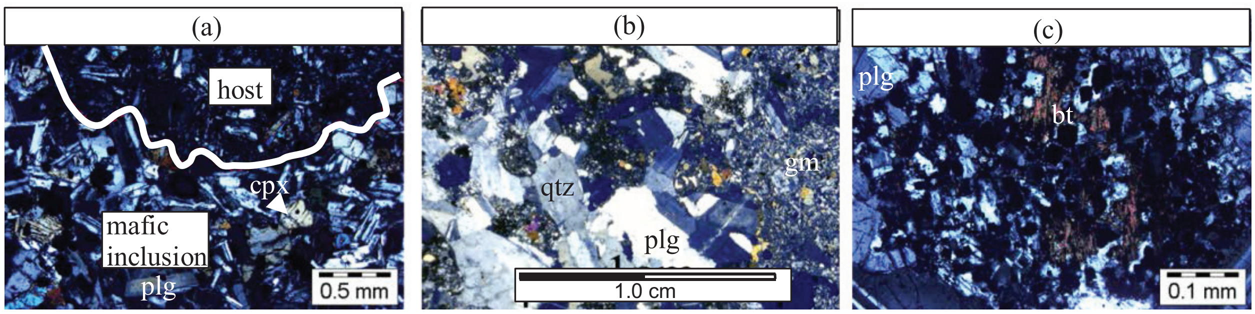

Figure 6. Photomicroscope images of the mafic inclusion (a), the plutonic inclusion (b), and the decomposed biotite (c) in the plutonic inclusion. gm, groundmass; plg, plagioclase; qtz, quartz; cpx, clinopyroxene; and bt, biotite.

6. Rock compositions of Hiyamizuyama volcano

The whole rock compositional data are shown in **Table 2**. For this study, major elements were normalized to a 100% volatile free basis with total iron (FeO*) calculated as FeO. The rocks are medium-K, calcalkaline andesite to dacite based on the classification scheme reported by Gill [31] (**Figure 7**). SiO_2 contents are 61.8–63.5 wt.%. The rocks define same chemical trends in SiO_2 variation diagrams (**Figure 8**). In K_2O-SiO_2 diagram, rocks from Hiyamizuyama volcano plotted on an area far away from those of stages 4–6. The area is near to the compositional ranges of stages 2 and 3 of Zao volcano, but still lower than the ranges. The compositions of the rocks of Hiyamizuyama volcano are compared to those from stages 2 and 3 of Zao volcano in other major elements and trace elements in SiO_2 variation diagrams (**Figure 8**). In the SiO_2 variation diagrams, rocks from Hiyamizuyama volcano are plotted far below in Ni and Sr and slightly below in MgO, Ba, Rb, and Nb from the areas of

Sample no.	130904-01-01	1011-HM	HM01	130530-4	130530-5
wt.%					
SiO_2	62.22	61.78	62.81	63.50	62.64
TiO_2	0.76	0.80	0.80	0.77	0.75
Al_2O_3	15.97	16.07	16.21	16.04	15.86
FeO*	7.09	7.24	7.27	7.03	7.21
MnO	0.16	0.16	0.16	0.15	0.15
MgO	2.76	2.81	2.84	2.56	2.81
CaO	5.83	6.18	6.19	5.79	6.30
Na_2O	3.32	3.38	3.41	3.40	3.38
K_2O	1.04	1.04	1.06	1.11	1.07
P_2O_5	0.10	0.09	0.11	0.11	0.10
	99.25	99.55	100.86	100.46	100.27
ppm					
Ba	357	335	337	347	332
Cr	11	12	12	11	10
Nb	4.4	4.4	4.6	4.3	4.1
Ni	N.D.	N.D.	N.D.	N.D.	N.D.
Rb	23	23	23	24	25
Sr	249	259	261	250	264
V	177	177	185	169	174
Y	31	30	30	42	44
Zn	83	84	85	80	82
Zr	118	113	113	115	111

Table 2. Whole rock major and trace element chemical compositions of rocks from Hiyamizuyama volcano.

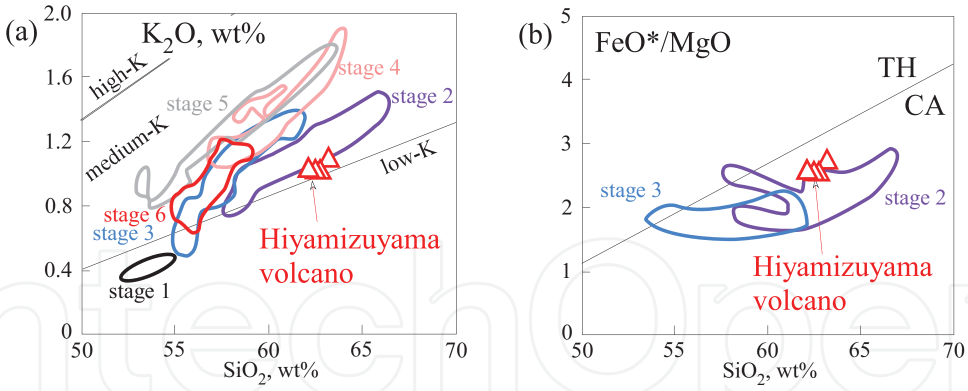

Figure 7. K_2O-SiO_2 (a) and FeO*/MgO-SiO_2 (b) diagrams for the rocks from Hiyamizuyama volcano. The areas of stages 1, 4, 5, and 6 of Zao volcano are from Ref. [14] and those of stages 2 and 3 are from Ref. [32]. Boundaries in the K_2O diagram are from Ref. [26]. Boundary of TH/CA is from Ref. [33]. The areas of stages 2 and 3 of Zao volcano are from Ref. [32].

rocks from stages 2 and 3 of Zao volcano. In the other elements, the rocks from Hiyamizuyama are in the area of stage 2, but plotted in higher part in TiO_2, Na_2O, and FeO*, whereas in lower part in CaO, Zr, and Cr. Thus, examining the whole rock compositions carefully, it is possible to distinguish the rocks from Hiyamizuyama volcano from those of Zao volcano.

7. Analytical methods for K-Ar dating

In a stainless bowl, approximately 80–100 g of the rock sample was crushed. The crushed grains were sieved to 180–250 μm in size. The sieved grains were cleaned with purified water and acetone in an ultrasonic bath. To minimize extraneous ^{40}Ar [34], the phenocrysts were removed by using an isodynamic separator (Frantz). The groundmass concentrated part was used for the analyses. Some portion of the groundmass concentrate was grinded to powder for the potassium analysis. Potassium concentration was measured by a flame emission photometer with an internal lithium standard and a peak integration method, similar to that described by Matsumoto [35]. About 100 mg of powdered sample was dissolved in a mixture of HF and $HClO_4$. After dried, it was dissolved in HCl and diluted. The lithium standard solution was added as internal standard to sample solution. Each sample was measured twice. Analytical error is 1%, estimated from standard deviation of multiple analyses of geological standards, provided by the National Institute of Advanced Industrial Science and Technology, Japan.

The argon isotopic measurement was performed using the peak height comparison (unspiked) method [36, 37]. We used the MM4500Ar mass spectrometer operated in static mode, which is connected to extraction and purification lines. The groundmass concentrated portion was wrapped in the copper foil and set in the line. To extract gases, the sample was melted in molybdenum crucible at 1500°C. The gases were purified with a Ti-Zr getter at ~700°C and two SAES getters at 200°C and room temperature, respectively. K–Ar age was calculated using the

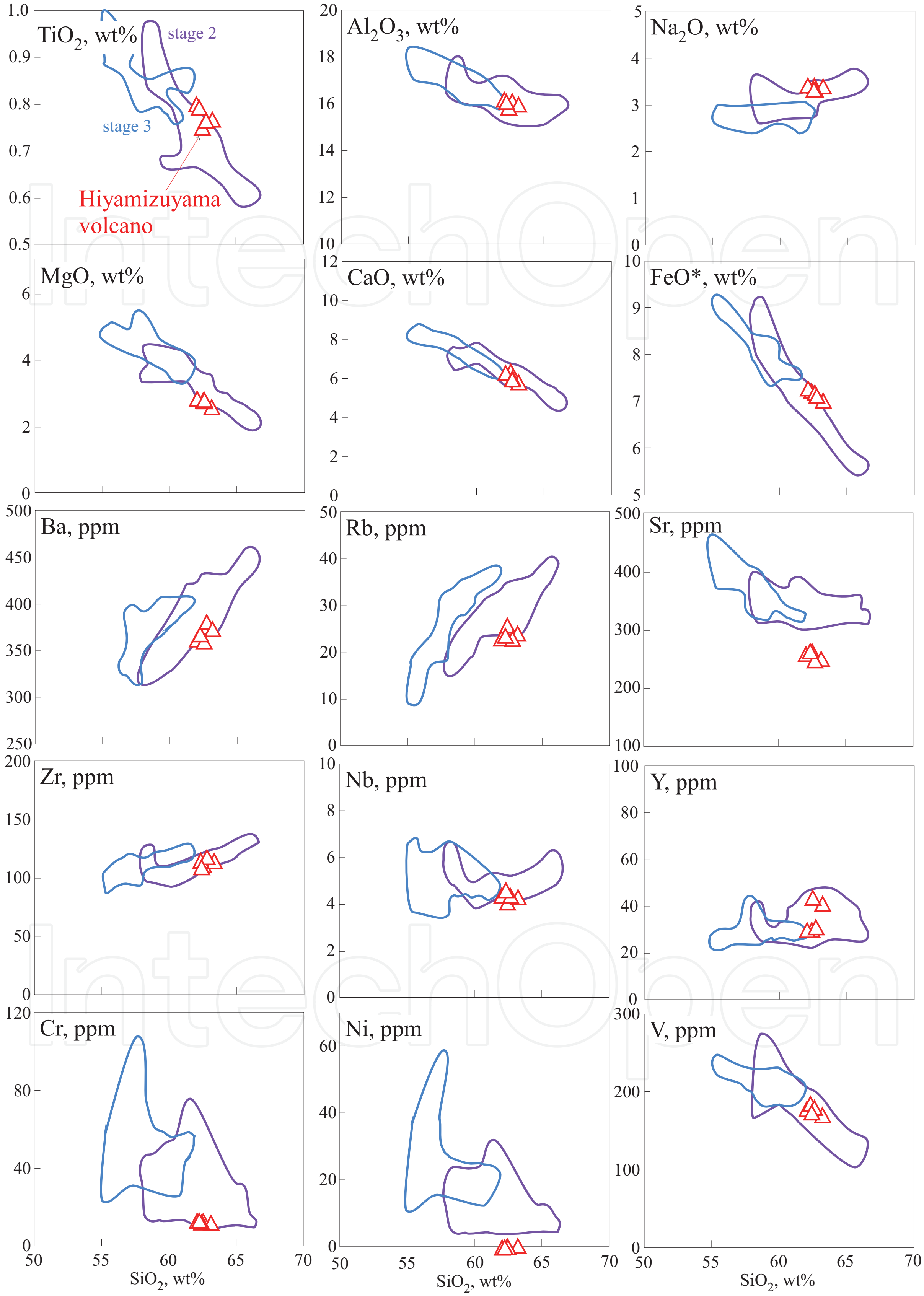

Figure 8. Major and trace elements SiO_2 variation diagrams of rocks from Hiyamizuyama volcano.

isotopic abundances and decay constants for ^{40}K recommended by the IUGS Subcommission on Geochronology ($^{40}K/K = 1.167 \times 10^{-4}$, $\lambda e = 0.581 \times 10^{-10}$ year^{-1}, $\lambda\beta = 4.962 \times 10^{-10}$ year^{-1}) [38]. We note that the initial $^{40}Ar/^{36}Ar$ ratio was obtained by applying the mass fractionation correction based on $^{38}Ar/^{36}Ar$ ratio, see [39, 40] in detail. All the analyses were conducted at the geochronology laboratory in the Geological Survey of Japan.

8. K-Ar age of Hiyamizuyama volcano

The K-Ar dating result on representative rock is presented in **Table 3**. Since the $^{38}Ar/^{36}Ar$ ratio of 0.1873 ± 0.0008 is very similar to the atmospheric value, the ages of the mass fractionation corrected and uncorrected are very similar. This means the mass fractionation effect is very limited for the age of this sample. Also, low nonradiogenic ^{40}Ar of 52.3% indicates the obtained age is very reliable.

The obtained age of 1.45 ± 0.03 Ma for the sample from Hiyamizuyama volcano is very old, which is much older than approximately 1 Ma, the age of the stage 1 Zao volcano. There are about 450,000 years gap between the activity of Hiyamizuyama volcano and the initiation of activity of Zao volcano.

9. Comparison of petrologic features with the other stratovolcanoes

(1) Temporal change of chemical compositions of frontal stratovolcanoes in NE Japan

Temporal change of petrologic features of frontal volcanoes in NE Japan during the past 4 million years was firstly examined by Ban et al. [41]. They revealed that (1) disruption of frontal volcanoes into petrologically distinct western and eastern groups, and those belonging to each group arrange near parallel to the elongated direction of the Japan trench, occurred at about 1.0–0.7 Ma, (2) the volcanoes with higher K_2O rocks appeared after the disruption, and (3) the western group includes the volcanoes with higher K_2O rocks and lower K_2O rocks, whereas the eastern group includes only volcanoes with lower K_2O rocks. These features are presented in K_2O (57.5) of the volcanoes in age-space variation diagram (**Figure 9**). We note that K_2O (57.5) is the K_2O contents of stratovolcanoes at 57.5% SiO_2. These features were recently reconfirmed by Takahashi [42].

(2) Comparison of K_2O (57.5) of Hiyamizuyama volcano with those of other frontal volcanoes in NE Japan in age-space diagram

Hiyamizuyama volcano is plotted in **Figure 9**. We can see three plots of low K_2O (57.5) volcanoes near the plot of Hiyamizuyama volcano. These three volcanoes are in northern part of NE Japan, whereas Hiyamizuyama volcano is in the central to southern part. Thus, Hiyamizuyama data indicate that the characteristics of temporal change in petrologic features revealed by Ban et al. [41] are those of whole NE Japan frontal volcanoes. Such change, occurred in whole arc, must reflect the changes of regional tectonics.

Sample no.	K_2O (wt.%)	Sample wt (g)	int.^{40}Ar (V)	^{36}Ar (10^{-9}mlSTP/g)	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar	int.^{40}Ar/^{36}Ar	rad.^{40}Ar (10^{-9}mlSTP/g)	non rad.^{40}Ar	K-Ar age (Ma)	uncorrected age (Ma)
Z12101105	0.98	0.644	0.99	0.17	0.1873 ± 0.0008	576 ± 6	296 ± 2	46.5 ± 0.8	52.3	**1.45 ± 0.03**	1.45 ± 0.02

*uncorrected age = mass fractionation of initial ^{40}Ar/^{36}Ar ratios are uncorrected.

The age calculation is the same as the conventional K-Ar dating procedure.

The decay constants used in the present study are 4.96X10–10/y, $\lambda e = 0.58X10^{-10}$/y, $\lambda\beta = 4.962 \times 10^{-10}$ /y,

and 40 K/K = 0.01167 atom% (Steiger and Jäger [38]).

Errors are given at the one σ uncertainty level.

Table 3. K-Ar age data by the peak comparison method for the sample from Hiyamizuyama volcano.

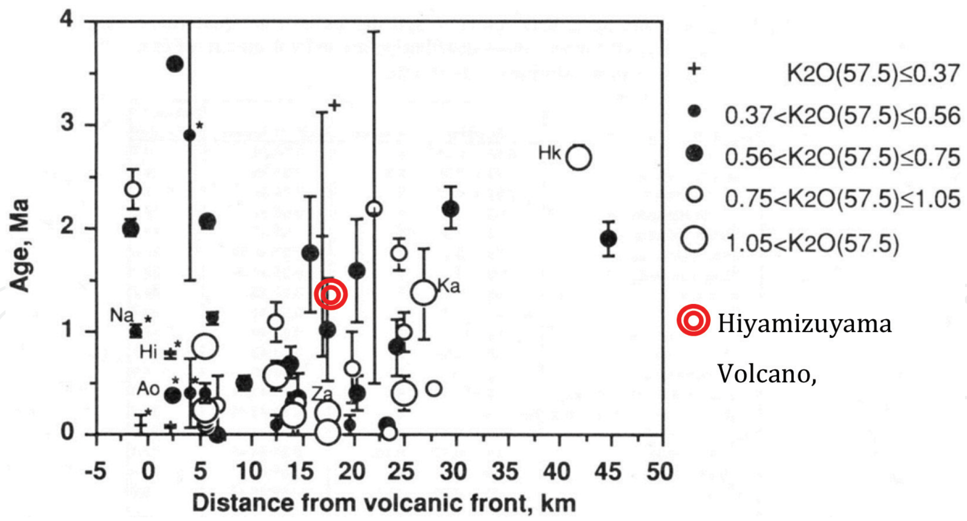

Figure 9. Temporal variation of the K_2O content for the volcanoes distributing around volcanic front of NE Japan arc during the past 4 million years [36]. Double circle, Hiyamizuyama volcano (K_2O (57.5) = 0.82).

It is suggested that regional uplift of basements of volcanic front region in NE Japan started at about 1.0–0.6 Ma, for example, see [43]. This uplift would be caused by the enlargement of the crust. The increased stress of E-W direction, caused by the speed up of westward movement of the Pacific plate, would accelerate the rate of the formation of magma in the wedge mantle. The ascended magma would underplate beneath the crust under volcanic front and resulted in the enlargement of the crust [44]. If the lower part of the crust gained the thickness, depths of magma formation areas, upper most mantle for the basaltic magma and lower crust for the intermediate to felsic magma, become deeper. The magmas formed in the deeper areas would have higher K_2O contents, because lower degrees of melting are expected when the melting depth gets deeper. The appearance of volcanoes with higher K_2O rocks would suggest that the lower crust gained thickness effectively beneath the western group after approximately 1.0 Ma. We note the coexistence of the volcanoes with lower K_2O rocks as well as with higher K_2O rocks in the western group would indicate that the thickening would be heterogeneously occurred.

10. Summary

We newly found Hiyamizuyama volcano in southern part of Zao volcano. We performed K-Ar dating and obtained the age of 1.45 Ma. Hiyamizuyama volcano was formed about 450,000 years before the initiation of Zao volcano.

The petrologic features of this volcano differ from those of Zao volcano. These include (1) lower phenocrystic modal composition, (2) including plagioclase megacrysts, (3) possessing plutonic inclusions, and (4) distinct whole rock composition, especially low-K_2O content.

Discovery of this older volcano is important to consider long-term temporal variation of volcanism and magmatism in this region as well as whole NE Japan.

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