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Chronology and products of the 2000 eruption of Miyakejima Volcano, Japan

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Abstract Lateral migration of magma away from Miyakejima volcanic island, Japan, generated summit subsidence, associated with summit explosions in the summer of 2000. An earthquake swarm beneath Miyakejima began on the evening of 26 June 2000, followed by a submarine eruption the next morning. Strong seismic activity continued under the sea from beneath the coast of Miyakejima to a few tens of kilometers northwest of the island. Summit eruptive event began with subsidence of the summit on 8 July and both explosions and subsidence continued intermittently through July and August. The most intense eruptive event occurred on 18 August and was vulcanian to subplinian in type. Ash lofted into the stratosphere fell over the entire island, and abundant volcanic bombs were erupted at this time. Another large explosion took place on 29 August. This generated a low-temperature pyroclastic surge, which covered a residential area on the northern coast of the island. The total volume of tephra erupted was $9.3 \times 10^6 \text{ m}^3$ (DRE), much smaller than the volume of the resulting caldera ($6 \times 10^8 \text{ m}^3$). Migration of magma away from Miyakejima was associated with crustal extension northwest of Miyakejima and coincident shrinkage of Miyakejima Island itself during July–August 2000. This magma migration probably caused stoping of roof rock into the magma reservoir, generating subsurface cavities filled with hydrothermal fluid and/or magmatic foam and formation of a caldera (Oyama Caldera) at the summit. Interaction of hydrothermal fluid with ascending magma

drove a series of phreatic to phreatomagmatic eruptions. It is likely that new magma was supplied to the reservoir from the bottom during waning stage of magma's migration, resulting in explosive discharge on 18 August. The 18 August event and phreatic explosions on 29 August produced a conduit system that allowed abundant SO_2 emission (as high as 460 kg s^{-1}) after the major eruptive events were over. At the time of writing, inhabitants of the island (about 3,000) have been evacuated from Miyakejima for more than 3 years.

Keywords Phreatomagmatic eruption · Miyakejima · Lateral migration of magma · Caldera · Tephra · Juvenile material

Introduction

Subsidence due to lateral migration of magma under the ground is known at basaltic volcanoes, for example, the 1924 eruption at Kilauea, Hawaii (Dvorak 1992), the 1968 eruption at Fernandina, Galapagos (Simkin and Howard 1970), and the 1975–1977 eruption at Tolbachik, Kamchatcka (Fedotov et al. 1980). The 2000 eruption at Miyakejima volcano, 180 km south of Tokyo (Fig. 1a), is another example. In this case, activity both above ground and below the volcano and surrounding areas were monitored in detail.

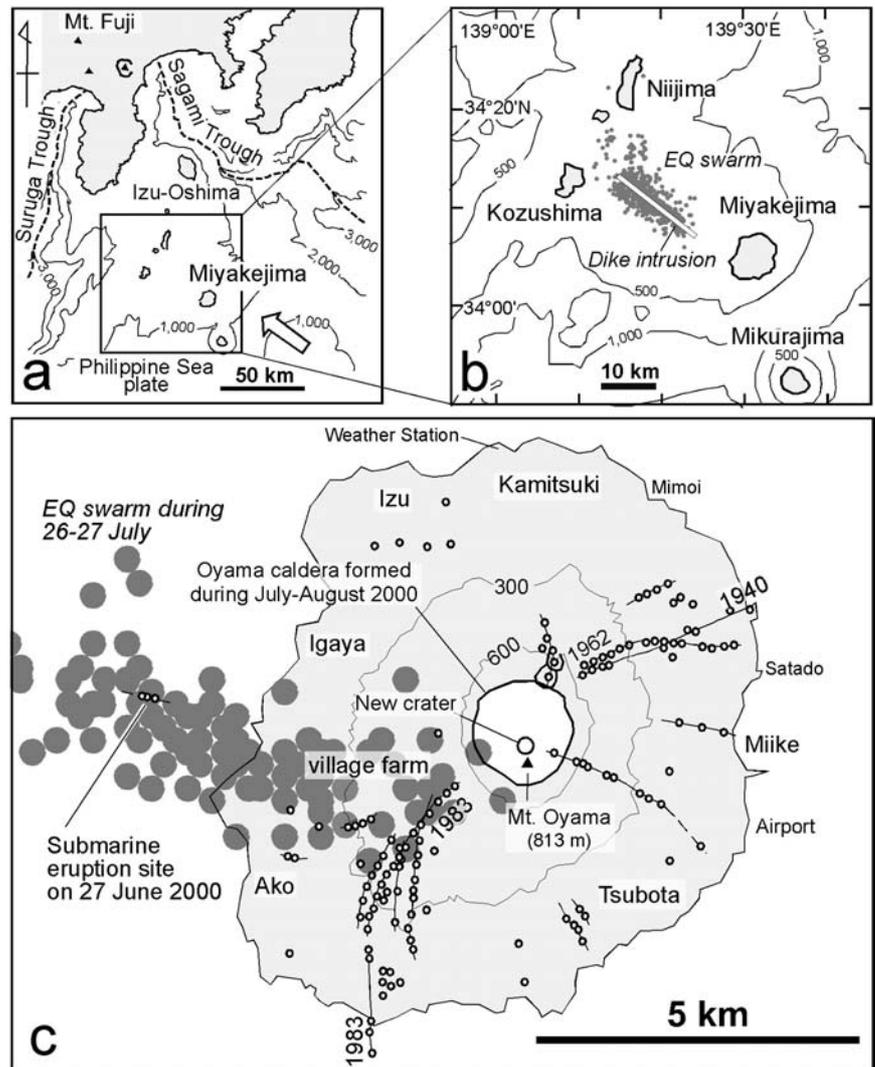
Brief summaries of various aspects of this eruption were reported by Nakada et al. (2001), Uto et al. (2001), and Geshi et al. (2002a). Eruptive activity at Miyakejima started with a small submarine eruption in late June 2000, followed by summit phreatic to phreatomagmatic explosions in July and August 2000, during which a caldera formed at the summit. Following the main stage of eruption, degassing of anomalously high amounts of SO_2 began and lasted for more than 3 years. The manner of eruption differed greatly from what had been experienced on this island during the last 100 years. Previous eruptions at Miyakejima began less than half a day after initiation of a seismic swarm, and lasted for periods as short as several

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Fig. 1 Index maps of Miyakejima Volcano. Contours are in meters. **a** The direction of Philippine Sea plate movement is shown by an *arrow*. **b** Earthquake swarms occurred in the area west of Miyakejima during July and August, due to lateral migration of magma from Miyakejima. Earthquakes that occurred during 2 July to 2 August (Sakai et al. 2001) are shown by *gray dots*. The dike model is from Nishimura et al. (2001). **c** New caldera (Oyama Caldera) and submarine eruption site. Earthquakes observed during 21:40 h of 26 June to 05:00 h of 27 June 2000 (JMA 2000) are shown by *large dark dots*. Radial dike pattern of Miyakejima (Nakamura 1984) is also shown. Craters are shown by small *open dots*. The 2000 eruption crater is located at the same site as the central crater that existed before 2000. The Hatchodaira Caldera of 2.5 ka nearly overlaps the new caldera



days. In 1940, the eruption continued for about a month. Lavas were always erupted along fissures extending more or less radially from the summit (Fig. 1c). According to geological studies (e.g., Tsukui and Suzuki 1998), Miyakejima had experienced a summit collapse about 2.5 ka, resulting in formation of the Hatchodaira Caldera, with a size similar to the 2000 Caldera. Thus, for Miyakejima, caldera-forming eruptions may repeat once every 2,500 years. In this paper, we describe the chronology of the 2000 eruption, and we discuss the mechanism of the eruption and caldera subsidence based on the characteristics of the eruption products. Detailed geological study of this eruption is continuing by one of authors (M.N.) and will be reported later.

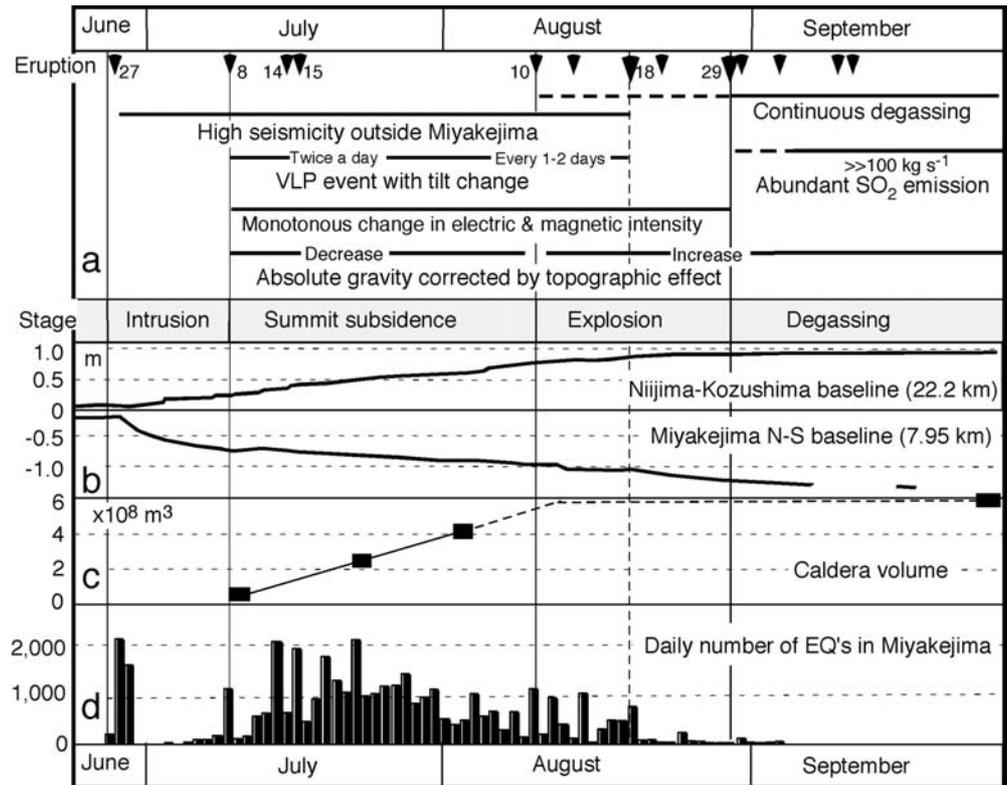
Eruption chronology

The 2000 activity of Miyakejima is divided into four stages based on surface phenomena (Fig. 2); magma intrusion, summit subsidence, explosion, and degassing stages.

Magma intrusion stage (26 June–7 July)

A seismic swarm of volcanic earthquakes occurred beneath the summit beginning on evening of 26 June 2000 (Fig. 2d) (JMA 2000). Eruption did not occur, although magma moved upward beneath Miyakejima to depths as shallow as 200 m below sea level (Fujita et al. 2002). Hypocenters of earthquakes moved westward beginning about midnight of 26–27 June (Uhira et al. this issue), associated with crustal movements, indicating intrusion of a dike oriented ENE–WSW and originating at the west coast of Miyakejima (Irwan et al. 2003). A submarine eruption occurred on the morning of 27 June (Fig. 1c), probably soon after the seismic swarm passed beneath the eruption site (JMA 2000). A discolored sea surface with bubbles was witnessed that morning about 1 km off the west coast of the island (Kaneko et al. this issue). A plume of bubbly, light-blue-colored water continued to be observed on the sea surface for a few hours after it was first discovered. Subsequently, felt earthquakes occurred mainly outside Miyakejima (Fig. 1b) (JMA 2000). Bursts of earthquakes, some of Magnitude 6, were repeated in

Fig. 2 Chronology of the 2000 eruption at Miyakejima Volcano. **a** Stages of eruptive activity based on surface phenomena. Major eruptive events are shown as arrows with representative variations of geophysical and geochemical phenomena (modified from JMA, 2000; Kikuchi et al. 2001; Sasai et al. 2001; Furuya et al. 2003; Kazahaya et al. 2001). **b** GPS data for baselines of Niijima–Kozushima (Fig. 1b) and Miyakejima. After Nishimura et al. (2001). **c** Temporal change in volume of the summit subsidence (Hasegawa et al. 2001). **d** Daily number of earthquakes that occurred beneath Miyakejima island. Data from JMA (2000)



the area between Niijima–Kozushima and Miyakejima from 27 June until the middle of August.

GPS measurements made by the Geographical Survey Institute (GSI) showed a steady lengthening of the baseline between Niijima and Kozushima during this stage. The deformation continued until August at a decreasing rate (Fig. 2b). As if to compensate for this, continuous shortening of a N–S baseline across Miyakejima Island was observed (Yamaoka et al. this issue). The shortening was accelerated after 18 August due to degassing (Nishimura et al. 2001, 2002).

A volcanic alert for Miyakejima was released by the Japan Meteorological Agency (JMA) on the evening of 26 June. Two-thirds of the islanders who lived in areas other than the northern part were recommended to evacuate to the northern part of the island. After recognition of magma migration to the west, people were permitted to return home.

Summit subsidence stage (8 July–9 August)

Following heavy seismicity beneath the island that resumed on 4 July (Fig. 2d), collapse of the summit area began suddenly on the evening of 8 July, accompanied by a small explosion (Fig. 3a). Subsidence of the summit area continued through early August (Fig. 2c) (Kaneko et al. 2001). During subsidence, phreatomagmatic explosions occurred on 14 and 15 July (Fig. 3b). Preceding the 14 and 15 July events, GPS data of the Geographical Survey Institute showed slight inflation of the volcano

(Miyakejima N–S baseline in Fig. 2b) (Nishimura et al. 2002). Tiltmeters installed along the hillside road indicated steady and continuous deflation of the summit area, periodically broken by sudden inflation (Ukawa et al. 2000) (“tilt change” hereafter). Synchronously, the number of volcanic earthquakes increased for a few hours and stopped with the occurrence of a very long-period (VLP) earthquake whose half-wave length was as long as 50 s (Kikuchi et al. 2001; Kumagai et al. 2001). Tilt changes were repeated at time intervals ranging from half a day to 2 days until 18 August 2000 (Fig. 2a). The time intervals tended to increase with time after early August. Large changes in electric and magnetic intensity on the island were observed in this stage (Sasai et al. 2001). These geophysical variations continued into the explosion stage.

Seismic activity beneath Miyakejima peaked during the summit subsidence stage and decreased thereafter, as shown in Fig. 2d. This reflects the interesting fact that caldera collapse and accompanying seismicity took place with little eruptive activity. No volcanic alert was released during the summit subsidence and explosion stages, due to some confusion regarding the nature of on-going volcanic activity. Timely public announcements were difficult due to very frequently changing eruption conditions.

Geologists pointed out the possibility to local village staff that heavy rains might trigger mudflows soon after the 14–15 July explosions. On the morning of 26 July, the first mudflows occurred in the eastern part of the island. Mudflows eroded valleys deeply, overflowed bridges along the coastal road and destroyed some buildings.

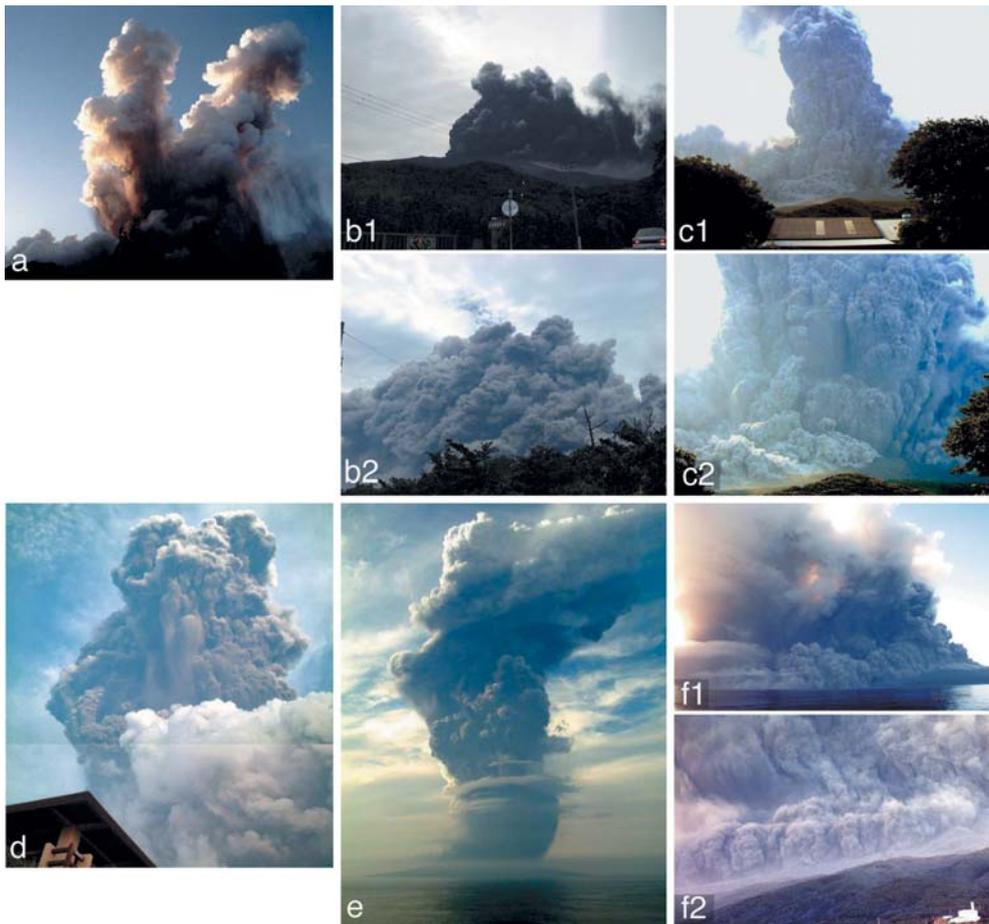


Fig. 3 Photographs of the eruptions during July–August 2000 at Miyakejima. **a** Phreatic explosion on the evening of 8 July 2000, taken by T. Aotani. **b** Phreatomagmatic events (1) from the Miyake airport on the evening of 14 July, and (2) from northeastern middle slope around noon on 15 July 2000. Both taken by S.N. **c** (1) Eruption column and (2) ash cloud expanding from at the base, taken from the Izu district by T. Shimazawa around 08:00 h on 10 August 2000. **d** Eruption column in the earliest stage of the 18

August explosion, taken from the Izu district by N Nishino around 17:10 h. **e** Eruption column reaching the stratosphere, seen from the Mikurajima, 10 km south of Miyakejima and taken by K. Takeiri at about 17:25 h of 18 August 2000. **f** Low-temperature pyroclastic surge (1) extending to the north and south (taken from the research vessel, SHINKAIMARU, about 6 km northwest of the Izu district), and (2) slowly descending the northern slope. Photos **f** (1) and (2) by S.N. during 05:35–06:00 h on 29 August 2000

Thereafter, mudflows repeatedly took place even after the main eruption phase was over.

Explosion stage (10 August–29 August)

The main explosive phase started on 10 August, and continued intermittently through 29 August (Figs. 2 and 3). The caldera had grown to about 1.5 km in diameter by early August (Figs. 2, 4, 5, 6), and was widened later by landslides off its steep walls, producing deposits with hummocky surfaces. The landslides off the caldera wall continued at the time of writing, the latest occurring in March 2003. Active craters had been located on the southern margin of the caldera floor (Fig. 4), just north of the former summit, Oyama (Fig. 1c), and in the place similar to previous craters. Pyroclastic cones of this eruption were formed against the southern wall of the caldera. The largest explosion occurred on the evening of

18 August (Fig. 3d and e), and the eruption column reached about 16 km above sea level (a.s.l.). The last tilt change took place during this explosion and the elongation between Kozushima and Niijima was almost complete (Fig. 2b). Eruption of low-temperature pyroclastic surges took place on the morning of 29 August (Fig. 3f), as described later. The residential area, Kamitsuki, where islanders remained was enveloped by a thick, relatively slow-moving ash cloud (Fig. 7f), but nobody was injured. Active seismicity continued during this period, but at relatively low levels.

Soon after the 29 August event, the National Coordinating Committee for Prediction of Volcanic Eruption officially forecast the likelihood of more explosions such as high-temperature pyroclastic flows. The chief of Miyakejima Village ordered all islanders to evacuate to the mainland on 3 September. Although the main eruption stage was over by September 2000, the evacuation continued for more than 3 years. This was because abundant

Fig. 4 Photographs showing growth of the caldera at Miyakejima since July 2000. **a** On the morning of 9 July 2000, just after Fig. 5a. **b** (1) Around noon of 10 August 2000, and (2) crater of eruption located in the southeastern margin of the caldera floor; Suo-ana is on the lower left. **c** Afternoon of 26 August 2000. **d** 3 September 2000. **e** 4 June 2001. **f** 16 October 2002. Photos **a–d** by S.N., **e** by T.K. and **f** by M. Yoshimoto

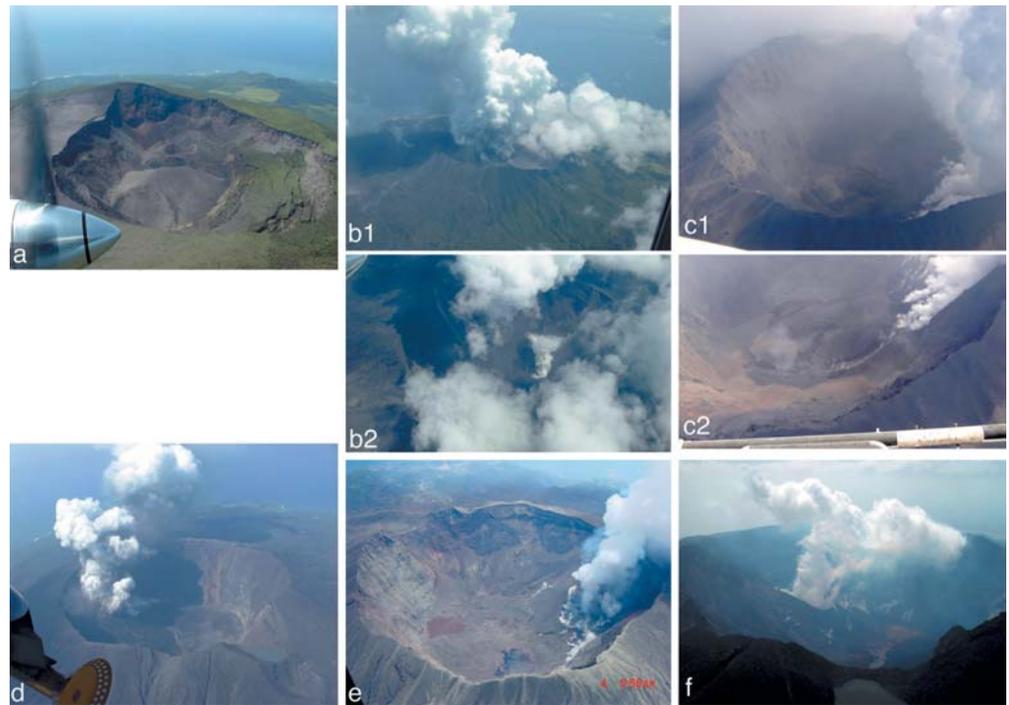


Fig. 5 Panoramic views of the summit collapse in July and early August 2000. **a** Morphology of the original surface was preserved on collapsed blocks, taken half a day after the first subsidence event, around 08:30 h on 9 July 2000. **b** around 11:50 h on 20 July 2000. **c** (1) and (2) around 14:30 h on 4 August 2000. A debris avalanche (*darker-colored*) that traversed a step fault can be seen on the caldera floor (**c** (2): from upper-right to center). All photos by S.N.





Fig. 6 Photographs showing deposits around the caldera. **a** Lava blocks issued in the 14 and 15 July explosions covered the summit parking lot, breaking a public toilet. This area had subsided into the caldera by early August 2000. The caldera rim is on the right back of the skyline, taken on 20 July 2000. **b** Eastern rim of the growing caldera, taken on 5 August 2000. **c** Southeastern edge of caldera rim, taken on 5 August 2000. **d** Eastern edge of the new caldera, taken on 21 November 2001. Craters under the caldera rim were producing a plume rich in SO_2 . All photos by S.N.

SO_2 continued to be emitted from the summit, and because repeated mudflows destroyed the infrastructure of the island during these years.

Degassing stage (after 29 August)

A mist of SO_2 and sulfuric acid aerosols had drifted near the summit since middle August, preventing geologists from approaching the caldera rim. The abundance of SO_2 in the plume emitted from the summit crater, which was measured with COSPEC first from the ground and later from helicopters, increased following 29 August. The abundance was as high as 460 kg s^{-1} (about $4 \times 10^4 \text{ t/day}$) at the end of 2000 (Kazahaya et al. 2001; Shinohara et al. 2003). Ash emission took place several times during the degassing stage, accompanied by continuous volcanic tremor. However, the scale of eruption was small, approximately $<10^4 \text{ m}^3$ DRE in volume. According to the Japan Meteorological Agency, the temperature of the craters measured from helicopter had increased up to about 400°C by the end of 2000. Glow of the summit at night was observed in December 2000 and January 2001 and in November and December 2001. The high temperature condition continued to at least the end of 2002.

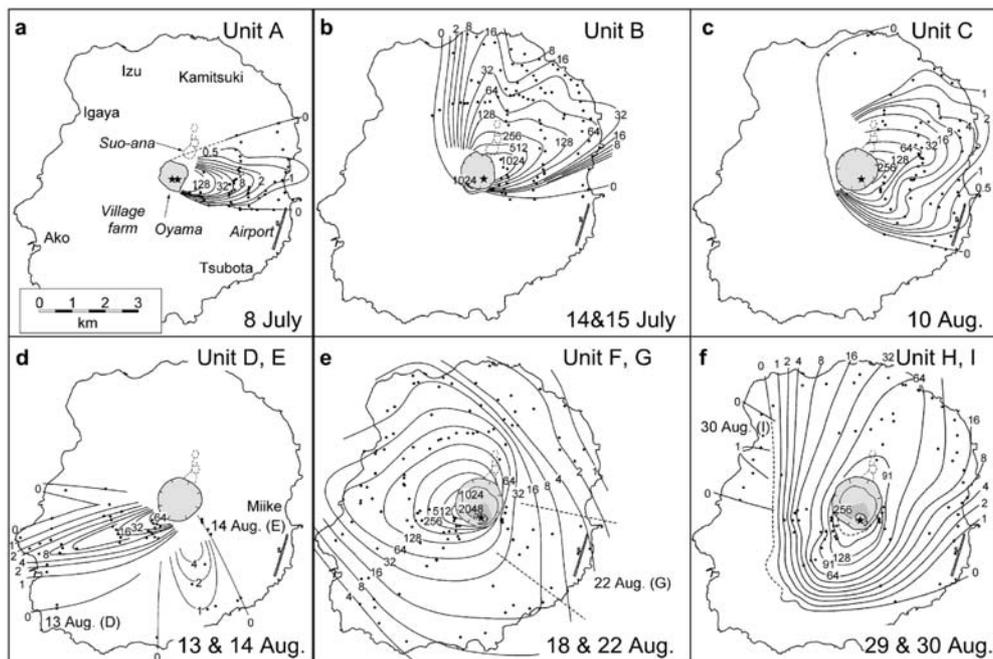
GPS data of the Geographical Survey Institute indicated that Miyakejima shrank horizontally by 80 cm and subsided by as much as 70 cm by mid-September 2000. On the other hand, the baseline between Niijima and Kozushima lengthened, reaching a total of 80 cm during July–October 2000, and Kozushima was uplifted about 20 cm during the same time (Nishimura et al. 2001).

Details of major eruptive events

8 July event

A sudden explosion tossed two or three jets of volcanic ash up to about 2,300 m a.s.l. at 18:41 h (Japan Standard

Fig. 7 Isopach maps of tephra during July–August 2000. Stars in the newly formed, caldera represent the eruption craters. Contours are in millimeters



Time; JST) (Fig. 3a). The eruptive event ended around 19:00 h. Volcanic ash with a total volume of $1.8 \times 10^5 \text{ m}^3$ (DRE) fell over the eastern part of the island (Fig. 7a). The ash consisted of old scoria and lava fragments, and formed a coating of reddish, fine ash near the crater rim. Ballistics of several tens of cm diameter fell over an area extending to 400–700 m east from the crater rim. In this event, the summit area of about 800 m across subsided about 200 m without significant modification of the topography (Fig. 4a). The subsidence volume measured using air photographs taken by the Aero Asahi Corporation was $5.6 \times 10^7 \text{ m}^3$. In the center of the subsided mass, two small craters of 50 to 100 m across were observed, from which ash had issued (Fig. 7a). Islanders who witnessed the 8 July evening event felt a rolling sensation, which may have been due to the occurrence of the first VLP event.

14–15 July event

Vigorous explosions occurred intermittently from 04:14 h of 14 July until around 13:00 h of 15 July. A cauliflower-shaped eruption column rose up to 2,600–3,100 m a.s.l. (Fig. 3b). The event consisted of four stages; morning and afternoon of 14 July, and early morning and daytime of 15 July. At around 18:00 h of 14 July, small-scale cock's-tail jets rose from a pyroclastic cone of 250 m across located at the SE corner of the caldera floor. These jets were soon enveloped by a following gray cauliflower cloud. Eruption products consisted of gray-colored fine ash derived from old volcanic rocks and a small amount of juvenile material. Ballistic blocks of older lavas were thrown about 1 km from the south caldera rim (Fig. 6a). The eastern to northern parts of the island were thickly covered with fine ash (Fig. 7b).

10 August event

For about one month after July 15, summit subsidence continued without eruption. Steam was reported from the lower slope of the southern caldera rim on 7 August. An eruption column formed on the morning of August 10 and reached about 8–10 km a.s.l. (Fig. 3c), but discharge declined in the early afternoon. Air inspection at noon showed a still-active white plume rising from a crater, surrounded by relatively flat outer slopes, located at the SE corner of the caldera floor (Fig. 4b). Dark-colored deposits were plastered against the steep eastern wall of the caldera. A muddy current of water was observed flowing from the crater wall onto the caldera floor. The eruption plume became white around noon, and eruption ended around 16:30 h, though white fumes continued to rise.

Although it was a dry day, mudflows were generated on the eastern slope during the eruptive event and a current of hot, muddy water crossed the coastal road, implying very wet conditions in the eruption column on

this day. Pyroclastic surges were observed at the base of the eruption column, moving slowly (up to 10 m s^{-1}) as a laterally expanding ring, but sometimes moving back inside the caldera (Fig. 3c). This may reflect complex wind currents generated both outside and inside the caldera during eruption. Video footage taken by M Furuya just after this event did not reveal any evidence of plants burning on the southern rim of caldera, though that area was covered by new ballistics and ashfall.

Small-scale eruptive events occurred during 11–14 August. After the August 10 event, only infrequent inspections inside the caldera were made. However, a TV air-shot from a helicopter on August 11 showed black cock's-tail jets rising intermittently from a crater filled with a hot muddy pool. Mudflows descended directly from the crater to the caldera floor. Field inspection of the southern slope on 14 August showed an accumulation of small, fresh crystals of pyrite in a small water pond resting on tephra. A white plume rising from the caldera on 14 August was separated into three columns just above the caldera rim, probably indicating the existence of three active craters inside the caldera.

18 August event

On 18 August, an eruption column ascended to about 16 km a.s.l. Ash fell over the entire island and ballistics, including juvenile bombs, were thrown in every direction from the caldera (Fig. 7e). A lava block as large as 50 cm across penetrated asphalt on the coastal road in Igaya (Fig. 1c). This was thrown through the lowest notch of the caldera rim. According to records from a camera set in Tsubota, a dark eruption column rose first at 17:04 h in the southern part and then at 17:05 h in the eastern part inside the caldera. The column head reached about 5 km a.s.l. at 17:10 h, giving an average ascent speed of $\sim 14 \text{ m s}^{-1}$. Around 17:20–17:25 h, the column head reached over 10 km a.s.l. (Fig. 3e). Around this time, TV footage showed airborne ballistics near the base of the eruption column, and a black basal eruption cloud moving down the middle northwestern and southern slopes of the volcano. According to local people, lapilli of scoria and lava fell in Miike, Tsubota and Ako around 18:10–18:40 h. The eruption column became like an umbrella of height 10–16 km at 18:15 h; fallout at Ako and Tsubota continued until about 20:30 h. Ash from the 18 August explosion fell at Mikurajima and Hachijojima, about 20 km and 100 km south of Miyakejima, respectively. The VLP event that occurred at 18:08 h was the last of a series of such events accompanied by tilt change. The climax of the 18 August eruptive phenomenon probably was coincident with this seismic event.

Cattle houses and grass in the village farm on the middle slopes of the southwestern sector of the island, about 1.5 km away from the crater, were not burned, even though wooden roofs were penetrated by ballistics. A house in the village farm closest to the summit (around 1 km), was ignited, probably by volcanic bombs (Fig. 8b).



Fig. 8 Photographs showing effects of the 18 August 2000 explosion and accompanying volcanic bombs. **a** Cattle cabin whose ash-covered roof was penetrated by ballistics, taken in the village farm on the middle of western slope of the volcano on 20 August 2000. **b** Debris of a house burnt on 18 August, in the easternmost area of the village farm, taken on 22 November 2001. **c** Cauliflower-shaped bomb fallen in the village farm, taken on 20 August 2000. **d** Partly carbonized wood stem under a bomb (*in circle*) on the upper slope of the village farm, taken on 22 November 2001. All photos by S.N.

This may be due to the larger size, high temperature and concentration of bombs near the caldera rim.

Small-scale eruptive events also occurred on 22 and 24 August.

29 August event

In the early morning (around 04:15 h) of 29 August, an eruption column rose to about 8 km a.s.l. and ash clouds repeatedly moved, very slowly to the north-northeast and southwest. The authors observed partial collapses of eruption columns, where masses of dark cloud broke away from the rising column and fell on the caldera rims. The clouds moving on the volcano slopes resembled those of vigorous hot pyroclastic surges (Fig. 3f), though the speed and temperature were very different. The velocity measured from a boat sailing northwest of the island was around 4 m s^{-1} . Pulsed values of the wind speed (to the NNE) were recorded as 5 m s^{-1} at 05:30 h in the Miyakejima Weather Station at the northern end of the island (Fig. 1c). Video footage taken from the south gives the speed of 15 m s^{-1} near the source down to 5 m s^{-1} at the terminus. Temperature measured at the Miyakejima Weather Station rose from 25 to 29°C at 05:40 h when an ash cloud enveloped the station. Houses and cars encountered the ash cloud associated with the descending pyroclastic surges. J Oikawa and M Ueshima met this ash cloud in a car on the coastal road in the eastern part of the island (near Satado). They felt a weak wind in the car but did not notice any heat associated with the ash. Some

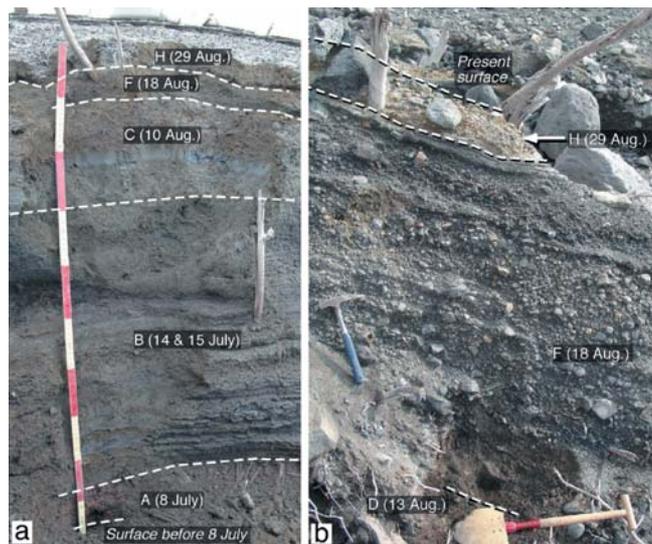


Fig. 9 Exposures of the products of the 2000 eruption at Miyakejima. **a** Deposits near the eastern rim of the new caldera. The scale bars on the left are painted every 10 cm. **b** Deposits near the southwestern rim of the caldera. Original photos by M.N.

residents from Kamitsuki witnessed invasion of fine ash into their houses and smelled sulphurous gas.

Eruption products

Tephra from each event of the 2000 eruption is relatively easy to identify, based on its characteristic color, existence of accretionary lapilli, shrinkage cracks formed between eruptive units, or sandy layers formed during reworking by rain (Figs. 9 and 10). For example, the 8 July eruption products (Unit A) are porous and reddish coarse-grained ash. Large grains are oxidized scoria, probably remnants of pre-existing scoria cones at the summit. The 14–15 July products (Unit B) are gray to dark yellow, consisting of several layers of different grain size. The 18 August products (Unit F) are rich in juvenile materials. The 29 August deposits (Unit H) are brownish yellow to dark yellow, with the characteristics of sediments deposited by density currents. Accretionary lapilli are abundant in Units F and H. Ash deposits were lithified like plaster under sunshine after rainfall, where abundant tiny crystals of gypsum and anhydrite were precipitated. However, anhydrite was not found as a stable phenocryst phase.

Distribution maps of ash deposits for individual eruptive events were produced by the authors soon after each eruptive event. The volume of deposits for each eruptive event was calculated from isopach maps using the method of Fierstein and Nathenson (1992). The total volume of deposits in June and August eruptive events is about $9.3 \times 10^6 \text{ m}^3$ dense-rock equivalent (DRE) or about $2.3 \times 10^{10} \text{ kg}$ (Table 1). The volume of the products of individual events ranges from 10^3 to 10^6 m^3 DRE, and the largest volume is Unit F ($4.2 \times 10^6 \text{ m}^3$ DRE). This does not

Table 1 Tephra volume for representative events of the 2000 eruption at Miyakejima

Eruptive event	Tephra (m ³) DRE ^a	Scoria (m ³) DRE ^a	Scoria (%)
8 July	1.8×10 ⁵	5.1×10 ³	3
14–15 July	2.6×10 ⁶	5.9×10 ⁵	22
10 August	4.9×10 ⁵	2.4×10 ⁴	5
13 August	7.6×10 ⁴	1.7×10 ⁴	22
14 August	4.4×10 ³	1.3×10 ²	3
18 August	4.2×10 ⁶	1.9×10 ⁶	45
29 August	1.6×10 ⁶	3.8×10 ⁴	2
30 August	4.0×10 ³	–	–
Total	9.3×10 ⁶	2.6×10 ⁶	28

^a Densities of tephra and dense rock were assumed to be 1,400 and 2,500 kg m⁻³, respectively, except for 8 July tephra of 1,000 kg m⁻³

include volumes of pyroclastic cones that were formed within the 2000 Caldera. The latter are probably of the order of 10⁷ m³, assuming the maximum heights of 50–100 m. Even if the volume of the pyroclastic cones is taken account, the total volume of erupted material is much smaller than the subsidence volume of 2000 Caldera (about 6×10⁸ m³) (Hasegawa et al. 2001).

Eruption rates can be calculated for each eruptive event based on the volume and eruption duration estimated from geophysical monitoring data (tremor and air-shock) and video footage. The average eruption rates range from 10³ to 10⁶ kg s⁻¹. A more detailed calculation of eruption rate is also possible for subdivided layers in each event (MN, in preparation). The eruption rate for layers including the most abundant juvenile materials in the 18 August event (Figs. 9 and 10) was estimated at about 10⁶ kg s⁻¹. The eruption rate for surge layers of the 29 August eruptive event (Fig. 10) is between 10⁶ and 10⁷ kg s⁻¹. The latter is a surprisingly high value for the discharge of low temperature pyroclastic surges.

Grain size analysis of products of the July to August events, which were deposited near rims of the Oyama Caldera, is shown in Fig. 11. The August eruptive events are dominated by material of low phi (ϕ) value, –2 to –4 (4–16 mm), because abundant ballistics are included in the August products near the caldera. Figure 11 shows enrichment of fine materials ranging from 6 to 8 in ϕ value (4–16 μ m). Bimodality in the July products is probably caused by aggregation of abundant fine ash, which tended to act as coarser grains during falling. Due to this effect, sorting of the products is rather bad; 2–4 as σ_ϕ . When fragmentation and dispersion indices of Walker (1973) are examined, the products of the 2000 eruption show high fragmentation (F)/dispersion (D) ratios, and fall in the field of phreatomagmatic eruptions. Only the products of the 18 August event ($F=34\%$ and $D=14$ km²) fall close to the vulcanian and subplinian fields, consistent with magmatic eruption.

Ash from the July to August eruptive events contains kaolinite and smectite as hydrothermal minerals, in amounts of up to 20 wt% of particles less than 0.1 mm across (Yasuda et al. 2002). Their abundance is lowest in products of the 18 August event, consistent with the lar-

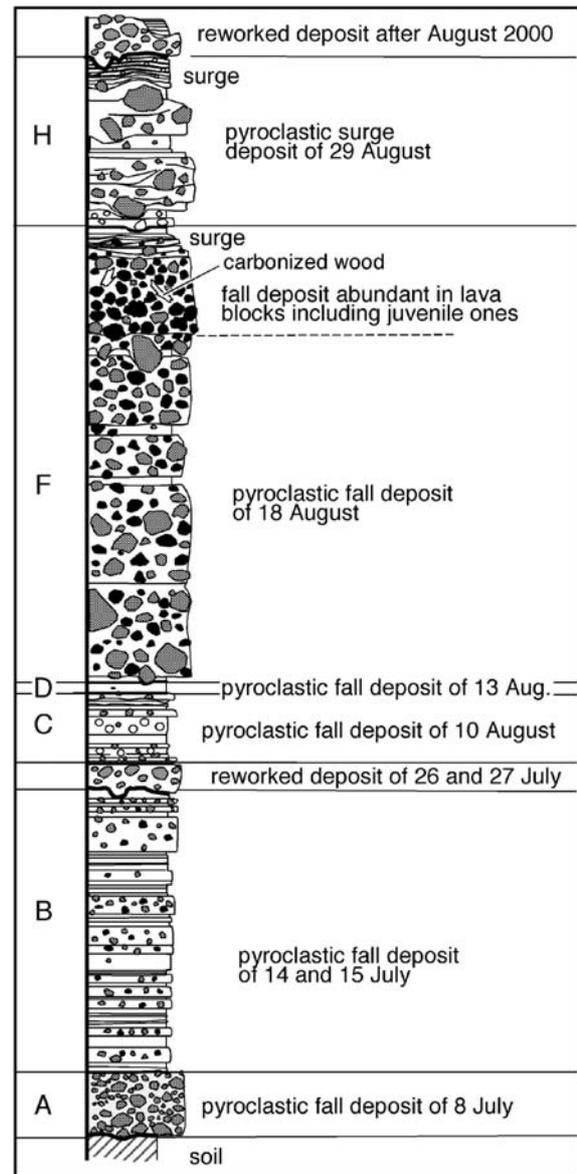
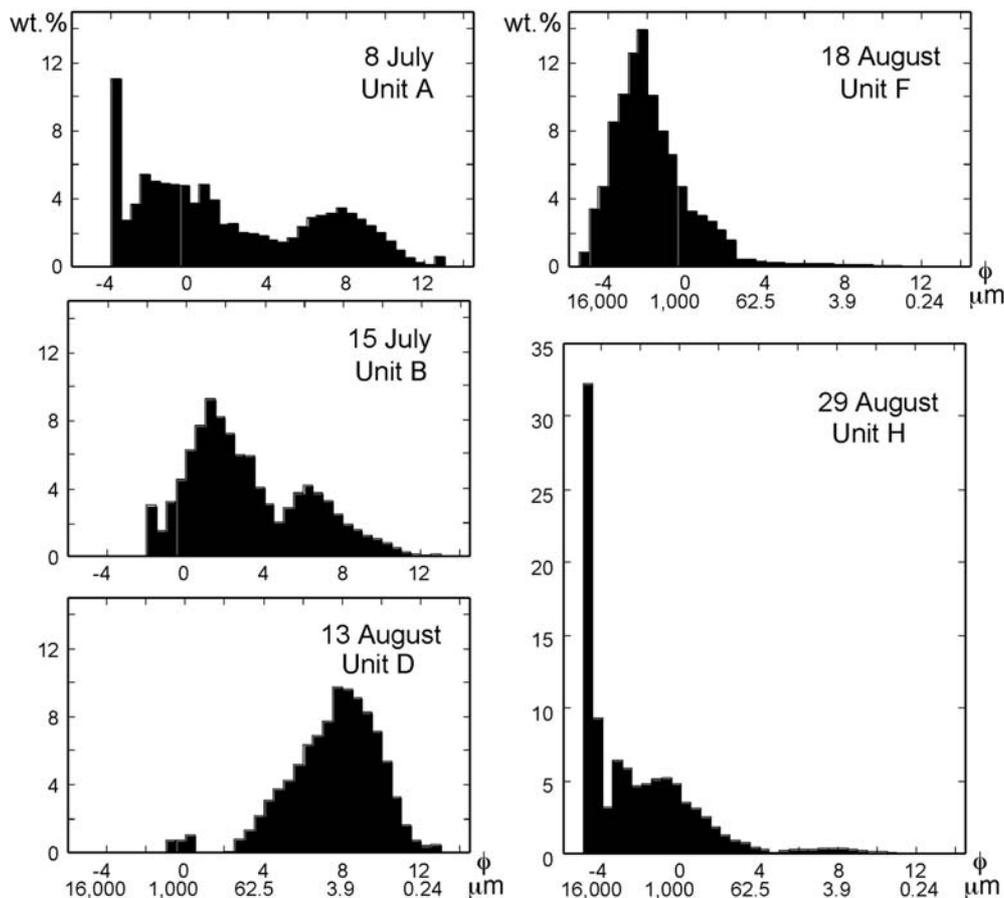


Fig. 10 Schematic cumulative section of tephra of the 2000 eruption at Miyakejima. Old lava and juvenile fragments are shown in gray and black, respectively

gest contribution of juvenile materials. Figure 12 shows the proportion of kinds of particles larger than 1 mm across. In this process, fresh and glassy basaltic fragments (mostly scoriaceous) that appear homogenous under the binocular microscope and similar to either spatter of the 27 June eruptive event or bombs of the 18 August event, were counted as juvenile. Fresh but non-glassy basalt fragments were occurred as crystalline lava. Abundant juvenile materials were found in products of the 18 August eruptive event and also in 14 and 15 July events. A lesser amount of juveniles is found in products of the 8 July, and 10, 14 and 29 August eruptive events. Therefore, it is concluded that the 18 August eruptive event was magmatic, whereas the eruptive events on 8 July, 10, 14 and 29 August were mainly phreatic.

Fig. 11 Grain size distribution of tephra of representative eruptive events. All samples were collected near the summit caldera



Juvenile materials

The thermal history of volcanic bombs of the 18 August eruptive event was investigated by measuring their thermoremanent magnetism. There was a possibility that volcanic bombs might be recycled materials derived from the pre-existing crater, though at least one bomb ignited a fire and others produced carbonized wood chips near the summit. Ten oriented, volcanic bombs and seven angular to subangular lava blocks that fell on 18 August were collected from the village farm in January and April 2001. All bombs are rounded and have bread-crust skins, coated by reddish ash, with diameters up to 20 cm across (Fig. 8c and Fig. 2 of Kaneko et al. this issue) (Uto et al. 2001; Saito et al. this issue). Lava blocks are up to 30 cm across. Samples of bombs and blocks were processed at the paleomagnetic laboratory of Kobe University with a SMM-85 spinner magnetometer. A stepwise thermal demagnetization method was used to obtain the characteristic paleomagnetic direction. The principal component analysis technique was employed for handling the demagnetization data.

All samples show one-component remanent magnetization during progressive thermal remanent magnetization. Unblocking temperatures of blocks are between 560 and 590°C, whereas those of the bombs are between 530 and 560°C. Both types show a single thermal history. Directions of characteristic remanent magnetization of all

blocks are scattered (Fig. 13a), whereas those of bombs (with the exception of six points for three samples) are clustered, pointing to the present magnetic north. These results indicate high-temperature emplacement of the bombs and cooler emplacement of the angular blocks. Recycling of the bombs is difficult to accept. Three bombs samples with different emplacement directions may have been partially rotated after emplacement, for example, by small-scale mudflows, because their inclinations are almost the same as the other clustered bomb samples.

Two kinds of juvenile materials of the 2000 Miyakejima eruption are distinct in chemistry and mineralogy from one another (Fig. 13b) (Amma-Miyasaka et al. this issue; Kaneko et al. this issue). The 27 June spatter is aphyric glassy basaltic andesite with minor phenocrystic plagioclase, clinopyroxene and magnetite. The chemistry is very close to that of lava from the 1983 eruption. On the other hand, the 18 August volcanic bombs are phyric basalt containing abundant phenocrysts of plagioclase with minor amounts of clinopyroxene and olivine. The total phenocryst content is about 20 vol%. The chemical composition and the phenocryst assemblage of the 18 August bombs are unique among historically erupted lavas. The incompatible element ratios (e.g., K/Zr or Ba/Zr) of these two juvenile materials, however, are almost identical (Geshi et al. 2002b), suggesting that they may have a common source. Addition of phenocrysts found in the 18 August bomb to the 27 June spatter (20 wt% of plagi-

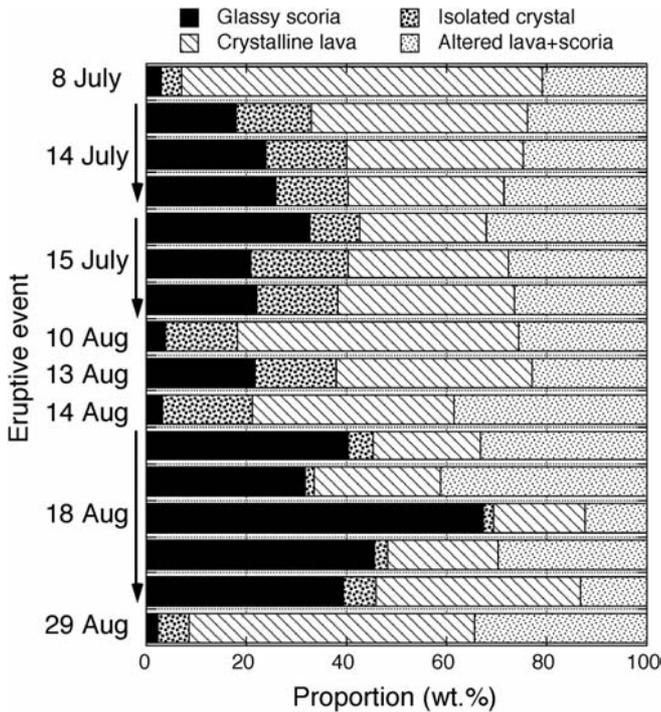


Fig. 12 Proportions of constituents, larger than 1 mm across, in tephra of the 2000 eruption. Glassy scoria is juvenile. *Arrows* indicate stratigraphically ascending order

close, 2% of clinopyroxene and 3% of olivine) can explain the chemical difference between the two juvenile materials. Kaneko et al. (this issue) propose a model in which melt that had survived since 1983 was mixed with the 18 August magma ascending from below. Melt inclusions in plagioclase phenocrysts of the spatters and bombs have chemical trends similar to each other, though those in the spatter are relatively evolved, including volatile elements such as S and Cl (Yasuda et al. 2001, 2002).

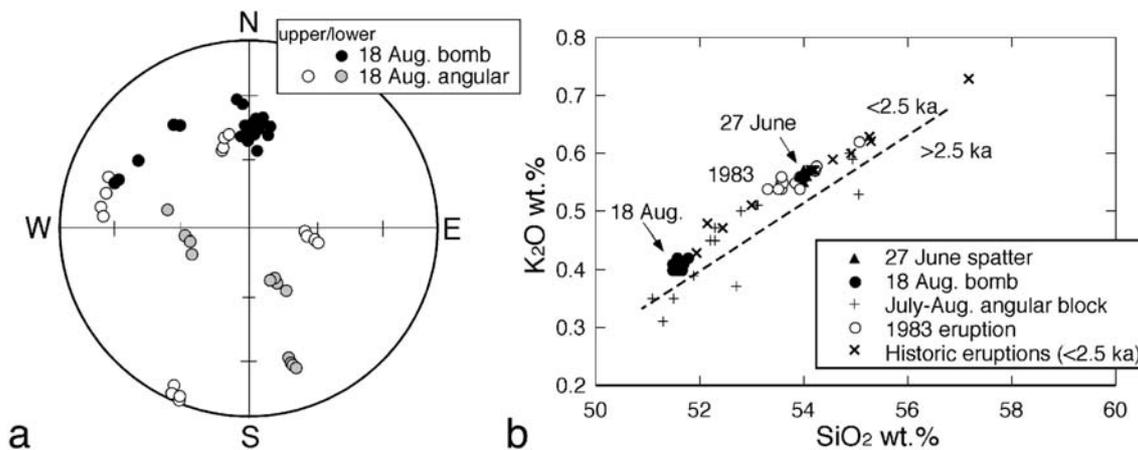


Fig. 13 Paleogeomagnetism and chemical composition of ballistics from the 18 August 2000 eruptive event. **a** Equal-area projection of basaltic bombs and angular lava blocks (positive inclinations are shown by *black* and *gray circles*, negative inclinations by *open circles*). All samples were collected from the village farm in 2001. **b** Volcanic bombs fall within a narrow compositional range, con-

Geshi et al. (2002b) reported that the juvenile materials from the 14–15 July eruptive event have the same bulk chemical composition as that of spatter from the 27 June eruptive event and are distinct from volcanic bombs erupted in August. These data indicate that basaltic andesite magma related to the early eruption had been replaced with basaltic magma before mid-August.

Discussion

Caldera formation

As shown in Fig. 2, the growth rate of the summit caldera was nearly constant and the volume of caldera attained its maximum value of about $6 \times 10^8 \text{ m}^3$ before the explosion stage (Hasegawa et al. 2001). The first appearance of summit subsidence resembled collapse depression formed experimentally by Roche et al. (2001). By analogy with their experiments, a large cavity or space filled with light, frothy magma may have already formed at a shallow level before the onset of collapse on 8 June. The existence of a large negative gravity anomaly ($-145 \mu\text{gal}$) at the summit area a few days before the first collapse (Furuya et al. 2003), supports the idea of a cavity just below the summit in early July. As the amount of juvenile scoria in the 8 June tephra ($5.1 \times 10^3 \text{ m}^3 \text{ DRE}$; Table 1) is smaller by four orders of magnitude than the volume of the collapse that took place that day ($5.6 \times 10^7 \text{ m}^3$), the cavity must have been filled by either gas or extremely foamy magma. As the top of the magma reservoir is considered to be about 3 km depth (e.g., Sakai et al. 2001), we consider that the cavity space rose upward by stopping, as shown in the experiments of Roche et al. (2001) in late June and early July. Seismic data during 4–8 July by the Earthquake Research Institute (ERI) clearly indicated that the shallowest limit of hypocenters for volcano tectonic earth-

trasting chemically to the 27 June spatter and 1983 lavas. Angular lava blocks of the 18 August eruptive event are scattered. A *dashed line* marks the chemical boundary separating lavas older and younger than 2.5 ka (from Amma-Miyasaka and Nakagawa 2002). Angular lava blocks of the 2000 eruption include lavas older than 2.5 ka

quakes had ascended from about 3 km depth during that period. It is likely that these earthquakes accompanied stoping process above the magma reservoir. Sasai et al. (2001) modeled temporal changes in electric and magnetic intensities measured before 8 July, and hypothesized that they were caused by upward migration of a reservoir filled with hydrothermal fluid from about 1.5 km below sea level to the summit. These observations support a stoping model involving a rising cavity at least in the early stage of caldera collapse.

Kumagai et al. (2000) introduced a piston model for caldera subsidence to explain the repeated VLP events and tilt changes during the period of caldera collapse from 8 July to 18 August. Their model successfully predicts that sinking of a large piston into a magma reservoir, accompanied by friction against the cylinder wall, causes VLP events with step-like tilt changes preceded by swarms of earthquakes of a few hours duration. If so, most parts of the piston should be composed of lava blocks and fragments that were stopped during cavity ascent. The following two facts have to be explained by the piston model if it had acted continuously up to the 18 August eruptive event. Caldera subsidence had almost finished within the summit subsidence stage (by early August) (Fig. 2c). The time interval between VLP events became longer (0.5–2 days) beginning in early August (Kikuchi et al. 2001).

Lateral migration of magma

Though the initial magma ascent in late June might have been triggered by the input of basalt magma into the reservoir of basaltic andesite, as proposed by Kaneko et al. (this issue), it is unlikely that the overpressure in the magma reservoir was maintained during the summit subsidence stage. This is because magma was drained out laterally. Shrinkage of the reservoir is best able to occur by sinking of a gravitationally unstable roof into the magma body, proposed by Uto et al. (2001) and Saito et al. (this issue). Their model is that roof rocks such as cumulate gabbro sank into the magma body. The density contrast becomes larger when magma in the reservoir is foamy.

It is likely that the lateral migration of magma was controlled within a plate-tectonic framework. Hamada et al. (1985) compiled seismic activity around Miyakejima during the 1962 and 1983 eruptions. Swarms of earthquakes including M5 took place in the area of the present magma intrusion for a month after the 1962 eruption. Swarms of earthquakes took place over a few tens of kilometers south–southwest of Miyakejima, beginning a year before the 1983 eruption. This strongly indicates an intimate relationship between eruptions at Miyakejima and regional tectonic movements. Nakamura (1984) hypothesized that eruption fissures develop radially from the summit at Miyakejima under the control of a nearly neutral horizontal tectonic stress (Fig. 1c). The alignment of submarine craters of the 27 June eruptive event follows

this rule. On the other hand, distribution of hypocenters and focal mechanisms of major earthquakes between Kozushima–Niiijima and Miyakejima indicate NE–SW extension for this area during the seismic activity (Kaidzu et al. 2000; Sakai et al. 2001), concordant with the principal stress caused by the movement of the Philippine Sea plate (Fig. 1b). This strongly implies the possibility that magma was released from under Miyakejima by tectonic control.

Cause of the explosive events

The middle July eruptive events may have been triggered by interaction of magma with groundwater from the surrounding rocks during the summit subsidence. The 14–15 July tephra contains glassy scoria chemically identical to the submarine spatter (Geshi et al. 2002b). It is plausible that the magma that had nearly stopped ascending in the conduit in late June and remained within the stoped blocks or cavity still possessed enough heat to drive further explosions.

The 18 August explosion discharged the most abundant juvenile materials among the eruptive events of 2000. The facts that an abundant mist of sulfuric acid was issued from craters in middle August and that gravity corrected for topographic effects increased since middle August (Furuya et al. 2003), indicate that magma was approaching the surface in the explosion stage. The volume of magma intruded as a dike under the sea between Niiijima and Kozushima during the 2000 eruption was estimated as 1.2–2.0 km³, and is much larger than the volumes of the summit collapse and of Miyakejima shrinkage during the same period (<1 km³) (Yamaoka et al. this issue). The different volume of magma should have been supplied from the bottom of a dike or the magma reservoir beneath Miyakejima. The GPS data (Fig. 2b) suggest that the rate of magma lateral drainage out of the reservoir had decreased by middle August. Therefore, it is plausible that although magma was being supplied into the reservoir from the bottom in middle August, the supply amount became larger than the volume of magma drained out of the reservoir. Consequently, the overpressure may have been built up in the reservoir before 18 August.

Abundant hydrothermally altered minerals and anhydrite/gypsum in eruption products, and the beginning of intense SO₂ degassing after the explosion stage suggest a contribution of hydrothermal fluid to most of the eruptive events during July–August. This is also supported by electric and magnetic field changes that were synchronous with VLP events in the summit subsidence and explosion stages (Sasai et al. 2001). Rapid movement of fluid in an aquifer can introduce strong changes in electric and magnetic fields. We propose that the cavities formed by stoping were reservoirs of hydrothermal fluid rather than foamy magma. The fluid reservoirs may have acted as filter of SO₂ gas during the summit subsidence and explosion stages, and then were destroyed by the 18 and 29

August explosions. After the 29 August explosion, direct degassing of magma ascending and convecting within the conduit (Shinohara et al. 2003) may have brought a high abundance of SO₂ directly to the surface.

Low-temperature pyroclastic surge

Products of the low-temperature, slow moving pyroclastic surge of the 29 August eruptive event contain very scarce amount of glassy scoria and abundant hydrothermal altered minerals (Fig. 12 and Yasuda et al. 2002), suggesting a phreatic origin. Most of glassy scoria may be recycled from the 18 August eruption products. The volume of the 29 August event is the second largest among the events of 2000. We expect that, though a large vent had been opened to the caldera floor by the magmatic explosion on 18 August, it was soon plugged by collapsed material from the vent wall or crater rim. It is likely that hydrothermal fluid from the surrounding rocks may have been heated by underlying magma, generating the low-temperature pyroclastic surge on 29 August. Although the eruption rate of the 29 August explosion was large compared to the 18 August one, it did not send ash high into the stratosphere, because the thermal mass was too low. Therefore, although the initial velocity of the explosion was high enough, masses of ash cloud remained inside the caldera, overflowed and moved slowly down the slopes of the volcano.

Concluding remarks

The eruptive activity in 2000 was characterized by continuous lateral migration of magma from under Miyakejima Volcano to the northwest as far as 30 km from source. This poses two questions: (1) How could magma migrate toward the northwest as far as several tens of kilometers? (2) What was the trigger for the 18 August explosion, after magma migration stopped?

Magma migration probably was caused by northeast–southwest extension in the northern Philippine Sea plate. It is likely that magma was released tectonically through a dike from under Miyakejima, and that the roof rocks, gravitationally unstable above the foamy magma induced by decompression due to magma extrusion, collapsed into the reservoir. Subsequent stoping of the roof rocks above the magma reservoir caused caldera subsidence. Cavities formed in the stoping process became reservoirs of hydrothermal fluid, into which magmatic gases were absorbed. Phreatic explosions of middle July may have been triggered by interaction of magma with these hydrothermal fluids. Magma ascent was accelerated after the end of caldera subsidence and the most explosive, magmatic event occurred on 18 August. A cool pyroclastic surge generated on 29 August, probably due to boiling of hydrothermal fluid sealed inside the vent after 18 August. Finally, magmatic degassing emitted large amounts of SO₂ into the air.

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