Unzen Volcano : the 1900-1992 eruption

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10. Lava Domes and Pyroclastic Flows of the 1991-1992 Eruption at Unzen Volcano

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Introduction

After 198 years of dormancy, Unzen (Unzendake) Volcano in the Shimabara Peninsula, Kyushu, Japan, erupted on 17 November 1990 (Fig. 10-1). Preceded by phreatic and phreatomagmatic eruptions, a new lava dome formed at the summit of Mt. Fugen (Fugendake) on 20 May 1991. Continuous growth of lava dome and falls of lava blocks from the margins frequently generated pyroclastic flows.

Seven dome-like mounds, consisting of juvenile lavas and fragments, formed successively at the summit during the May 1991-April 1992 eruptions. Here, these dome-like mounds are referred to as Domes 1, 2, ..., and 7, in the order of formation.

In this paper, geological aspects of the 1991-1992 eruption are summarized. The chronological description of the 1990-1992 eruptions appears also in Ohta (1991), Nakada and Kobayashi (1991), Nakada and Fujii (1992), Geological Party, Joint University Research Group (1992), and reports from Smithsonian Institution (1991-1992).

Geological background

Unzen Volcano has grown since 500 Ka (500,000 years ago) in the Unzen volcanic graben where N-S tensile stress is dominant (Fig. 10-1; Ohta, 1984; Nakada and Tanaka, 1991). The growth history of Unzen volcano comprises four stages; pre-Takadake, Takadake, Kusenbudake, and Fugendake in the order of formation. Each stage, except the pre-Takadake stage, has a life time of about 100 Ka. Three individual cones formed in these stages. Older volcanic cones were eroded deeply and intensely deformed by normal faulting predominantly in the E-W directions. The youngest volcanic cone, Fugendake, in the eastern part of the Shimabara Peninsula, is slightly eroded and deformed. The geodetic data showed that both sides of the Unzen Volcanic Graben has been pulled apart in the N-S direction at a rate of 14 mm/year and the central zone has been subsided at a rate of 2 mm/year during these 100 years (Tada, 1985). Drill core data indicate that the graben is filled with thick volcanic piles which increase in thickness toward the center (NEDO, 1988). The volcanic piles extend down to about 1,000 m

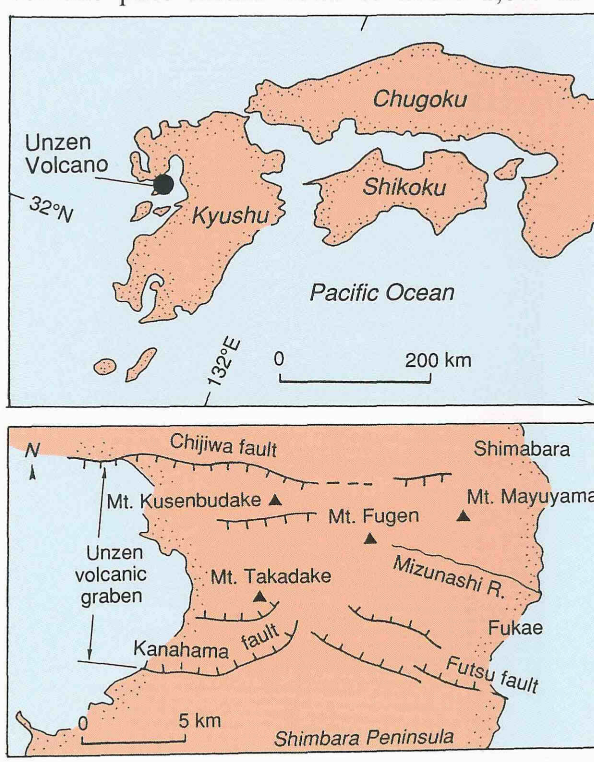

Fig. 10-1. Index map showing Unzen Volcano in Shimabara Peninsula, Kyushu Island, Japan, Active faults characterize the Unzen Volcanic graben.

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below the sea level.

Mt. Fugendake's summit cone probably collapsed 20 Ka, resulting in the formation of a horseshoe-shaped depression (about 1.5 km wide: Myoken Caldera) at the summit (Fig. 10-2; Tanaka and Nakada, 1988). Several domes formed in the caldera after the caldera formation, including the new dome complex of the 1991 eruption. Besides the new dome, the latest dome is found to have formed about 4 Ka, based on ^{14}C dating of pieces of burnt wood found in block-and-ash flow deposits, which were probably deposited during the dome formation. Two large lava domes, Mayuyama, formed outside the caldera (Fig. 10-1), probably contemporaneously with Fugendake domes. Collapse deposits such as debris avalanches and flows, and block-and-ash flows are thick and wide around the Fugendake volcanic cone.

Total volume of the Unzen volcanic rocks is about 103 km^3. Most of this volume is occupied by rocks of the pre-Takadake stage. Mainly dacite magma erupted throughout the Unzen volcanic activity. Thick lava flows and domes together with their collapse deposits (debris avalanches/flows, block-and-ash flows, and talus) characterize the eruption products. No scoria or pumice bed was recovered even in boring cores. The Fugendake Cone is about 10 km^3 in volume. Most of the Unzen volcanic rocks are porphyritic and contain hornblende and biotite phenocrysts.

1663 and 1792 eruptions

Historic eruptions occurred in 1663 and 1792. In 1663, andesite lava spouted from a crater opened in the Myoken caldera and flowed down the northern slope through the notch cutting the caldera rim (Fig. 10-2). The volume of magma erupted to the surface was about 2×10^6 m^3. This lava named "Furuyake" (the old burn) has the lowest SiO_2 content among the Unzen volcanic rocks (57 wt.%). In 1792, dacite magma erupted from the upper part of the gently sloped northeast flank of the Mt. Fugen and flowed down as block lava flow. The lava named "Shin-yake" (the new burn) was the most enriched in SiO_2 (67 wt.%). There is no record of pyroclastic flows during the 1792 eruption. The total volume of the 1792 lava flow was 2.2 - 3.0×10^7 m^3. The average eruption rate was about 5×10^5 m^3/day or

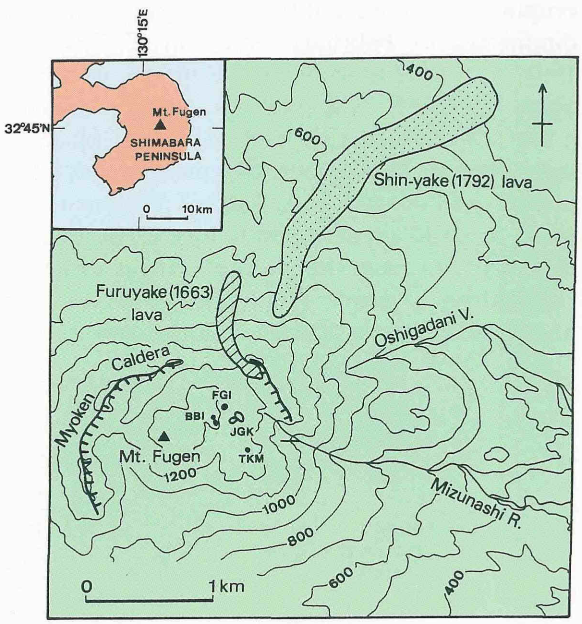

Fig. 10-2. Map showing craters in Mt. Fugen at Unzen Volcano. Also shown 1663 and 1792 lavas. JGK = Jigokuato Crater, TKM = Tsukumojima (Kujukushima) Crater, BBI = Byobuiwa Crater, FGI = Fugen-ike Crater.

more in the early stage and decreased in the later stage. Just after the 1792 eruption, a large collapse of the Mayuyama dome took place. This may have been triggered by strong earthquakes which occurred during the lava eruption. The collapse generated a large-scale debris avalanche which poured into the Ariake Sea and caused a tsunami to strike the opposite shore (Higo district). About 15,000 persons in Shimabara and Higo were killed by this disaster ("Shimabara Catastrophe"). The volume of collapse deposits was about 0.48 km^3 (Katayama, 1964; Ui, 1983)

Before the 1990 eruption, three craters (Jigokuato, Kujukushima, and Fugen-ike craters) have opened near the eastern caldera rim (Fig. 10-2).

Chronology of 1990-1992 eruption

November 1990 - May 1991

Following a series of earthquakes below the summit, a phreatic eruption took place at two summit craters (Jigokuato and Kujukushima) on 17 November 1990 (Umakoshi et al., 1991). This eruption has continued but the degree of activity diminished by February 1991. On 12 February 1991, a phreatomagmatic eruption occurred along a fissure. The volcanic activity became more active, such that eruptions took place at three craters. An eruption column with cock's tail plumes was observed on 9 April. Fragments as much as 20-30 cm across were ejected in the end of April and early May. The vertical eruption stopped on 12 May. The Jigokuato Crater had enlarged as large as 50 m in diameter and 30 m in depth. Very shallow volcanic earthquakes began to occur just under the eruptive site on 13 May. At the same time, the summit was swelling: EDM (electron-optical distance measurement) indicated a rapid inflation of the summit area (Saito et al., 1991). NW-trending parallel cracks formed around the Jigokuato Crater, which mirrored the graben structure of the crater area.

A lava spine within the Jigokuato Crater was first recognized by press aircraft on 20 May. The lava spine was capped by black-colored crater-fill

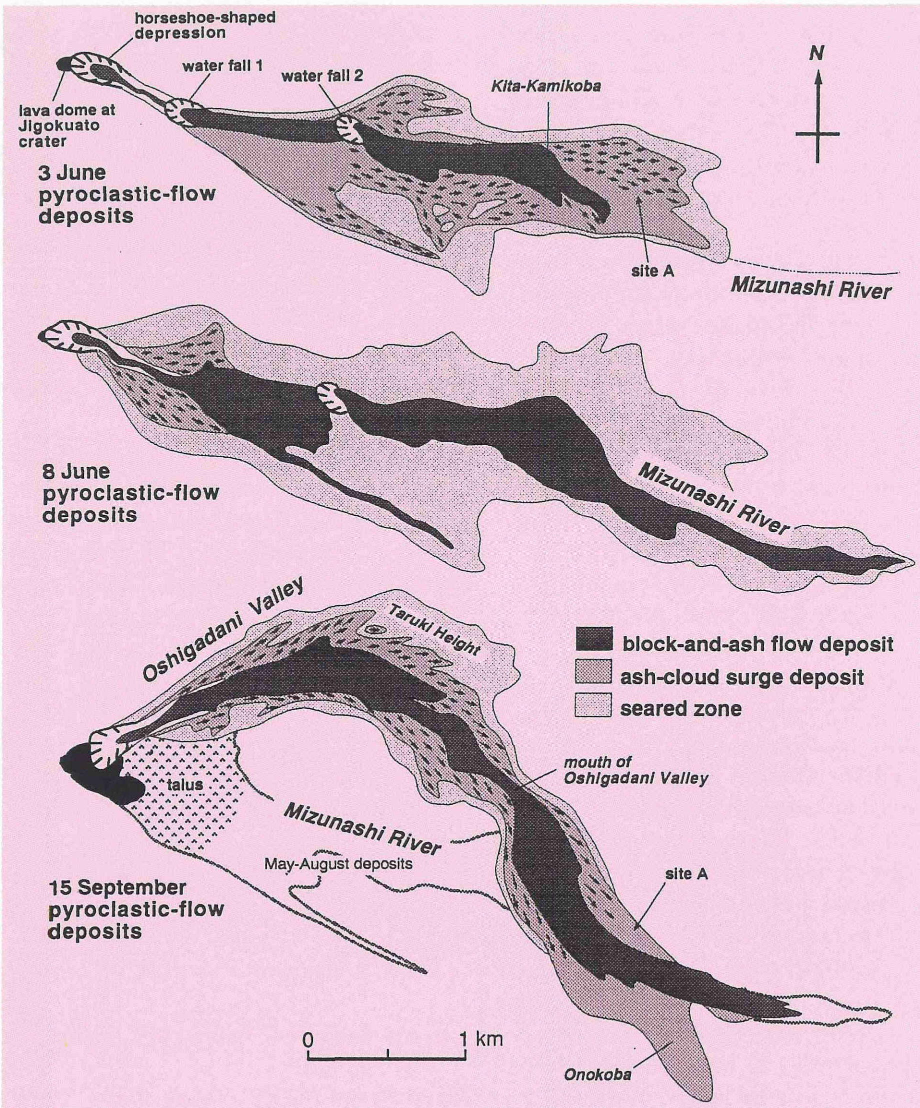

Fig. 10-3. Map showing pyroclastic flow deposits of 3 and 8 June, and 15 September 1991. Arrows represent the direction of trees toppled. The distribution of ash-cloud surge deposits of 8 June was not completely identified (Geological Party, Joint University Research Group, 1992).

sediments. The next day the lava spine was broken into several large blocks showing wide fracture surfaces. The blocks were uplifted by magma supplied from beneath them, resulting in the formation of a lava dome (Dome 1). A large, but crude, petal structure within the lava dome appeared in the E-W direction, implying the intrusion of magma with E-W elongation. The number of summit earthquakes decreased with time. By 23 May, the crater was filled with lava blocks, which began to fall down the steep outer-slope of the crater.

The first pyroclastic flows were observed descending the steep eastern slope on 24 May. Every pyroclastic flow discharge accompanied a burst of volcanic tremor (Shimizu et al., 1991). Thick rain clouds prevented visual observation of the summit area, and the lava dome, but on 27 May small pyroclastic flows were clearly observed descending to the eastern valley. The travel distance of pyroclastic flows increased day by day. On 26 May, one pyroclastic flow ran 3 km from the vent, injuring one person. Repeated collapses of the eastern margin of the dome successively produced pyroclastic flows. The lava dome grew in length, width, and thickness day by day and became unstabe, hanging over the eastern edge of Jigokuato Crater.

June-July 1991

Large pyroclastic flows occurred on 3 and 8 June (Fig. 10-3). Their volumes are $0.5\text{-}0.7 \times 10^6$ and $0.5\text{-}1 \times 10^6$ m^3, respectively. Multiple pyroclastic flows descended the eastern slope during the afternoon of 3 June. On this day a major pyroclastic flow at 16:09 JST (GMT + 9 hours) killed 43 people. About 180 houses were burned. A block-and-ash flow area and an ash-cloud surge area (Fig. 10-3) are distinguished. Large lava blocks, up to a few meters across, were found in the block-and-ash flow area, whereas large fragments of lavas were not identified in the surge area. These areas were surrounded furthermore by seared area in which leaves and barks of trees were burned. In the surge area, all the houses were completely damaged and partly burned, and cars were toppled over or pushed sideways. Many of the casualties were found within the ash-cloud surge area (site A in Fig. 10-5). A speed of the major flow on this day was estimated at about 135 km/hr (Geological Survey of Japan, 1991 personal communication). The eastern half of the lava dome collapsed during the eruption of the 3 June pyroclastic flows leaving a 150 m-wide horseshoe-shaped depression open to the east. The volume of the dome left behind (referred to as pre-3 June Dome 1) was about

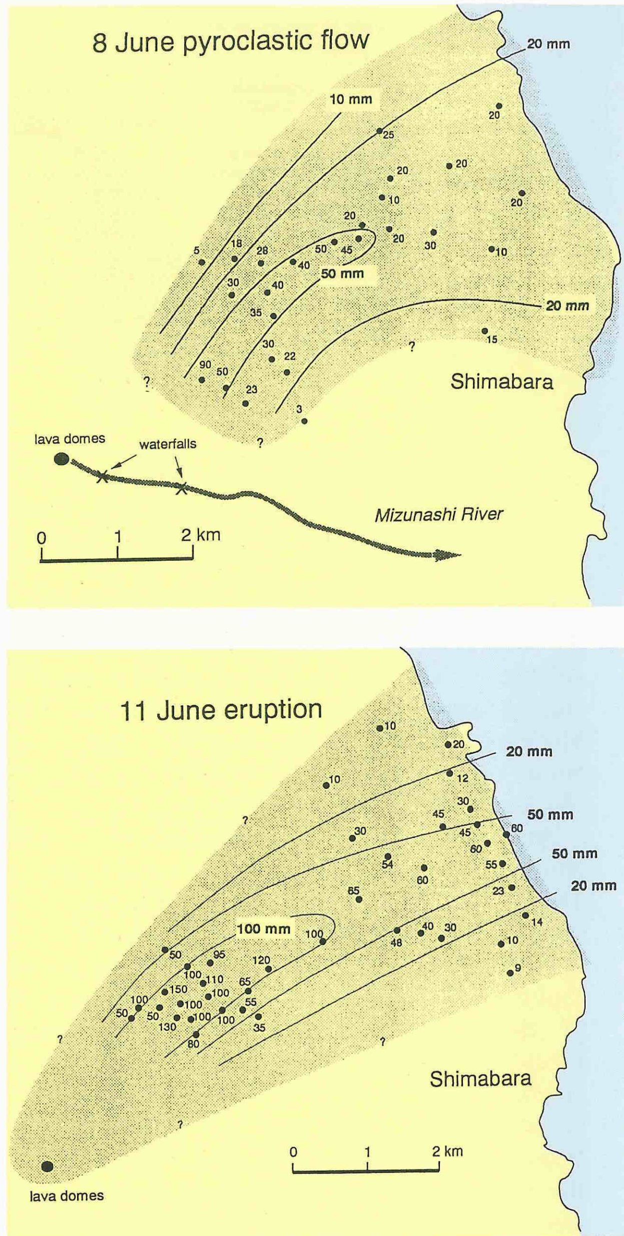

Fig. 10-4. Distribution of bombs which showered on 8 and 11 June 1991. Figures indicate the average sizes of three largest bombs (Geological Party, Joint University Research Group, 1992).

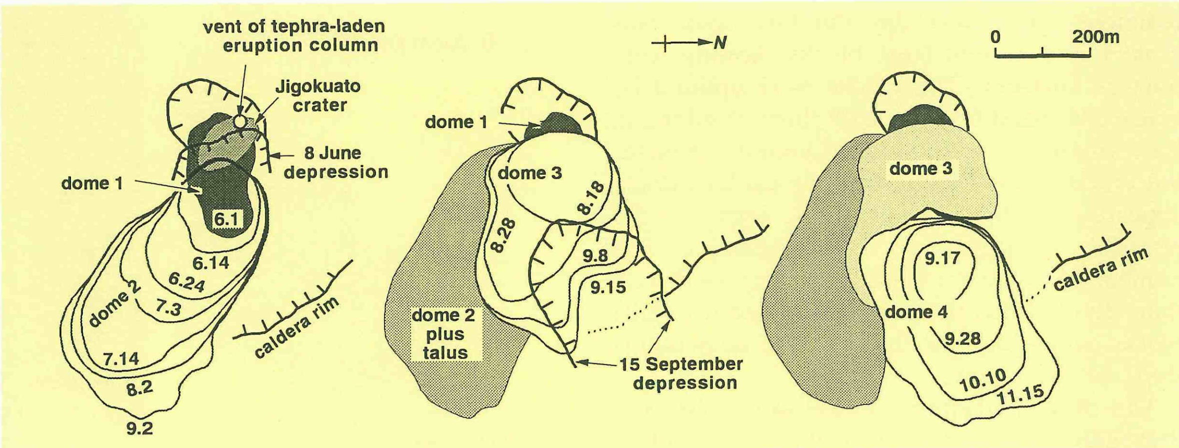

Fig. 10-5. Growth pattern of lava domes in Jigokuato Crater, May-November 1991. Dates are given as "month.day" and the adjacent lines represent the dome margins of those dates (modified from Geological Party, Joint University Research Group, 1992)

0.48×10^6 m^3. A new lava dome formed within the depression by 8 June, and recovered its volume as large as pre-3 June Dome 1 (post-3 June Dome 1). The upper waterfall in the Mizunashi River, whose original height was about 100 m (waterfall 1), had been buried by block-and-ash flow deposits by 8 June.

At 19:48 on 8 June, pyroclastic flows began to continuously cascade down the eastern slope. The flow front progressively moved to east and reached a point 5.5 km far from the vent. About 210 houses were burned but no casualties were reported. The 8 June pyroclastic flows consisted of three main flows. An infrared camera recorded a strong explosion at the summit at 20:06, at the moment when the third major pyroclastic flow pulse was just descending the slope. An extensive area of trees was burned by the ash clouds. Ash-cloud surge deposits were not clearly identified as the deposits on 3 June, because the ash-cloud surge area had already been devastated on 3 June. Breadcrust bombs of 5 cm across were ejected to a ditance of 3 km northeast of the crater (Fig. 10-4). The central axis of bomb distribution seems to point not to the Jigokuato Crater but to waterfalls. About 2/3 of dome (pre- and post-3 June) collapsed. This collapse expanded the horseshoe-shaped depression to 200 m. The western part of the dome of about 0.15×10^6 m^3 in volume remained. A lava dome appeared again within the depression (Dome 2; Fig. 10-5).

Vulcanian explosions on 11 June ejected breadcrust and cauliflower bombs, 46 cm long in maximum, to a distance of 3 km. The central axis of bomb distribution points to the Jigokuato Crater (Fig. 10-4). As a result, a new depression 20-30 m across formed within the old depression, just above the former Jigokuato Crater. On 17 June a continuous eruption column was observed, rising from the eastern dome, for the first time since the start of lava extrusion.

Heavy rains on 30 June caused a lahar in the Mizunashi River. The lahar originated at headwaters of the Oshigadani and Akamatsudani valleys (north and south of the Mizunashi River, respectively). The lahar deeply eroding the pyroclastic-flow deposits at Kitakamikoba (Fig. 10-3) flowed southeastward into the sea, opening a new channel off the Mizunashi River. About 190 houses along the new channel were damaged by this lahar.

Dome 2 continued to grow and collapse along its eastern margin, successively filling a steep valley on the eastern slope of the Jigokuato Crater. The dome grew, progressively overriding the valley-fill deposits on the slope gentler than the original valley floor. The surface part of the lava dome had a form of petal with two lobes. These lobes were created by extrusion at the head of Dome 2. After the middle of June, the lava surface part of the dome moved southeast at a rate of 40 m/day, the dome itself, however, lengthened only at a rate less than 10 m/day (Fig.

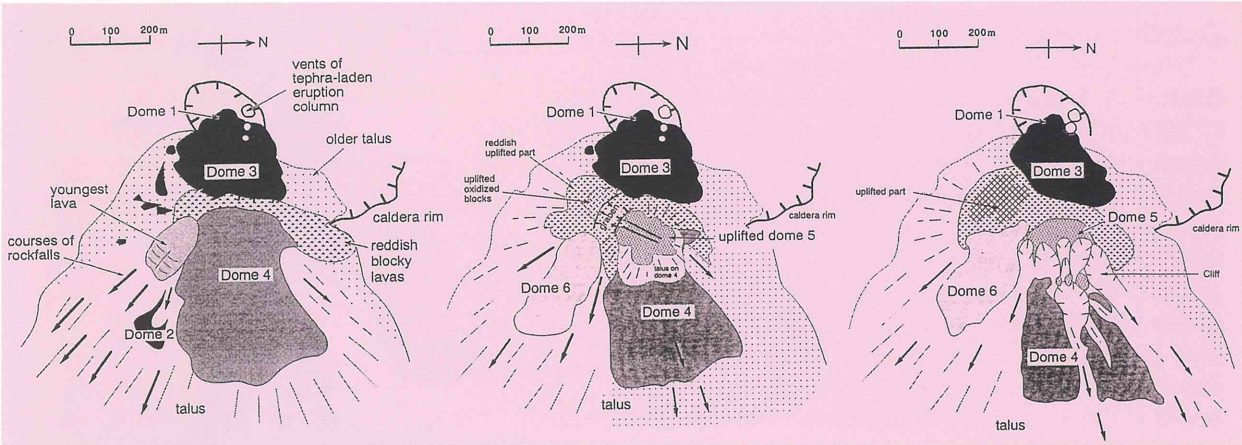

Fig. 10-6. Sketches of lava Domes, 5 December 1991, 15 January 1992, and 27 February 1992.

10-5). By the end of June the horseshoe-shaped depression has been filled with dome material, and lava blocks began to overflow toward the northeast onto the caldera floor. Relatively large pyroclastic flows occurred on 26 and 27 June (about 2.5 and 3.5 km in length, respectively). By the end of June, the dome had grown to a size of about 150m X 250 m and 80 m thick. The dome had grown to a size of 150m X 530 m and 80 m thick by 21 July.

August-September 1991

At the beginning of August, the ash-laden plume became stronger. A seismic swarm at the summit increased in mid-August. Incandescent-block ejection was seen between 00:00 and 02:00 on 12 August, and then followed by continuous ash emission all through the day. The eruption enlarged the vent to 20 m across and built a tuff cone around it. Dome 2 temporarily thickened for a few days prior to the new lava extrusion. A new lava dome (Dome 3), recognized at first from the air on 13 August, overrode on the western part of Dome 2 (Figs. 10-5 and 10-9). Pyroclastic flows, flowing down the Mizunashi River before, came to flow east-northeastward down the Oshigadani Valley (Fig. 10-2). Some of the larger pyroclastic flows from the new dome advanced 3 km down the Oshigadani Valley from late August through mid-September. Flows moving down the Oshigadani valley changed their course southeastward when they hit a height between the valley and a the residential area (Taruki Height). Ash-cloud surges climbed the barrier, burning or searing trees, but block-and-ash flows did not. By mid-September, the headwater of the Oshigadani Valley had been almost filled with pyroclastic-flow and talus deposits.

Another seismic swarm began beneath the crater in early September. Pushing of the crater wall by the extruded lava toward northeast led to a collapse of the crater wall and the adjoining Dome 3 in the 15 September evening. Red-colored ash plumes were observed intermittently earlier in the day, becoming stronger and more frequent until the start of multiple pyroclastic flows. The pyroclastic flows moved east-north-eastward in the Oshigadani Valley then south-eastward into the Mizunashi River, for 5.5 km from the dome (Fig. 10-3). A car in the Kitakamikoba, which was previously burned by June's pyroclastic flows, was thrown about 60 m by the ash-cloud surge (site A in Fig. 10-3). The surges detached from the flows at a confluence of the Oshigadani Valley with the Mizunashi River, kept moving southeastward into the Onokoba area. Although it appeared that the surge rapidly lost its force when it detached from the pyroclastic flow, its temperature remained high. About 190 houses were burned. Lava blocks in the block-and-ash flow deposits were massive, up to 10 m across, without the breadcrust or cauliflower surfaces, though they were seen in the 8 June pyroclastic-flow deposits. The speed of the last flow on 15 September was estimated at about 95 km/hr.

October-December 1991

Growth of lava Dome 4 had continued in the depression formed by the collapse of Dome 3 on 15 September (Fig. 10-5). By the end of October, Dome 4 was 500 m long with 2 lobes in a crude petal-shaped structure. Rough pressure ridges, convex downslope and long wavelength, formed on the surface of Dome 4. Thick lava layers piled successively up and formed a ramp structure, which were observed on their southern cliffs. New magma reached the surface along a narrow space between Domes 2 and 4, and between the head of Dome 4 and the remnants of Dome 3, where irregularly shaped lobes like rose flower were built. Endogenous intrusion of magma was indicated by swelling of the dome and uplift of the talus between Domes 3 and 4. The uplifted area expanded southward and northward, resulting in the replacement of the talus by reddish blocky lava. Older domes were pushed southward. Radial cracks were formed in Dome 3. The deformation continued in early December. Talus in front of the domes rested on the slope at angles as large as 33°. Parts of the Dome 4 surface were even steeper. Rockfalls from the dome front eroded and buried Dome 2, which had become invisible by mid December (Figs. 10-6 and 10-9).

Dome 5, growing since 21 November at the top of Dome 4, grew upward about 50 m in mid December (Fig. 10-9). Extrusion of a new lava

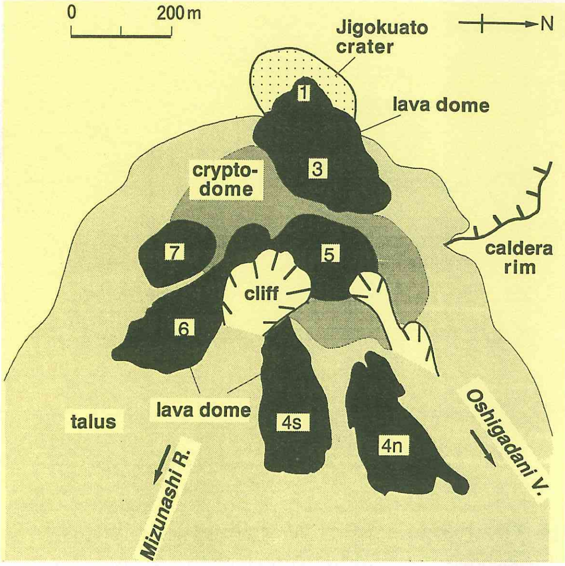

Fig. 10-7. Sketch of lava domes in early-April 1992

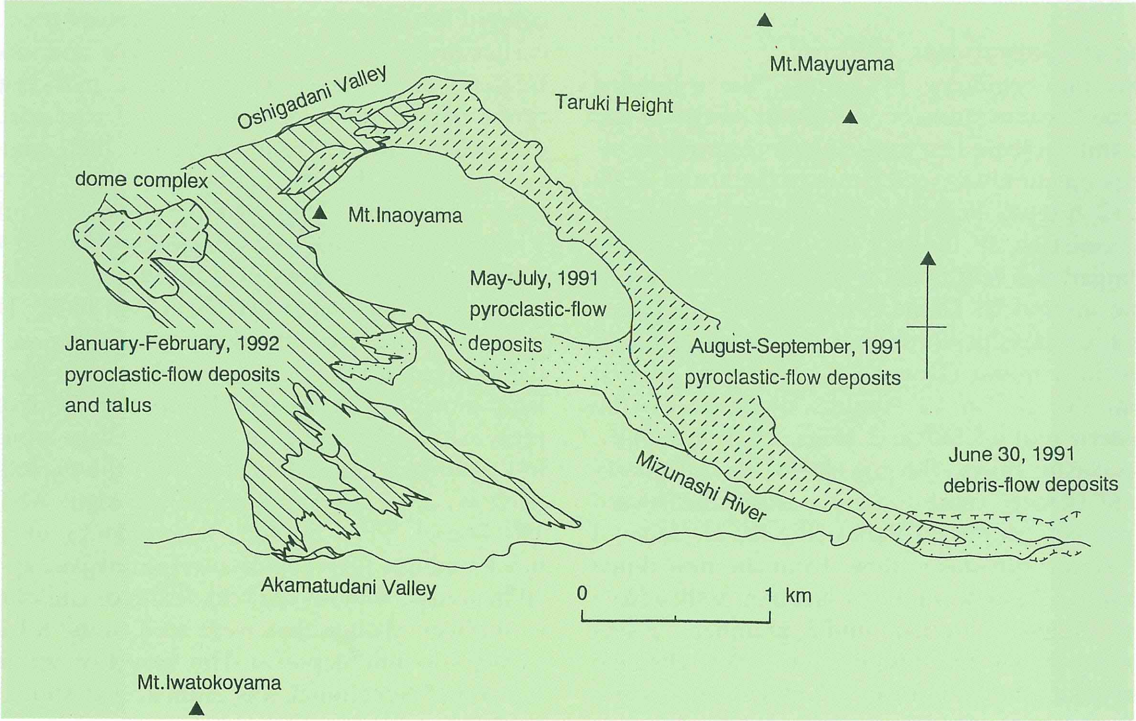

Fig. 10-8. Distribution of talus and pyroclastic-flow deposits in late-February 1992.

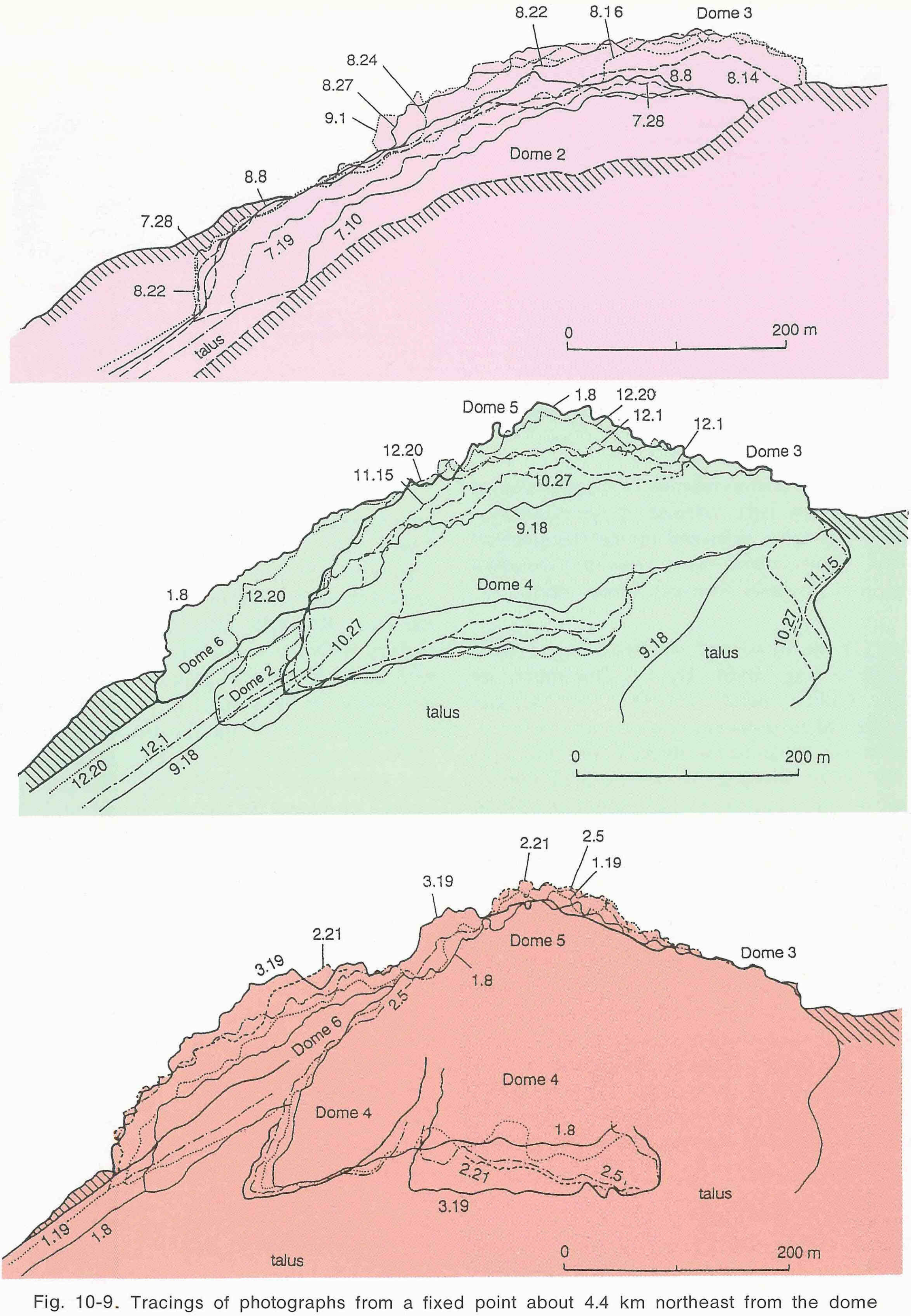

Fig. 10-9. Tracings of photographs from a fixed point about 4.4 km northeast from the dome illustrating dome growth during July-September 1991 (top), September 1991-January 1992 (middle), and January-March 1992 (bottom).

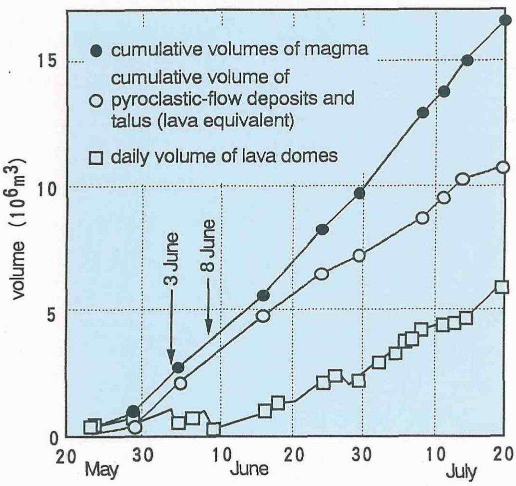

Fig. 10-10. Cumulative volumes of magma erupted during May-July 1991. Volumes of pyroclastic flow deposits and talus, estimated by the Geographical Survey Institute, Japan were reffered (Geological Party, Joint University Research Group, 1992).

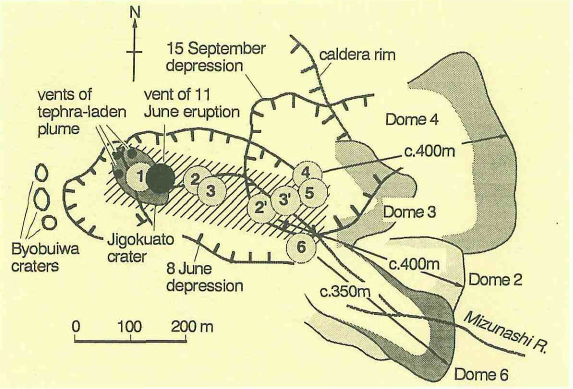

Fig. 10-11. Map showing vent sites in the dome complex and distribution of domes. Figures in circles represent vents of domes with those numbers.

dome (Dome 6) toward southeast began on 3 December (Fig. 10-6). By late-December, its initial 2-lobed petal structure had become diffused and its progression had nearly stopped. Lava blocks began to fall directly from the head of the dome, eroding the southern margin of Dome 4. On 7 January, Dome 6 was about 370 m long, 180 m wide, and 80 m high.

Rockfalls did not develop into pyroclastic flows as often as in October and November. Collapse of dome as large as 10^4-10^5 m^3 in volume seldom caused pyroclastic flows. Ash clouds generated by pyroclastic flows, reddish brown to dark brown in May to June, had changed to milky color. Ash-clouds from the largest flows rose 2 km high. Pyroclastic flows that traveled more than 2 km occurred at the beginning and the end of November. The pyroclasitc flow in early-November started from the top of Dome 4, advanced across the dome and then entered the Oshigadani Valley.

January-March 1992

Magma was supplied primarily to the top of Dome 6, causing the dome to thicken (to 80 m) (Fig. 10-9), especially over the vent. Magma intrusion into Dome 6 caused uplift of older domes in the west of the vent. The top of the growing cryptodome surpassed the summit of Mt. Fugen at 1,359 m elevation. The growth of the cryptodome pushed Dome 5 northeastward, and caused its partial collapse toward northeast and the east. Rockfalls from Dome 5 eroded the surface of Dome 4, and finnaly began to bury it with talus. A group of parallel and radial cracks developed on the surface of Dome 4. A central groove had formed and divided it into northern and southern parts by early February (Figs. 10-7 and 10-9). The northern part was found to be pushed eastward by the movement of Dome 5 and the cryptodome.

Pyroclastic flows flowed mainly to southeast and east from Dome 6 and the cryptodome. Some small pyroclastic flows and rockfalls occurred in the northeast and the east of Domes 4 and 5. Two blocks at the front of Dome 6 (estimated block volume, 3-5 $\times 10^5$ m^3) collapsed at 17:38 on 2 February. The pyroclastic flows traveled 3 km. The speed of the flows estimated by a TV monitor was at about 65 km/hr. A second series of pyroclastic flows, lasting about 30 minutes, occurred on 12 February when a pile of blocks (about 5×10^5 m^3), pushed southward by lava emerging from the vent, collapsed on the southern margin of Dome 6. All the pyroclastic flows descended along the same path and eroded a narrow v-shaped groove in the talus. It terminated at the top of a 100-m cliff. The flows spread at the base of the cliff, depositing material on the gentler slopes. Some of the southward-moving flows were deflected about 70° by the

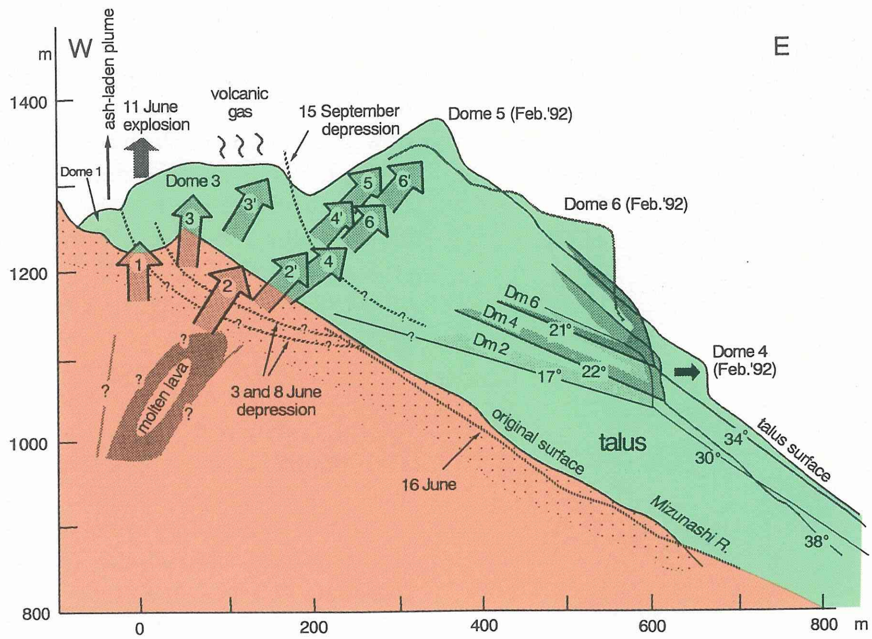

Fig. 10-12. Cross section showing vent sites in the dome complex. Note that lava domes flowed down on valley-fill deposits (talus) in Mizunashi River.

northern face of Iwatokoyama hill (roughly 1.5 km south of the vent) towards the east and into the Akamatsudani Valley (Fig. 10-8). The pyroclastic flows traveled about another 500 m (a total of 2.2 km from their source). Compared to pre-October pyroclastic flows, these flows were less energetic, with lower velocities, and a narrower area of devastation.

Growth of the lava dome at the summit continued through March (Fig. 10-7), with frequent pyroclastic flows generated by partial dome collapse. In late March, a new dome (Dome 7) formed to the west of Dome 6.

Volumes of magma and lava domes

The volume of lava domes was estimated based on photographs taken from a helicopter. A total volume of talus and pyroclastic flows are transformed to an equivalent volume of solid lava by multiplying by 0.7 (Fig. 10-10). An extrusion rate of magma was 0.8 to 1.0×10^5 m^3 /day for the first week after the first appearance of lava dome in Jigokuato Crater and then increased to about 3×10^5 m^3 /day. The daily eruption rate might have varied, the averaged rate for a week or a longer period, however, was nearly constant. Digital mapping of Geographical Survey Institute, Japan, also gave the same rate. The extrusion rate had been kept nearly constant, at least, until the end of February 1992. In late February, the total volume of the extruded magma amounted to about 82×10^6 m^3. The volume of domes at the summit was about 44×10^6 m^3.

A ratio of the daily extrusion to the daily dome collapse in volume was not constant but varied. Therefore, a daily growth rate of lava domes was not constant. Lava domes grew at the rate of about 0.2×10^6 m^3/day from June to mid-July. The rate decreased to about 0.1×10^6 m^3/day from late-July to mid-August. The average growth rate during May 1991 to February 1992 was 0.16×10^6 m^3/day.

Growth pattern of lava domes

Totally, 7 domes formed at the summit (Fig. 10-7). The dome growth seemed to have been controlled by a simple manner. A group of shallow earthquakes always occurred in or below

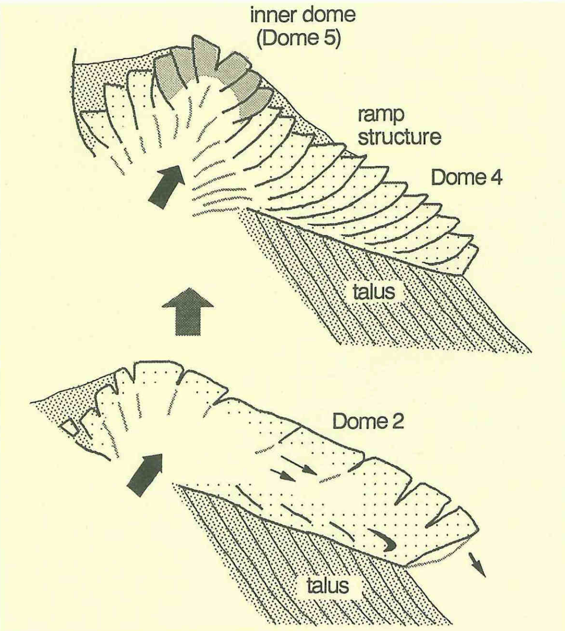

Fig. 10-13. Sketch showing growth pattern of lava domes at Unzen Volcano.

the lava domes before the appearance of a new dome, except the birth of Dome 2. Dome 2 appeared within a horseshoe-shaped depression formed after the landslide on 8 June. The landslide cut off the top of the magma conduit. Then the new dome seemed to have emerged smoothly in the depression. Domes 2, 4, and 6 very gently flowed eastward onto the talus, and showed elongated forms. Domes 3 and 5 overrode Domes 2 and 4, respectively. Lavas in a "petal" (such as petals with two lobes) or "peel" (such as peeling banana) structure formed right on the vent site. Their color was darkest among lavas extruded. The younger lava is generally darker gray in color. The older is more reddish. The vent sites in these domes were in a zone with about 100 m in a N80°W direction (Fig. 10-11). This trend was roughly in parallel with an axis of the graben which had once formed just before the start of dome extrusion. It was also parallel with the direction of upstream of the Mizunashi River. The active vent moved eastward roughly with time. Floors of the domes have gentler angles (about 20°) than the slope of talus (about 33°) in front of domes. This indicates that the dome flowed forward on the talus which was formed through collapse of the dome itself (Fig. 10-12). Although swarm earthquakes occurred within or beneath the dome complex just before the appearance of a new dome, almost no earthquake occurred during the continuous, eastward movement of the vent (for example, from 2 to 2' in Fig. 10-11). This implies that magma was supplied from beneath Jigokuato Crater, even to the eastern vents for Domes 4, 5, and 6 (Fig. 10-12). Magma was supplied into Domes 4, 5, and 6 through an inclined conduit. This is supported by facts that vents of 11 June vulcanian eruptions and tephra-laden column were in the Jigokuato Crater and that volcanic gas was always emitted through Dome 3 which lies in the crater.

The domes hardly lengthened when their lengths attained about 400 m. Domes 4 and 6 grew exogenously and smoothly, and extended up to this length. Then, many petals of lava tightly grew around the vent site to form a rose-flower structure. This suggests that the lava moved into the toe of the dome was cooled enough and became too viscous to be smoothly pushed forward by the following lava. A "ramp" structure, resultantly, appeared in Domes 4 and 6, in which younger lavas were thrust up on the older lavas one by one (Fig. 10-13). On the other hand, large "ropy" structures convex downward with wide wavelengths formed on the upper surface. Magma successively supplied from beneath did not push the dome any further. New lava endogenously intruded upward, and formed an inner dome above the vent (Domes 3 and 5).

Thus far, erupted magmas are dacite with a small compositional range (65.0 wt. % SiO_2; Yanagi et al., this book).