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Parasitic† Eruptions on Sakurajima Volcano

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Spatial distribution of parasitic vents is closely related to movements of magmas at a certain depths of main conduit of the central volcano. A simple method for studying distribution of parasitic vents is presented: That is numbers of parasites per unit area according to radial distances from the central vent. On and around Sakurajima volcano, two peaks of the distribution diagram are found at roughly 2.5 and 8.5 km in radial distances. These can be interpreted into that the magmas branched away at different depths of the main vent. The branching mechanism is discussed from a standpoint of material mechanics. In this case, magmatic forces are assumed to be due to point dilatations that have proved effective in interpretation of surface deformations observed at various volcanoes. To interpret formation of parasitic vents, or outward fractures, on the flanks of a polygenetic volcano, the theory of maximum shear stress is adopted. As a result, a parasitic vent branches off from the main conduit at a depth that is related to the radial distance of the parasitic vent from the center of the volcano, and theoretically we may expect twin parasites symmetrically with respect to the center of the volcano. Whether new magmas outburst at the main crater or a new parasitic-vent fractures at the flank may depend on conditions of the main crater, the relative strengths of both the sites, and mechanism of branching. The three largest parasitic eruptions on Sakurajima volcano in historical times, the 1471～76, the 1779～80, and the 1914 eruptions, are examined: Each of these eruptions opened two vents on the opposite flanks of the central summit with a partly exception in the 1779～80 eruption. The exceptional case is suggestive for formation mechanism of twin parasitic cones. Formation of such twin vents is mechanically normal but empirically odd. An empirical fact that parasitic volcanoes only erupt once is hypothetically interpreted: Surroundings of parasitic conduits are probably strengthened mechanically by intrusion of magmas, and the sub-conduit may be tightly choked with lavas. We may say that the next eruption of Sakurajima volcano may take place at the summit crater, and otherwise, statistically, parasitic eruptions may burst probably on the flank and rarely at the sea. The parasitic vents would open at a region of "parasite-gap" on the flank, and would twin at the opposite sides of the summit. To improve the forecast, we need to clarify the formation mechanism of parasites in more detail.

Key words: parasitic eruptions, monogenetic volcanoes, maximum shear stress, Sakurajima volcano, twin parasitic vents.

1. Introduction

Parasitic volcanisms have been deemed as secondary though they are actually an important manifestation of volcanic forces. Parasitic eruptions on a polygenetic volcano occur when magmas branch off from the central conduit at a certain depth and erupt on the flanks forming cones. These parasitic cones are different from monogenetic ones formed in volcanic fields or volcano groups. The latter involves with the ascent of individual magma batches from great depths. Parasitic volcanoes are nevertheless considered to be monogenetic because their vents are generally not expected to experience additional activity when once an eruption cycle is over. Understanding the causes of parasitic eruptions, rather than eruptions from the central vent of a polygenetic volcano, is important because such vents may bring volcanic activity closer to human settlements, and because lava flows erupted from parasitic vents may more readily inundate areas low on the flanks of the volcano. Therefore, it is important to examine the distribution of parasitic vents and interpret the mechanisms that give rise to this distribution.

Of many historical records of eruptions on Sakurajima volcano, the three biggest eruptions all produced two vents on the opposite flanks of the central summit. Such characteristics of the Sakurajima eruptions should be the most suitable subject in the discussion of parasitic volcanisms.

† In the present paper, the author prefers "parasitic" to "lateral" because the former expresses the meaning of origination better. P.O.D. says that "parasite" is an animal or a plant, living in or on another & drawing nutriment from it.

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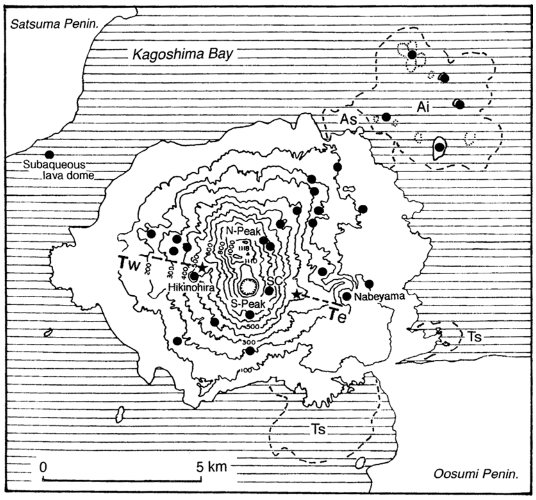


Fig. 1. Distribution of parasitic vents over Sakurajima volcano after Yamaguchi (1975) and Kobayashi (1988). "**Tw**" and "**Te"** indicate the series of vent (5 each) formed by the 1914 eruption, and "Ts" does the lava flow from land in the 1914 eruption. "Ai" and "As" are the lava flows of submarine origin and the lava flows from land, respectively and both were issued by the 1779 eruption. "SC" is "Showa Crater".

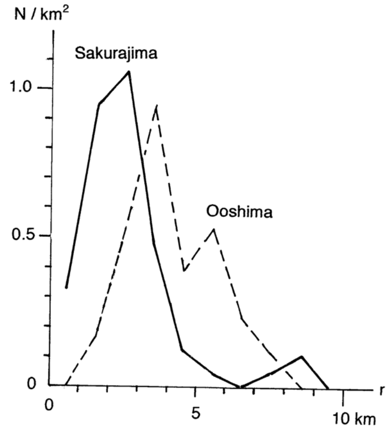


Fig. 2. Radial density distribution of parasitic vents (per km^2) over Sakurajima and Ooshima volcanoes.

2. Spatial Distribution of Parasitic Cones on Sakurajima Volcano

The spatial distribution of volcanic cones is an important subject in studying the origins of volcano groups. Hasenaka and Carmichael (1985) discussed distribution of vents in the Michoacán-Guanajuato volcanic field in Mexico (1016 cinder cones over an area of 6×10^4 km^2). The cinder cones in the field are usually random-spaced and indicate no preferred orientation. They estimated the density of vents in various areas and found that roughly 75 % of the volcanoes are located between 200 and 300 km in the distance from the Middle America Trench. To the same volcanic field, Connor (1987, 1990) applied cluster analyses and two-dimensional Fourier analyses and found that the vent alignment data imply the stress field on a regional scale. In this field, there are so many monogenetic cones that his methods are successful.

In the following, spatial distribution of parasitic cones on some polygenetic volcanoes shall be examined from a consideration of that there are usually not so numerous parasites there.

2-1 Sakurajima volcano

The island of Sakurajima volcano was originated at the sea bottom in Holocene. The island was connected with the Oosumi Peninsula by lava flows of the 1914 eruption. The present Sakurajima volcano is composed of three main cones on a line from N to S. Parasitic eruptions have occurred frequently on this polygenetic volcano. The rocks of the ejecta from the volcano are all andesitic. The historical records of eruptions on Sakurajima volcano date back to 708 A.D. At present, it is one of the most active volcanoes in Japan.

On the volcano, there are many cones formed in historical times, but it is rather difficult to distinguish all parasitic cones exactly because the older ones are covered with lava flows of the later periods. In the present discussion, identification of parasitic cones is fundamentally important. The author can count 25 parasitic cones on and around Sakurajima volcano on geologic maps provided by Yamaguchi (1975) and Kobayashi (1988). The distribution of parasitic cones on and around the volcano is shown in Fig. 1. Parasitic eruptions were historically recorded as in 764, 1471～76, 1779～80, and 1914. In 1939, a crater ("SC" in Fig. 1) was formed at a height of about 750 m a.s.l. and about 500 m distant from the center of the summit crater of South-Peak (1040 m a.s.l.). This is named "Showa Crater" (formed in the Showa era). In the present discussion, this crater is excluded from the parasitic vents because it is vey close to the main crater and may be deemed as an auxiliary crater: Its vent may have branched from the main vent of South-Peak at a shallow depth due to some local structures.

Numbers of parasitic vents per unit area against the radial distance from the center of the volcano (the middle point between N-Peak and S-Peak in Fig. 1) are obtained as shown in Fig. 2 where the 1914 vents at the eastern and western flanks are represented by those of the highest altitudes in respective group because the lava flows issued first from the highest vents and later from the lower ones on both the flanks: This means that their origins are the same in respective group. The distribution in Fig. 2 shows double-peaked densities around 2.5 and 8.5 km in radial distance; the former is the mode presenting the flank vents

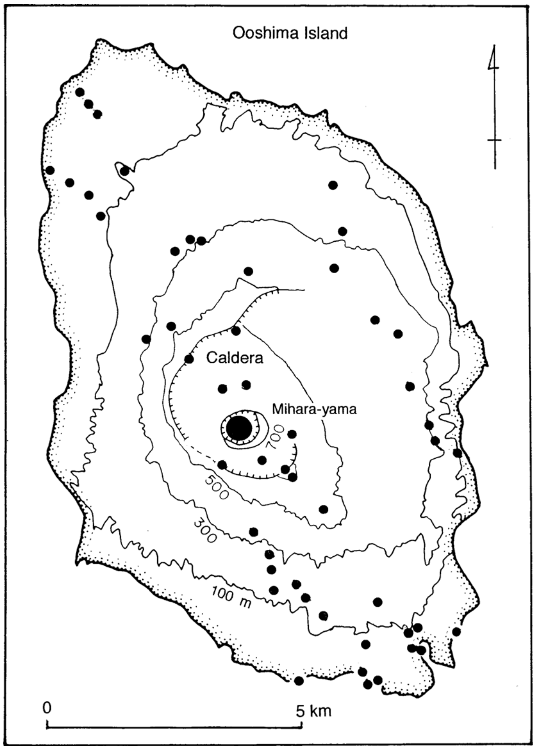


Fig. 3. Distribution of parasitic cones over Ooshima volcano after Nakamura (1961).

around a height of 300 m a.s.l. and the latter presents the islets in NE off the volcano island, formed in 1779～1780 by submarine eruptions.

In the following, for reference, in comparison with Sakurajima volcano, the similar discussion shall be extended to the other polygenetic and monogenetic volcanoes.

2–2 Izu-Ooshima volcano

Izu-Ooshima volcano belongs to the Shichito (Seven-Izu-Islands)-Mariana arc. In the following, we call this volcano simply Ooshima volcano. The distribution of parasitic cones on this volcano is shown in Fig. 3 after Nakamura (1961). We have no historical records of parasitic eruptions on this volcano. The radial density distribution of parasitic cones is also shown in Fig. 2. The cones within the caldera and on the caldera rim are excluded from the data because they are closely related to the main conduit of the main cone (Mihara-yama): They are auxiliary to the main cone. The diagram for Ooshima volcano in Fig. 2 shows double-peaked frequencies around 3.5 and 5.5 km in radial distance from the center of the volcano: The former is the mode corresponding to the parasitic cones around a height of 300 m a.s.l. and the latter does to the cones at the N and S ends of the island.

Nakamura (1961, 1977) discussed the activity of parasitic cones in stratigraphic studies of Ooshima volcano. He measured trends of parasitic cones with the eye, and found that the distribution of whole parasitic cones is restricted to two narrow zones running nearly parallel to the long axis of the island, and proposed that these fracture zones were produced mainly by regional stress rather than that they were produced independently within the island by up-thrusting stresses of a magma reservoir. His viewpoint is different from that of the present author, and the distribution of the parasites on Ooshima volcano may exhibit dual patterns for different viewpoints, i. e. linear arrangements and circumferential ones.

Even if a linear trend of the parasitic cones is recognized on Ooshima volcano, not the same on Miyake volcano (Nakamura, 1984). The latter is located at a distance of about 70 km S, both the volcano-islands belonging to the Seven-Izu-Islands and similarly originated from basaltic magmas. This means that the tendency proposed on Ooshima volcano is rather local not regional. It is problematical whether a volcano body is a simple accretion on the earth crust or a derivative of the crustal structure.

Here, in order to recognize characteristics in distribution of parasitic cones on polygenetic volcanoes, the similar method shall be applied to a monogenetic volcano group.

2–3 The East-Izu monogenetic volcano group

This volcano group is located at the eastern part of the Izu Peninsula and off the eastern coast. Aramaki and Hamuro (1977) studied geology of the group. There are about 70 cones on land and 80 in the sea as shown in Fig. 4 (a). In March～May 1930, earthquakes swarms were felt around Ito City. And in November of the same year, the North-Izu Earthquake (Ms 7.3) occurred. Further, both the 1978～1979 earthquake swarms and an earthquake of Ms 6.7 were located at the E of the Izu Peninsula. In July 1989, earthquake swarms started again: On July 13, a small submarine eruption occurred at the northernmost part of the group, about 3 km N of Ito City (a star symbol in Fig. 4 (a)). The eruption site coincides with the epicentral area of the 1930 earthquake swarms (Ueki, 1992). This is the first historic eruption of this group.

Among the group, there is no central volcano. To examine a trend in the distribution of monogenetic cones in this area, if any, tentatively the center of the group is set at the cross mark in Fig. 4 (a). Along the E shore of the peninsula, some cones may have been eroded. Then the distribution of the cones is plotted against the radial distance from the cross as shown in Fig. 4 (b). In comparison with polygenetic volcanoes, Sakurajima and Ooshima, the diagram has not so prominent peaks. This means that the distribution does not largely depend on position of the assumed center, or there is no principal vent forming a central cone. An interpretation for the origin of this monogenetic group shall be discussed later.

3. Formation of Parasitic Vents

Formation of parasitic vents on polygenetic volcanoes

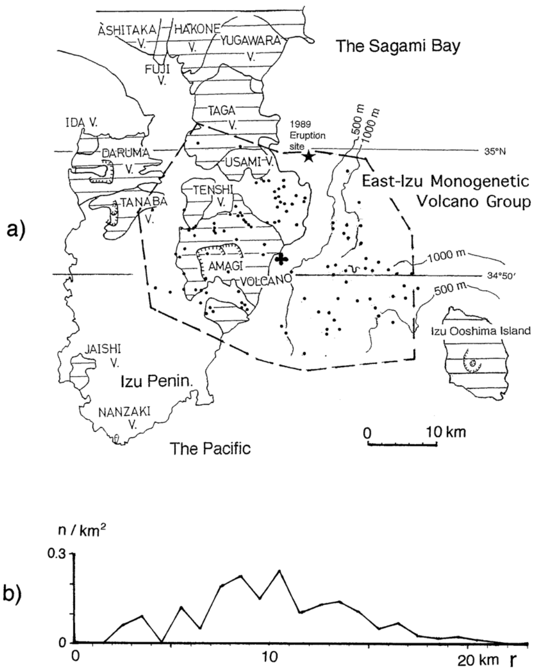


Fig. 4. The East-Izu monogenetic volcano group.
(a) Distribution of monogenetic cones after Aramaki and Hamuro (1977). A cross symbol is assumed as the center of the group.
(b) Density distribution of cones (per km^2) against the radial distance from the assumed center of the group.

shall be discussed from viewpoint of their magmatic force and crustal strength. Here we assume magma conduit of main crater to be pipe-shaped for the purpose of general discussion admitting planar dikes as an alternative path to the crater. The magma proceeds upward due to buoyancy or magma pressure in excess of lithostatic pressure, and reaches a certain depth. Hereafter, the magma movement depends on the condition of pre-existing central vent. If the conduit to the main vent is available, or magmatic force can form a new conduit to the main crater, the magma will reach there, and if the main conduit is tightly choked against the ascending magma, the magma should take another way aiming at the highly stressed points.

3-1 Models of magmatic forces at the origin

In principle we deal with magmatic forces acting upwards and pipe-shaped conduits beneath an active polygenetic volcano. Here, for the sake of analytical treatments, we assume a pressure source embedded in a semi-infinite elastic body. The source can be at the middle of the conduit, and not necessary at a magma reservoir. We adopt a coordinate system for a spherical pressure source of radius a, and depth D and pressure distribution at the origin is expressed by spherical harmonics. Two simple and fundamental models are considered:

a) A uniform expansion of the source (point dilatation): Constant pressure $P=P_0$ and intensity a^3P_0. This is a model of a magma reservoir exerting pressure uniformly and radially around the source. The deformation at the surface caused by this model was analytically calculated first by Sezawa (1931). On the other hand, Anderson (1936) used the same model to discuss the formation of various dykes, sills and cone-sheets.

b) We may assume another similar model: source pressure $P=P_0 \cos\,\theta$, in which all the components of the force are upward parallel to Z-axis. This may better approximate force acting at the uppermost part of a magma conduit. Soeda (1944) calculated deformation caused by force of this type, analytically but with some approximations.

These models are simple and have amply proved to be successful in interpretation of volcanic deformations in various cases. It is reasonable for us to start with these models. Deformation at the ground surface caused by the above two models are given in detail by Yamashina (1986) assuming radius a to be much smaller than depth D. The results obtained by the two models are substantially similar. In the following discussion, the present author adopts the point dilatation model for convenience.

3-2 Criteria of fracture

Criteria of fracture in material mechanics (*e.g.* Jaeger, 1964) are applicable to the discussion of fractures on volcanoes caused by subterranean force. Formation of central vents at the summits of polygenetic volcanoes can be explained by the **maximum principal stress theory** while formation of parasitic vents may be a subject of discussion by the **maximum shear stress theory** (or **the maximum stress difference theory).**

When the pre-existing central crater or vent, right over the origin, is strongly solidified and blockaded, magma can't break out at this point. Instead, the magma at depths should proceed obliquely toward the mechanically most stressed point under various conditions. In this case, the theory of maximum shear stress is applicable as already reviewed by De la Cruz-Reyna and Yokoyama (2011). According to the theory of maximum shear stress, the critical stress is equal to a half of the horizontal differential stress and is represented as:

$$1/2(\sigma_x-\sigma_z) \tag{1}$$

where σ_x and σ_z denote the greatest and least principal stresses, respectively. And the maximum shear stress occurs across a plane whose normal bisects the angle between σ_x and σ_z. In the present discussion, we do not know how the principal stresses are distributed on each volcano. However, some general results may be appropriate to explain the formation of parasitic vents.

In the following, we assume a simple source model beneath a horizontal plane: point dilatation, $P=P_0$ at depth

D and with intensity a^3P_0. The free surface displacements and the corresponding strain tensor are:

$$u_z = C_0 D/R^3, \text{ and } \varepsilon_{zr} = -3C_0 Dr/R^5,$$

$$u_r = C_0 r/R^3, \text{ and } \varepsilon_{rr} = C_0(D^2 - 2r^2)/R^5, \quad (2)$$

$$u_\theta = 0, \quad \text{ and } \varepsilon_{\theta\theta} = C_0/R^3,$$

where $C_0 = (\lambda + 2\mu)\ a^3 P_0/\{2\mu(\lambda+\mu)\}$, $R = \sqrt{D^2} + r^2$, and μ and λ denote the Lame's parameters.

At the ground surface, $\sigma_{zz} = 0$, and the maximum shear stress ($\sigma_x - \sigma_z$) is expressed in polar coordinates (r, φ, θ) as:

$$\sigma_{rr} - \sigma_{\theta\theta} = -6\mu C_0 r^2/R^5. \quad (3)$$

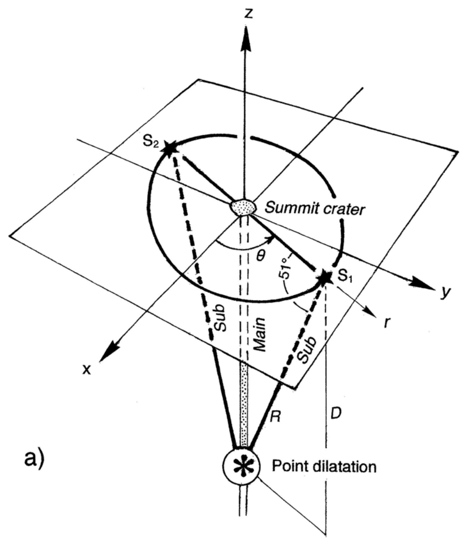
The value of (3) takes positive or negative maximum at:

$$r = \pm\sqrt{6}\ D/3 = \pm 0.82D, \text{ or } D = 1.22r \quad (4)$$

In other words, the medium receives the maximum shear stress at a radial distance $r = \pm 0.82\ D$, or where the dip angle of the pressure source from the fracture point at the surface is 51°. In the equation, we expect the maximum horizontal differential stress at two points, $r = \pm 0.82\ D$, or on the opposite sides of the center of volcanoes and these are independent on declination θ though the maximum shear stress acts in the limited plane. Possibility of such a pair of fracturing points may depend on particular conditions on each volcano. When one of the parasitic vents is opened, the stresses may concentrate there and the other vent probably cannot be opened. Therefore, twin parasitic vents are odd in general. And furthermore, as shall be mentioned later, parasitic vents are usually monogenetic, and so parasitic vents cannot be repeatedly formed at the same spots. The relation (4) is shown in Fig. 5 agrees to the result by Anderson (1936, Fig. 8). In the figure, a branch point from the main conduit may be a singular point in the volcanic plumbing system such as a magma reservoir and a kind of knots along the conduit.

On actual volcanoes, flank surfaces are not horizontal, and the volcano structure is heterogeneous, and so the above results should be considered as rather approximative.

Whether magma breaks out from main crater or from parasitic vents depends on the condition of existing main crater and strength of the medium concerned, or on the balance between magma pressure and rock strength at the sites concerned. Main craters at the summits suffer from compressive stress, and parasitic sites do from both compressive and shear stresses. Thus, rock strength plays an important role in the above determination. Compressive rock strength is roughly in order of 100 MPa and shear strength roughly in order of 10 MPa (Jaeger, 1964, Tables III and IV). The place of fracture depends on balance between upward compressive force against the strong compressive strength and shear force against the weak shear strength. At present the balance cannot be estimated quantitatively because some parameters in the above discussion are not accurately determinable. Strict exclusiveness between summit eruption and parasitic eruption has not been recognized in many historical eruptions. On some volcanoes, parasitic eruptions have occurred simultaneously with summit eruptions.



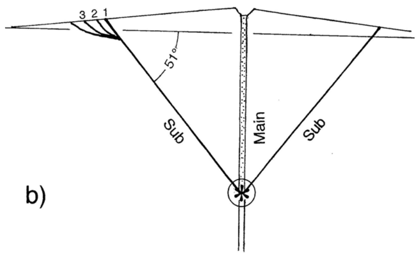


Fig. 5. Schematic model for formation of parasitic vents.
(a) Geometrical distribution of the magma paths.
(b) A simplified elevation showing small branches from sub-conduit. Numerals 1, 2, 3 - - - denote the order of outburst in usual cases.

3-3 Examples on some volcanoes

We apply the above interpretation to some volcanoes; Sakurajima, Ooshima, Usu volcanoes and the East-Izu monogenetic volcano group.

Sakurajima volcano: As mentioned above, in Fig. 2, radial distribution of parasitic cones shows clearly separate two peaks, at 2.5 and 8.5 km from the central summit crater. Future parasitic eruptions may statistically take place around a circle of 2.5 km in radius. The branching points of the two groups from the main conduit are roughly 3 and 10 km deep, respectively by the relation (4). These are the branch points of the oblique magma paths, and in such cases, the magma pressure is not enough to break out at the summit crater through the main vent and the magma may search weak points at lateral sides. Locations of parasitic cones depend on the position of the branch point from the main vent.

If we assume that the volcano structure has remained to be the same since the past parasitic eruptions, the above two branch points may be correlated with any characteristics of the actual subsurface structure: Kamo *et al.* (1980) located an attenuating zone of seismic shear waves at a depth of 3～6 km beneath the volcano. Ishihara (1990) deduced existence of a magmatic and pressure source zone at depths of 4～6 km that caused the surface deformation, and Iguchi (2007) clarified another magmatic zone at depths of 6～15 km that extruded dykes toward SW causing A-type earthquakes. The above two branch points from the main vent are located in such particular zones. The zones may be attributable to magma batches and magma reservoirs.

Ooshima volcano: In Fig. 2, the two groups of parasitic cones, 3.5 and 5.5 km distance from the center of the volcano, may have branched from the main conduit at depths of about 4 and 7 km, respectively. The shallow one may correspond to a pressure source or a magma batch at a depth of 4 km that was determined by Ida *et al*. (1988) who interpreted the deformations occurring in November 1987 after the 1986 eruption. On the other hand, the deeper one may be related to the top of scattering body at a depth of 8～10 km beneath the caldera located by Mikada (1994) who applied tomographic methods using seismic waves.

Usu volcano: Magmas in the historical activities of this volcano are dacites, and have produced lava domes within the summit crater and on the flanks, and occasionally pyroclastic flows. The three historical eruptions, in 1910, 1943 and 2000, producing parasitic vents were observed with the instruments of those days. They are distributed all along a contour of roughly 200 m a.s.l. or a circle of roughly 2.5 km from the center of the main volcano as shown in Fig. 6. According to the relation (4), the depth of the branch may be roughly 3 km beneath the volcano. Hereupon, Onizawa *et al*. (2002) accurately determined the hypocenters of the earthquakes in the 2000 eruption at a depths 2～4 km beneath the volcano using the three-dimensional P- and S-wave velocity structures. This offers a suggestion regarding the character of the branches. In Fig. 6, "HM" denotes a round mound measuring about 100 m in relative height, formed in prehistoric period. The 1910 eruption formed more than 40 vents of various sizes and also mound MS-Hill measuring about 100 m in relative height, accompanying phreatomagmatic and phreatic explosions. Such a group of vents may have branched from the sub-conduit at a certain depths as the case of the 1914 eruption of Sakurajima volcano (Fig. 5 (b)). In the 1944 eruption, first "YH" point in Fig. 6 gradually lifted about 30 m without explosions and then the upheaval migrated towards the N. There, lava dome SS, Showa-Shinzan (new mountain in the Showa era) grew up to about 200 m in relative height accompanying explosions for 21 months. The 2000 eruption was phreatic and phreatomagmatic, and outburst at more than 60 vents, tiny and small in diameter. It is noticeable that the vents of the 1910 eruption and the 2000 eruption did not overlap each other even at their contact area (KP in Fig. 6). This means that parasitic cones are monogenetic. Concerning the future eruptions of Usu volcano, we may expect that it should occur at the summit, or otherwise at "parasite-gap" around the volcano, probably along the contour of 200 m a.s.l.

As for the seismic activities in the last four eruptions of Usu volcano, the largest magnitude of the precursory earthquakes were determined as follows:

The 1910 eruption (parasitic, phreatic and phreatomagmatic): Ms 5.1

The 1944 " (parasitic, lava dome): Ms 5.0,

The 1977 " (summit, magmatic): Ms 4.3,

The 2000 " (parasitic, phreatic and phreatomagmatic): Ms 4.6 (14 hrs after the outburst).

Roughly speaking, parasitic eruptions were accompanied with larger earthquakes than those of the summit eruptions. These earthquakes may have been related to the formation of the parasitic conduits.

The East-Izu monogenetic volcano group: As discussed by De la Cruz-Reyna and Yokoyama (2011), the Michoacán-Guanajuato volcanic field occupies a large area, roughly 100 km × 200 km, and its monogenetic cones, *e. g.* Jorullo and Paricutin, prove to have their origins independently around 30～60 km deep. On the contrary, the East-Izu group occupies a rather small area, roughly 30 km × 40 km, and according to Kuno (1954), the monogenetic cones derive from a magma batch at rather shallow depth (around 10 km deep) in the granitic layer. From this viewpoint, the monogenetic volcano groups in East-Izu and Michoacán-Guanajuato are of different types in their origins. As discussed previously on the East-Izu group, density distribution of cones around the tentative center has no prominent peaks: This means that there is no main vent in the group. To such a geological condition, the maximum shear stress theory is applicable to explain formation of the East-Izu group. In this case, at the surface, compressive rock strength must be much higher than shear strength, and hence the magma proceeds obliquely toward a point of maximum shear stress ($r = 0.82\,D$) to form a monogenetic vent that is not parasitic. If there are similar magma batches in the area, a monogenetic volcano group finally may be formed. This is a possible interpretation upon formation of the East-Izu monogenetic volcano group under particular conditions.

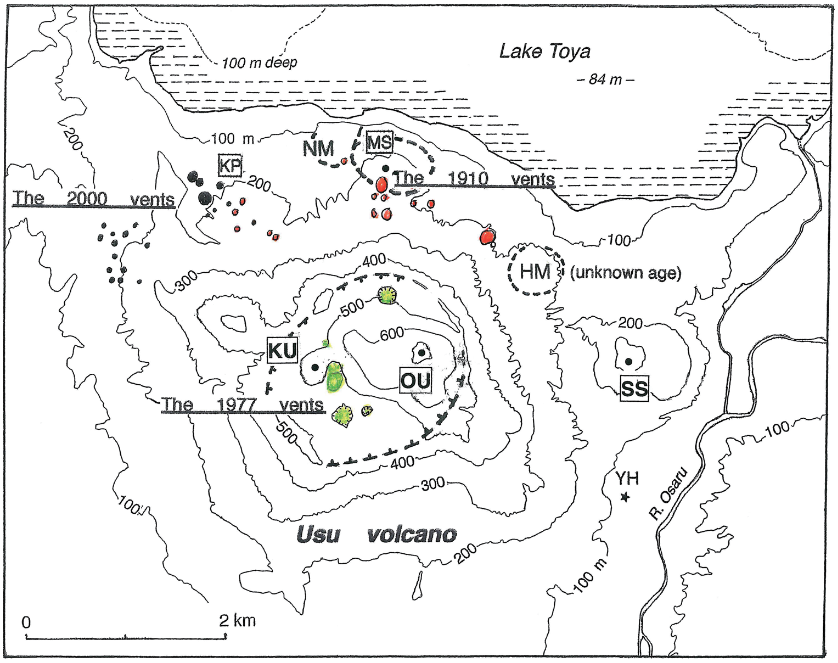


Fig. 6. Parasitic vents on Usu volcano.
Red marks denote the 1910 vents, black ones the 2000 vents, and green ones the 1977 vents in the summit crater.. KU and OU lava domes were formed in 1769 and 1853, respectively. MS mound was formed in 1910 and SS lava dome in 1944. "HM" mound is pre-historic.

4. Parasitic Vents formed in Historical Times on Sakurajima Volcano

The eruptions of Sakurajima volcano have been historically recorded since 708, small or large, more than 40 in total number, and the three large eruptions occurring in 1471～76, 1779～80, and 1914, were all parasitic and produced twin vents in each eruption. In the following, the three cases shall be briefly commented based on the report of Yamaguchi (1975).

4-1 The 1471～76 eruption (the Bunmei era)

The volcano burst into an eruption at a height of 500 m a. s. l. on the NE flank of N-Peak, and the lava flows reached the E shore. Identification of the vents is not always easy because the ejecta of later eruptions thickly cover them. On the SW flank of S-Peak, a vent opened at a height of 400 m a.s.l. and two vents followed at the lower heights. The lava flows from these vents reached the SW shore. The two groups of eruption vents are roughly symmetrical with respect to the center of the volcano, and marked with "**Bn**" and "**Bs**" in Fig. 7 where the star symbols denote the vents of the first eruptions. The radial distances of the parasitic vents from the center of the volcano are roughly 3 and 2 km, and 2.5 km on the average. As discussed above, their branching points were roughly 3 km beneath the volcano. The magma may have branched

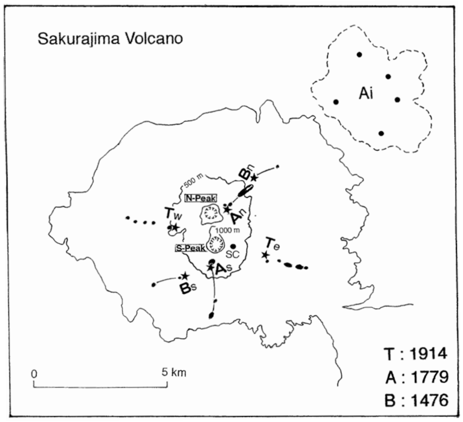


Fig. 7. Twin parasitic vents on Sakurajima volcano after Kobayashi (1988). "Ai" denotes the vents of submarine origin, formed in the 1779 eruption.

into two directions, NE and SW.

4-2 The 1779～80 eruption (the An-ei era)

The eruption took place at the vents of the two groups, "**An**" and "**As**" in Fig. 7. The "**An**" vents were located at a height of 650～750 m a.s.l. on the flank of N-Peak, and the "**As**" vents at a height of 680 m a.s.l. on the flank of S-Peak. Considering that the summit craters of the two peaks were not active, we may suppose that the twin parasitic vents were not auxiliary to the main crater but may have been formed by the fore-mentioned mechanism. The depth of the branch point was roughly 1.2 km beneath the volcano.

According to Kobayashi (1988), explosions began at both the NE and S flanks of the volcano, and the lava flows from the NE vents reached the sea ("As" in Fig. 1). At the last stage, almost simultaneously with the flank eruptions, submarine eruptions occurred at the NE sea bottom forming a few islets ("**Ai"** in Figs. 1 and 7). It is interpreted that the magmas branched into only the NE direction at a larger depth. The submarine eruption sites are about 8 km in radial distance from the center of the volcano. Then we estimate the depth of a branching point roughly as 10 km by the relation (4). This point is situated in a magmatic zone suggested by Iguchi (2007). Both the lavas from the flanks and the sea bottom are analogous in chemical components (Yamaguchi, 1975).

Here, it is noticeable that "Ai" vents were not accompanied by their counterparts at the opposite side of the island. This should arouse a question: This may suggest a difference between shallow (1.2 km) and deep (10 km) tectonic structures beneath Sakurajima volcano.

4−3 The 1914 eruption (the Taisho era)

Its sequence was as follows:

[16 30 h, Jan. 9] The first precursory earthquake was registered at the Nagasaki observatory located at 150 km distance from Sakurajima volcano.

[08 00 h, Jan. 12] A column of white smoke was suddenly shot up in the form of a pine tree from the top of S-Peak. The present author doubts that some gases leaked to the main conduit from ascending magma and sub-conduits had not reached the flank surface yet.

[10 00 h, Jan. 12] Explosions began from two vents formed at heights of 550 and 400 m a.s.l. on the W slope of S-Peak. And 10 min. later, on the eastern flank, explosions occurred from a few vents around height of 380 m a.s.l. The explosions gradually intensified and the explosion clouds reached a height of about 8 km before 11 00 h.

According to Kotô (1916) and Yamaguchi (1975), finally 5 vents were formed on each flank as shown in Fig. 8 (a) where the highest vents on both the flanks were formed at first. Radial distances of the both parasitic vents are about 2 km on average, and the branch depths are about 2.5 km beneath the volcano.

[18 28, Jan. 12] During the explosions, an earthquake of Ms 7. 1 occurred. It was re-examined by Abe (1981) applying modern seismological methods to the data from the worldwide stations of those days, and determined the hypocenter at shallow part at the S of Sakurajima volcano. This earthquake may have no relation to formation of the sub-conduits.

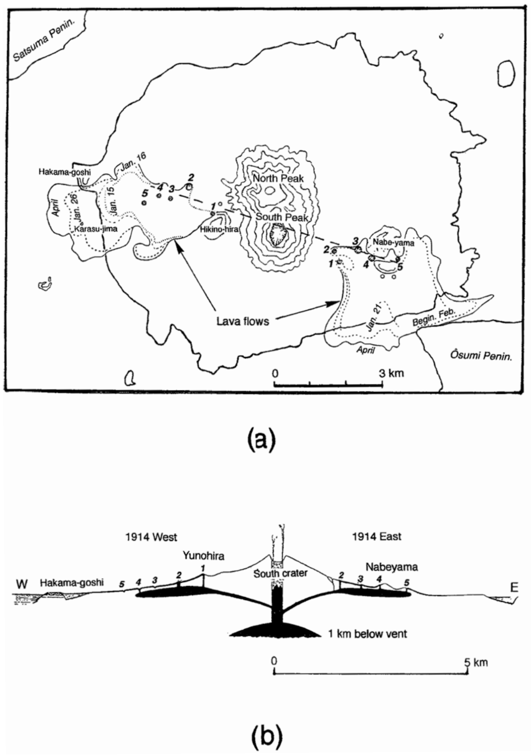


Fig. 8. Parasitic vents formed on Sakurajima volcano in the 1914 eruption after Kotô (1916).
(a) Distribution of parasitic vents (numerals 1〜5 indicate the order of outbursts of each group).
(b) A bilateral injection-chamber model of the parasitic vents formed by the eruption.

[20 00 h approx., Jan. 13] Lavas began to flow out from both the flanks, eastern and western vents, and continued for about 25 days. It took about 65 hours from the first precursory earthquakes to the outburst, and about 100 hours to the beginning of lava effusions. These time intervals may suggest that the sub-conduits were completed in a few days.

[Early February 1914] The main lava flows stopped on both sides. The lavas from the vents on the western and eastern flanks covered areas of 11. 0 and 12. 7 km^2, respectively. The total volume of the lavas amounted to 1.56 km^3 in about 25 days. Thus, the discharge rate of a single vent amounts to roughly 400 m^3/s, that is somewhat larger than those of Kilauea and Etna for the similar duration of activity (Wadge, 1981). Originally discharge rates of lavas depend on position and size of vents, viscosity of lavas and driving forces. Considering that the lavas of Kilauea and Etna are basaltic and more fluidal than the lavas of Sakurajima, we may suppose the high discharge rate of the 1914 Sakurajima eruption is due to the low altitudes of the vents and strong explosivity.

4‒4 Eruption models of twin parasites

There is a hypothesis that the vents on both sides, eastern and western flanks are on the same vertical planar dike passing the center of the volcano. The present author doubts that the central vent should erupt more possibly in this hypothesis. For reference, Kotô (1916) proposed a model for the mechanism of parasitic eruptions assuming bilateral injection-chamber shown in Fig. 8 (b). He may have assumed the equilibrium of magma-heads. However, as above-mentioned, at the first phase of the eruption, the explosion clouds issued from the parasitic vents reached a height of about 8 km: It is rather difficult to interpret such activities by the above injection-chamber. On the other hand, we need to explain why the central vent did not work during the parasitic eruptions.

An alternative model extended from the present discussion is as follows: The sub-vents of the both groups of flank vents, "**T**e" and "**T**w" in Fig. 7, are located at about 2 km from the central summit. Then, the branching points of both vents from the main conduit are estimated at about 2.5 km deep by the relation (4), as schematically illustrated in Fig. 5 (b). And on both the slopes, the vent at higher altitude erupted earlier with high explosivity. The summit craters remained quiet during the 1914 eruption except ejection of a column of white smoke from the summit crater of S-Peak in the morning of the first day of the eruption. This fact does not support the assumptive intrusion of a vertical, radial and planar dyke from the center of the volcano. Lava effusions were not fissure ones, but migrated from the top vent to the bottom one probably due to hydraulic magma-pressure.

We know a few examples of flank eruptions that occurred simultaneously at two opposite sides on the slope, symmetrically with respect to the central summit: *e.g.* the 1970 eruption of Hekla, Iceland. At Hekla, two fissure eruptions at the SW and NE flanks occurred within only 70 minutes. The vents of the eruptions were located at about 3～4 km distances from the central crater of Hekla. Thorarinsson and Sigvaldason (1972) interpreted these eruptions from petrologocal discussion as to have been deep-fed separately by magma chambers different from that of Hekla. Anyhow it is a confronted problem why twin parasitic vents have been repeatedly produced on Sakurajima volcano.

Petrological compositions of the lavas issued in the three eruptions: According to Yamaguchi (1975), the SiO_2 contents of the lavas from the three eruptions changed from 66, 64 to 60 % in chronological order. As mentioned above, the branch depths of the three parasitic eruptions are 2. 5 km, 1. 2 and 10 km, and 2. 5 km, respectively. At present, we do not find any clear correlation between the SiO_2 contents of the lavas and the branch depths.

4‒5 Activities of Sakurajima volcano after the 1914 eruption

The 1935 eruption: 21 years after the 1914 eruption, Sakurajima volcano first erupted in a minor magnitude ejecting ashes for a few days. The eruption formed a vent within the crater of S-Peak.

The 1939 eruption: "Showa Crater" ("SC" in Figs. 1 and 7) opened at a height of 700～750 m a.s.l. on the eastern flank of S-Peak of which crater rim is 1060 m a.s.l. The dimension of the crater was 50 m in diameter and 100 m in depth. The crater issued pyroclastics, not lava flows. As mentioned before, this crater is regarded as an auxiliary to the main crater.

The 1946 eruption: After 1939, minor explosions were repeated in 1941, 1942, 1943 and 1945 at Showa Crater. In 1946, the crater was activated and extruded lavas of 0.15 km^3 (DRE) of which SiO_2 content is 61 %.

The explosion activities after the 1946 eruption: Small explosions were observed at Showa Crater in 1947 and 1948. In 1955, explosive activities began at the summit crater of S-Peak, and the eruptive activity declined near the end of the century. Then the activity migrated to Showa Crater in 2006.

Iguchi *et al.* (2010) compared the activities of Showa Crater during 2006 to 2010 with the previous activity in the crater of S-Peak, and examined 4 parameters: (1) moments of long-period phase of explosion earthquakes, (2) amplitudes of air-shock caused by explosions, (3) intensity of pressure source causing the ground deformation associated with explosions, (4) weights of volcanic ash issued by explosions. Finally they concluded that explosive eruptions at the summit crater are larger by 10～100 times than those at Showa Crater. This conclusion does not totally contradict with the above presumption that Showa Crater is auxiliary to the S-Peak crater.

4‒6 "Parasitic volcanoes only erupt once."

The three twin parasitic eruptions occurring in the historical period on the flank of Sakurajima volcano afford us suggestive information: They don't overlap each other as well as on Usu volcano (Fig. 6) though both the volcanoes are relatively small, 10 and 5 km respectively in basal diameter. In this sense, parasitic volcanoes behave as monogenetic volcanoes although the latter originates from deep sources and usually cluster in rather wide area. The following is a hypothetical explanation of the fact that parasitic volcanoes only erupt once:

During a cycle of volcanic activity, the surroundings of parasitic vents must be compacted and strengthened mechanically by magma intrusions (piling effects). The central vents of polygenetic volcanoes, after an eruptive activity stops, may be loosely choked with lavas and ejecta to a certain depth due to their own weight. On the other hand, sub-conduits of parasitic volcanoes probably remain almost the same as the beginning because the volcanoes do not always repeatedly explode to enlarge the conduits and end the activity after one cycle, and also may be tightly choked with lavas due to oblique slope of the sub-conduit.

When magma re-activates at the depths of volcanoes, it begins to ascend for the summit crater through the main conduit. If upward magmatic pressure is strong enough to clear the main conduit, the summit crater should reopen. On the other hand, under the same situation, the magma reaches the branch point for sub-conduit that is choked tightly. In this case, oblique pressure is unfavorable to clear sub-conduit leading to a parasitic vent. If particular conditions are satisfied, a parasitic vent may be newly formed as discussed in the previous chapter.

5. Conclusion

A simple method to find a trend, if any, in spatial distribution of parasitic cones is proposed: Estimations of numbers of the cones per unit area with increasing radial distance from the centre of volcano. And its application is exemplified on Sakurajima and Izu-Ooshima volcanoes. By simple mechanical assumption, the radial distances of dense distribution of cones are related to the depth of the branching point from the main conduit. In this paper the branching points are assumed to correlate with magma reservoirs and some singular points though the mechanism is not yet resolved. As far as we cannot clarify the mechanism of branching from the main conduit, it is difficult for us to predict the exact site of the next parasitic eruption on the flanks.

The parasitic eruptions on and around Sakurajima volcano in historical ages are briefly described from the viewpoint of their formation mechanisms. The twin parasitic vents are normal on Sakurajima volcano, and odd on the other volcanoes. In the later stage of the 1779～80 eruption, the submarine vent ("Ai") branched from 10 km depth, but the vent were not accompanied by its counterpart at the opposite side of the island. This may suggest a difference in tectonic structure between shallow and deep parts (3 and 10 km) beneath Sakurajima volcano.

Future eruptions of Sakurajima volcano probably may take place at the summit craters, or otherwise statistically parasitic vents may be formed at circumferential zones of radial distances 2. 5 or 8. 5 km from the center of the volcano, on the flank and in the surrounding sea area, respectively. And surely the vents on the flanks may appear at "parasite-gaps". In case of parasitic eruptions on the flanks, twin vents may be formed very probably. It is difficult to comment further on future eruptions of this volcano as far as the plumbing system of magma reservoir, main-conduit, and sub-conduits are not clarified.

As to the theory of parasite formation, there is much to be done for its completion. A satisfactory theory would only be completed after field observations of parasitic eruptions over a long period.

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(Editorial handling Masato Iguchi)

桜島火山における寄生火口の噴火

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桜島火山には多くの寄生火口が地質及び地形の面から認められている．また，その噴火史において寄生火口の噴火がしばしば記録されている．寄生火口の分布パターンを調べるのに，色んな方法が提案されてきたが，ここでは，火山中心から半径方向の密度分布（km^2当たり）を調べた．

一般論として，火山の下に点力源を仮定して，地表面で直応力の分布と水平差応力の分布を考え，岩石の強度を考慮すると，寄生火口の生ずる地点の見当がつく．それは，地表で力源を伏角 51°で見る山腹の地点で，火山中心に対して対称な 2 点である．多くの火山では，対で生ずることは少ない．桜島火山の寄生火口の火道が主火道から分岐する深さを求めると，深さが 3 km と 10 km の 2 群となる．これらの深さと既に推定されているマグマ溜まりとの関連につぃて触れた．桜島火山の歴史時代の（1471 年以降の 3）回の大噴火は総て，山頂に対称的に対をなして形成された．このことは力学的には正常であるが，事例としては例外である．ただ，分岐の深さが 10 km の場合（1779～80 年噴火），山頂に対して対称位置に寄生火口が生じていない．この例外的な事例は，桜島地下で，浅部と深部で地殻構造が異なることに起因するのかも知れない．更に，寄生火口が再噴火しない機構について仮説を述べた．

次の桜島火山の噴火地点は何処であろうか．山頂火口か，それでなければ，寄生噴火である．その場所は統計的に，山体の中心軸から約 2.5 km 或は 8.5 km の円環上で，かって噴火したことのない地点が考えられる．寄生火口の火道が主火道から分岐する機構が未解明である限り，これ以上のことは言えない．

Appendix:

After this paper was accepted in April 19, 2012 by the Bulletin, a paper discussing the 1888 eruption of Bandai volcano was published on this Bulletin ---- Hamaguchi, H. and Ueki, S. (2012) Notes on the 1888 Phreatic explosion at Bandai volcano (1) The re-examination of the location of explosive source and direction of outbursts. *Bull. Volcanol. Soc. Jpn*, **57**, 111-123 (in Japanese with English abstract). They newly interpreted the 1888 eruption of Bandai into two lateral ones around the summit and proposed a mechanical model for producing the two vents by tensional stress exerted from a pressurized spherical source. Their results are similar to those of the present paper.