"CLUSTERS OF SMALL MONOGENETIC CONES: A PARTICULAR TYPE OF CONFINED VOLCANISM „

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ABSTRACT

Monogenetic volcanoes are a frequent type of volcanisms on Earth. They are frequently paired with polygenetic ones. We can distinguish them by their place of origin. If a new vent opens on or near an existing volcano, it will join with a main crater of the volcano, or form a parasite on a flank of the volcano. If the vent opens at a certain distance from an existing volcano, its activities are independent of that volcano and its magma sources are also separate. At present we have difficulty in distinguishing between monogenetic and polygenetic volcanoes, when we do not know the formers' history of eruptions. We are sure that Jorullo and Paricutin, both born before our eyes, are important and indispensable examples for discussion on monogenetic volcanism. The present discussion starts fundamentally from the knowledge of these two volcanoes. Among examples of monogenetic cones, we find clusters of monogenetic cones much smaller than Jorullo and Paricutin in volume, and densely distributed in a certain area of the world. The present paper discusses the three areas in the Far East. Morphological characteristics of the three areas show a strong volume contrast between component cones of the cluster areas and the twins of Jorullo and Paricutin. Averaged component volume of the former is approximately equal to $1 / 10^2$ times as large as that of the latter. The present author tentatively presents qualitative interpretation of the above quantitative characteristics, mainly from a geophysical standpoint.

1. MONOGENETIC VOLCANOES

1.1 DEFINITION OF MONOGENETIC VOLCANOES

When a new volcanic vent opens on or near a polygenetic volcano, it would usually continue activities as a parasitic vent simultaneously with the main crater, and the volcano will be occupied by a number of parasites with time. When a new vent occurs at a certain distance from polygenetic volcanoes, it would be difficult to predict whether it will be monogenetic or poly-genetic. At present, we know of only two historical eruptions of monogenetic volcanoes, Jorullo in 1759 and Paricutin in 1943, both in Mexico. From these two examples, the pioneers have studied developments of volcanic activities, deep magma movements, petrological and geochemical properties of their ejecta, to confirm the two cones as monogenetic.

De la Cruz-Reyna and Yokoyama [2011] discussed characterization of monogenetic volcanism from a geophysical standpoint. They first reviewed the activities

of Jorullo and Paricutin, and further, compared those with Monte Nuovo (1538), Wudalianchi (1719-21), Waiowa (1943-44), and East-Izu (1989). Thereafter Yokoyama [2015] discussed eruption patterns of parasitic cones on polygenetic volcanoes in contrast with monogenetic cones. According to them, some particular characteristics of Jorullo and Paricutin are summarized as follows:

1) Independency from nearby existing volcanoes: the two volcanoes originated at the nearest distance of about 3 km at Jorullo and 12 km at Paricutin, respectively from existing polygenetic volcanic vents. In fact, the distance is not important but independency of the magmatic origin is essential.

2) Their activity periods: these were 16 and 9 years, respectively. Such short periods are related to their relatively small volume.

3) Total volume of their ejecta: the estimated volume is 2 km^3 (DRE) for 16 years at Jorullo, and 1.4 km^3 (DRE) for 9 years at Paricutin [after Luhr and Simkin, 1993]. Their average volume of 1.7 or roughly 2 km^3 in order of magnitude may be a unit volume of magma discharge at basaltic volcanoes.

4) Their plumbing system: De la Cruz-Reyna and Yokoyama [2011] concluded that the main sources of magma beneath both the volcanoes are deep, probably below the base of the crust by the discussion of precursory seismicity and the absence of significant regional deformations around the volcanoes. On the other hand, Németh and Kereszturi [2015] presented theoretical models for the plumbing system of monogenetic continental volcanoes including Jorullo and Paricutin based on chemical signatures of erupted materials, and assumed magma storage of the volcanoes at crustal levels. Meanwhile, Smith and Nénmeth [2019] recognized that small-scale volcanic systems are commonly monogenetic and they were produced by a temporally restricted eruption of a distinct batch of magma, referring to many monogenetic fields all over the world.

In the present paper, monogenetic volcanoes, of which formation were recognized with our eyes, such as Jorullo and Paricutin, are named "proper monogenetic cones". The cones of this group may have possibility of increase in number by future worldwide investigations.

In contrast to the above definition of monogenetic volcanoes, we know small or large clusters of mono-genetic cones formed by respective eruptions simultaneously or independently in a certain area on the earth: These were probably controlled by special magma feeding systems which shall be discussed in Chapter 2.

In order to solve some fundamental problems in volcanology, studies of particular phenomena on particular volcanoes should provide us with important clues. Hence, the discussion on the three monogenetic volcano fields, the Wudalianchi area, Jeju Island and the East-Izu area in the Far East may help us to gain an insight into the magma ascents and vent formation processes under particular conditions. In the present paper, a possible mechanism of formation of the clusters shall be interpreted from a geophysical standpoint exemplifying mainly the three fields in Chapter 2. All of the fields originated from basaltic magmas, and have no direct genetic relationships among them because the distances between them are more than 1000 km as shown in Figure 3.

1.2 SHEAR FRACTURE MODEL FOR THE FORMATION OF PARASITIC VENTS

Formations of parasites are generally related to upward magma movements originated from magma reservoirs, directly or indirectly. Here, to interpret the formation of parasites, we adopt a simple mechanical model that should be related to the structure and the strength of main volcanic edifices and the origin of magmatic forces. Actual volcano structure is not always uniform and there may be structural weaknesses within roughly stratified edifices. Even if volcano edifices are under such condition, the results of a modeling may furnish hints of parasite formation.

As a criterion of fracture in material mechanics [*e.g.* Jaeger, 1964] for brittle materials, the theory of maximum shearing stresses has proved to be of wide application in various experimental tests. Formation of main or summit craters of volcanoes or polygenetic ones is usually interpretable by theory of maximum stress, tensional and compressive. On the other hand, formation of parasitic vents distributed widely around the central conduits can be interpreted more rationally by the theory of maximum shearing stress. Based on this theory, the free surface displacements are already obtained by De la Cruz-Reyna and Yokoyama [2011] and here shall be briefly referred.

In the discussion of volcanic activities, origin of movements is usually derived from magmatic force that may be assumed to be a dilatational pressure P_0, for simplicity. We adopt a combination of cylindrical and plane polar coordinates with the origin at a pressure source (R, Φ, Θ) and (r, θ), respectively as shown
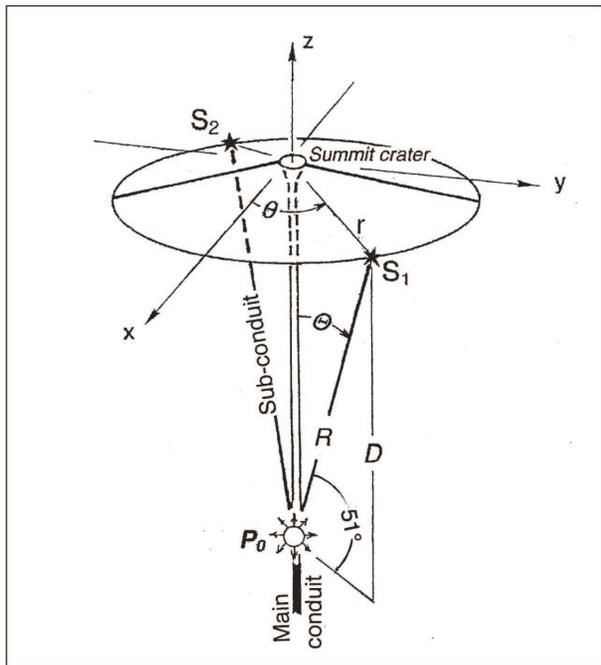
FIGURE 1. Shear fracture model.

P_0: dilatational pressure, S_1 and S_2: twin fracture sources.

in Figure 1. The maximum shear stress is equal to a half of the horizontal differential stress and is represented as:

$$\frac{1}{2}(\sigma_{rr} - \sigma_{\theta\theta}) \qquad (1)$$

where σ_{rr} and $\sigma_{\theta\theta}$ denote the principal stresses. The maximum shear stress occurs across a plane whose normal bisects the angle between the greatest and least principal stresses. After some calculations, we get the value of the term (1), positive or negative maximum at

$$r = \pm 0.82\ D, \quad \text{or} \quad D = 1.22\ r \qquad (2)$$

where D is the depth of the pressure source. Therefore, the medium receives the maximum horizontal differential stress at a radial distance $r = \pm 0.82\ D$ and these two points are denoted as S_1 and S_2 in Figure 1. And the elevation angles of S_1 and S_2 at the origin are 51° in arc. Consequently, shear fracture takes place there in the radial direction on the surface or along the slope. We expect theoretically the maximum horizontal differential stress to be present at two points S_1 and S_2 or on symmetrical sides of volcanoes. The possibility of such a pair of fracturing point may depend on particular conditions on each volcano. When a parasitic vent is formed, the other symmetric fracturing point is probably not present due to stress concentration at the former.

Furthermore, the majority of volcanoes are not uniform in structure and hence, the above results are not always determined and formation of twin parasites has not been common. However, we know of several examples of twin parasitic vents formed before our eyes: Yokoyama [2015] mentioned the examples such as the 1476, 1779 and 1914 eruptions of Sakurajima, Japan that has been erupting at the summit crater since 1946, and the 1951 eruption of Fogo, the Cape Verde Islands, the 1970 eruption of Hekla, Iceland and the 1973 eruption of Tyatya, the Kurile Islands.

Whether the main crater erupts or the parasitic fracture does, depends on the condition of the existing main crater and strength of the cap rock in either location. Compressive rock-strength is roughly on order of 100 *MPa* and shearing strength roughly on order of 10 *MPa* [Jaeger, 1964] though these two kinds of strengths are very variable according to mechanical texture of the medium. At central craters of existing volcanoes, compressive force of magmas would easily break down their crater bottoms.

Figure 2 was originally drawn by Anderson [1936, Figure 8] when he discussed the formation of con-sheets and ring dykes. In the figure, the broken lines show iso-static surfaces across which there is a pressure, and the thin solid lines show isostatic surfaces across which there is a tension possibly forming magma paths. Considering Figure 1 and Equation 2, the present author added red lines S_1 and S_2 in Figure 2. These two lines are the limits of magma paths. A conical part bounded by S_1 and S_2 - lines shall be finally destructed by the increased pressure of the magma acting at P_0 in Fig.1: This leads to caldera formations according to Anderson [1936]. Outside of S_1 and S_2 - lines, any fractures do not appear at the surface, and become sill-like intrusions.
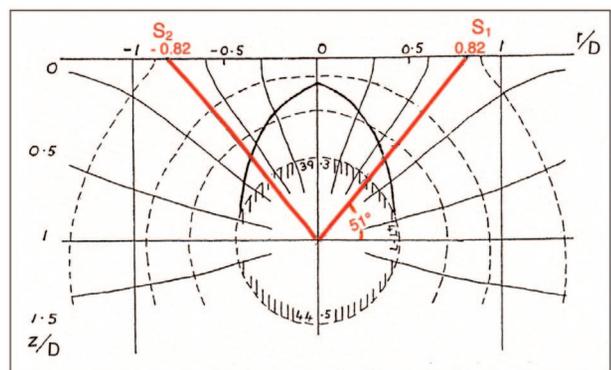

FIGURE 2. Isostatic surface produced by point dilatation beneath free surface, after Anderson (1936). Red lines S1 and S2 are added by the present author.
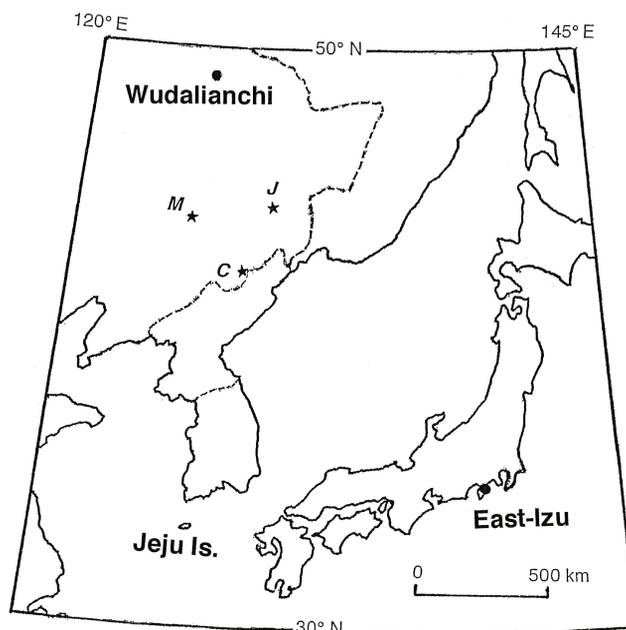
FIGURE 3. Locality map of the Far East. *M*: Ma−On−Shan, *J*: Jingpo, *C*: Changbaishan.

2. CHARACTERISTICS OF MONOGENETIC CONES AT THE THREE CLUSTERS IN THE FAR EAST

The two clusters in the Far East, Jeju Island and the East-Izu area, shall be discussed in the following sections. The Wudalianchi monogenetic volcano field shall be described preparatorily because their component cones are not so many at present comparing with the other two.

2.1 THE JEJU ISLAND CLUSTER OF MONOGENETIC CONES IN KOREA

Jeju Island is located between the Korean Peninsula and the Islands of Japan. Its area is about 800 km^2 and more than 300 cones are found as shown in Figure 4. The age of the cones covers the Pleistocene (2.6 ~ 0.01 Ma) and Hasenaka et al. [1998a] mentioned eruptions in 1002, 1007, 1440 and 1670. The basement of this island is Miocene granite that is now covered with volcanic material. All lavas of this island belong to alkali rock series. Geology and petrology of this island were first summarized by Lee [1982 a, b] and later, Brenna et al. [2012] discussed basaltic magmatic systems in the Jeju Island volcanic area mainly from a geochemical standpoint.

Hasenaka et al. [1998 a, b] discussed geomorphological characteristics of the monogenetic volcanoes on this island, and completed a catalogue of these cones. Hasenaka et al. [1998a] counted 318 monogenetic cones after their elaborate field studies. In their catalogue, volumes of each volcanic cone are given on assumption that the ed-

ifices are circular truncated cones. The dimensions of the cones range 1 ~ 2.5 km in basal diameter and 50 ~ 250 m in relative height, and the largest one is 0.3 km^3, the next three are 0.2 km^3, the following three are all 0.1 km^3, and the others are all smaller than 0.1 km^3. Hasenaka et al. [1998 b] estimated the total volume of monogenetic cones as 5 km^3, but commented that lava flows are more voluminous than the cones.

Independently of the Hasenaka's group, the present author utilized a topographic map only to estimate the volume of the cones. The map is 1: 78,500 in scale, with contour intervals of 20 m, published in 1983. He distinguished 278 cones only by topographic features on a map and estimated the total volume of the cones at 3.1 km^3 assuming the cones to be circular cones. Considering that volume estimations of volcanic ejecta, in the general, are very imprecise, and should be only an order of magnitude indicator. In the present paper, the author adopts that the total number of the cones on this island as 318 and the total volume of the cones as the mean value of the two estimates, 4 km^3 in the strict sense.

Monogenetic cones numbering 318 were formed all over the island and the formation continued from about 0.2 Ma to historical ages [Hasenaka et al., 1998 b]. Considering the fact that the last formations of monogenetic cones of historical age occurred at the seashore of the island, and may have started around the central part through deep conduits from the depths and thereafter may have migrated outward. Besides these cones and lava flows, there are many lava tunnels on the island.
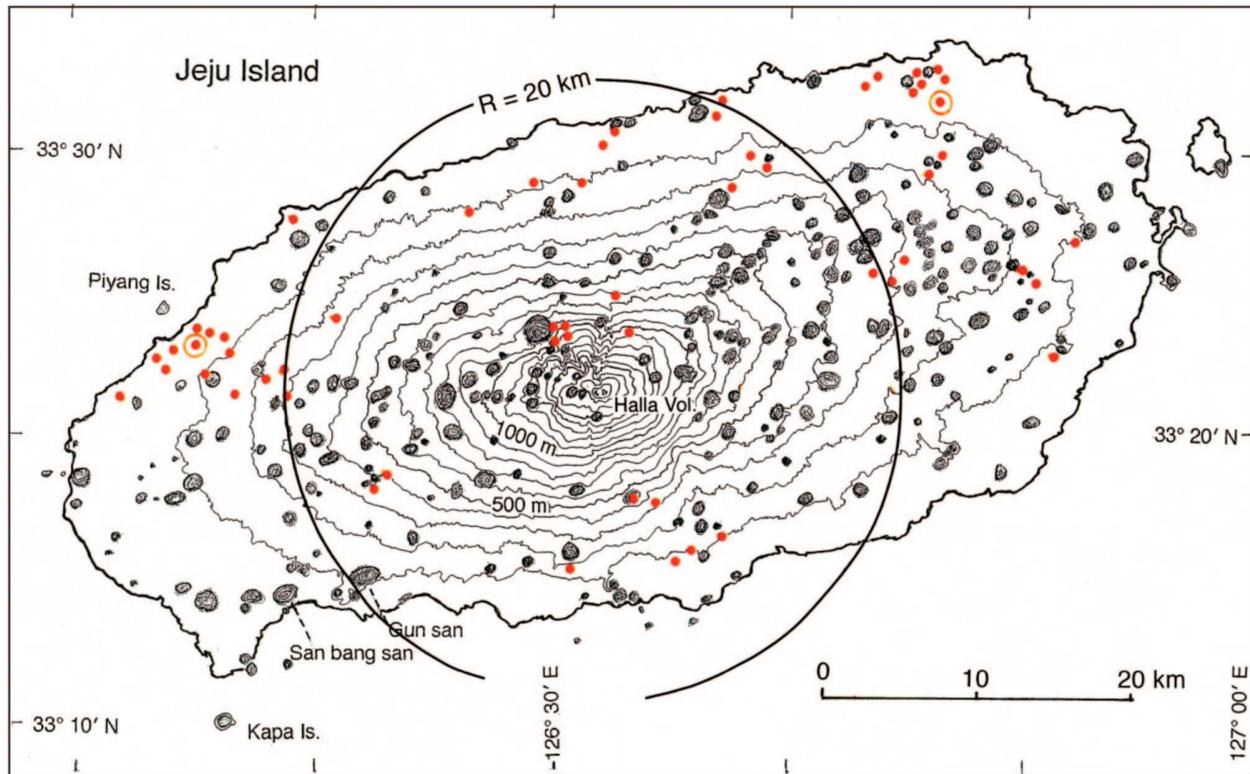
FIGURE 4. Monogenetic cones on Jeju Island. dots: monogenetic cones, red dots: entrances of lava tunnels, red double dots: those of larger lava tunnels.

In Fig. 4, their entrances are marked by red dots and those of the longest two by double dots. The lava tunnels are distributed all around the island and somewhat concentrated at the two areas, the NE and the NW of the island. Around these areas, we find few monogenetic cones. However, it is not clear whether activities of lava tunnels have supplanted those of the monogenetic cones because explorations of lava tunnels have not been completed.

As for volcano geology, Lee [1982 a] divides the periods of volcanic activity of this island into four periods as follows:

1) The 1st period: basaltic magma formed the basements of this island.

2) The 2nd period: near the end of the Tertiary and the beginning of the Quaternary periods, volcanic activities began and a large quantity of basaltic lavas formed a wide lava plateau.

3) The 3rd period: a large quantity of basaltic lavas formed Halla volcano (1950 m a.s.l.) at the center of the island and later trachyandestic lavas were ejected. At the summit part of Halla Volcano, lava domes with relative height of 300 ~ 400 m were formed.

4) The 4th period: formation of monogenetic cones all around Halla volcano. The dense distribution

of the cones, small and large in dimension, as shown in Figure 5, suggests that each of them may have erupted once, or more appropriately speaking, in a single eruption cycle. As a result, the island has become full of monogenetic cones.

On the other hand, historical documents mention that eruptions in 1002 and 1007 produced two cones, but these cones are not confirmed. People say that they are Piyang Island (114 m a.s.l.) and Gun-san cone (235 m relative height), in the W part of the island (Figure 4). In the future, the events should be clarified by geological studies and age determinations. At present, no volcanic and fumarolic activities are reported on Jeju Island.

Distribution of monogenetic cones may be controlled by tectonic stress striking N 70°E. In the present discussion, frequency distribution of parasitic cones every 4 km along the direction of N 70°E is checked, and there is no particular tendency. Next, radial distribution of the monogenetic cones every 10 km from the center of Halla Volcano is counted in Figure 4 and then the numbers of per unit area of each circular division or ring are plotted in Figure 5 (top) which is axially symmetrical around the vertical center, and shows a peak around r = 14 km. Near Halla Volcano, monogenetic cones are

rather few because there is a wide lava plateau, as mentioned above.

In relation to the formation mechanism of numerous monogenetic cones, Smith and Németh [2019] assume that each cone was separately fed from magma batches derived from the deep reservoirs. However, such magma supply systems should be unlikely because many long conduits such as 50 km long and densely distributed such as at 2 km apart within an area of 500 km^2 may intertwine and be mechanically unstable, especially in unconsolidated upper crust.

In the shear fracture model, we assume magma supply routes to be branched from the "main conduit" to several "sub-conduits" and further to many

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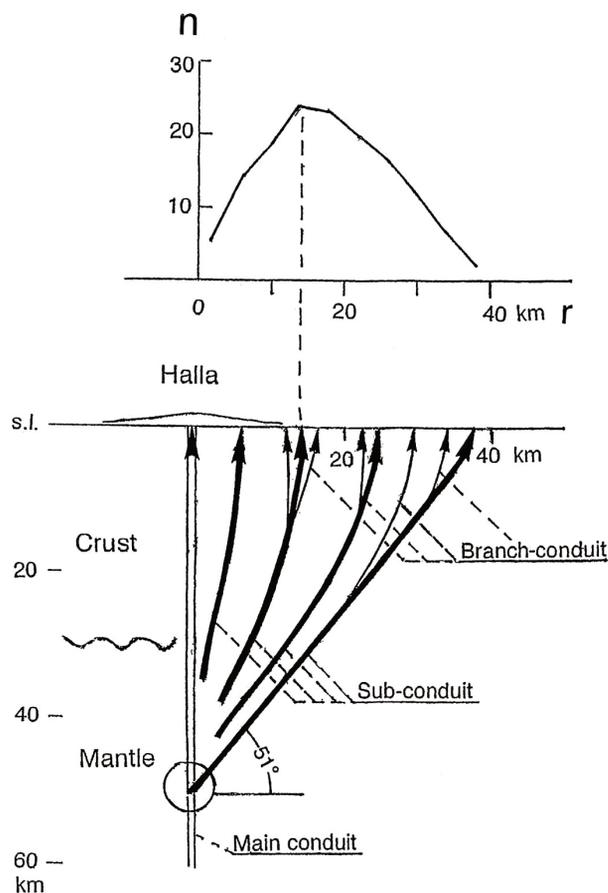
FIGURE 5. A conceptual model of monogenetic cones on Jeju Island. (Top) Radial distribution of the cones around Halla Volcano. This figure shows one side of the symmetric distribution. n: number of cones per Δr = 4 km. (Bottom) A hypothetical image of magma con–duits toward the component cones. In fact, there are more "branch conduits" to form many cones. The ge–ological section is approximate.

"branch-conduits" as schematically illustrated in Figure 5 (bottom). The branch point along the main conduit is not always a magma reservoir but may be a "magma stop" that is a magma block likely caused by restriction of magma flows. This configuration of the conduits is qualitatively deduced from the shear fracture model. In fact, sub-conduits and branch-conduits in the figure must be most dense around r = 14 km. Thus, a small amount of magma may have been fed through the branch-conduits to the vents as schematically shown in Figure 5 (bottom) where the main conduit, sub-conduits, and about 159 (= 318 / 2) branch-conduits are to be located but they are simplified in the figure. Such configuration of the conduits has been completed by the volcanic activities for long periods (~ 0.2 Ma). Sub-conduits do not reach the surface outside of S_1 and S_2 in Figure 2, and branch-conduits between the sub-conduits all reach the surface to form numerous vents.

In the present paper, the shear fracture model is applied to formation of sub-conduits in Figure 5 and further, branch-conduits may have formed by fractures in heterogeneous medium of the shallow crust. In Figure 5, the outermost monogenetic cones are at about 40 km distance from the center of the island. In the shear fracture model, the sub-conduits reaching this point branched from the main conduit at a depth of (40 km × 1.2 =) 48 km by eq. (1). This depth is likely in the mantle of this area. All magmas are substantially basaltic, and any petrographic differences among the ejecta from different depths are not reported. As exemplified above, first, a magma conduit is assumed to reach the upper mantle from the magma sources, and hereafter, the shear fracture model is effective in forming numerous branches of conduits leading to clusters of small cones.

2.2 THE EAST-IZU CLUSTER OF MONOGENETIC CONES, THE CENTRAL JAPAN

This volcano group is located at the E part and offshore from the coast of the Izu Peninsula. There are about 70 cones on land and 80 in the sea as shown in Fiure.6. Area of the cluster is roughly 30 × 30 = 900 km^2. Aramaki and Hamuro [1977] studied this monogenetic group on land from geological standpoint and estimated volumes of componental cones and their ejecta and compiled geomorphological data of the East-Izu cluster of monogenetic cones summarized in a table. According to them, ages of volcanisms of the clusters are 0.04 Ma. They estimated volumes of the 75 monogenetic cones including 5 submarine cones of the same age: The largest one is Omuro-yama Volcano (OM in
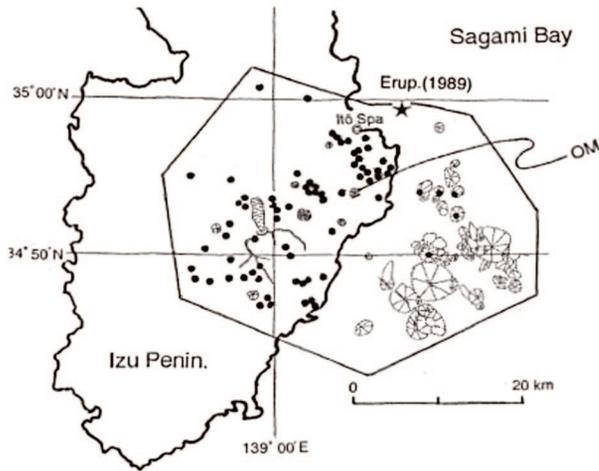
FIGURE 6. Monogenetic cones in the East–Izu area after Ara–maki and Hamuro (1977) and Hamuro et al. (1980). A polygon surrounds the monogenetic cluster. OM (Omuro–yama) is assumed to be the central cone.
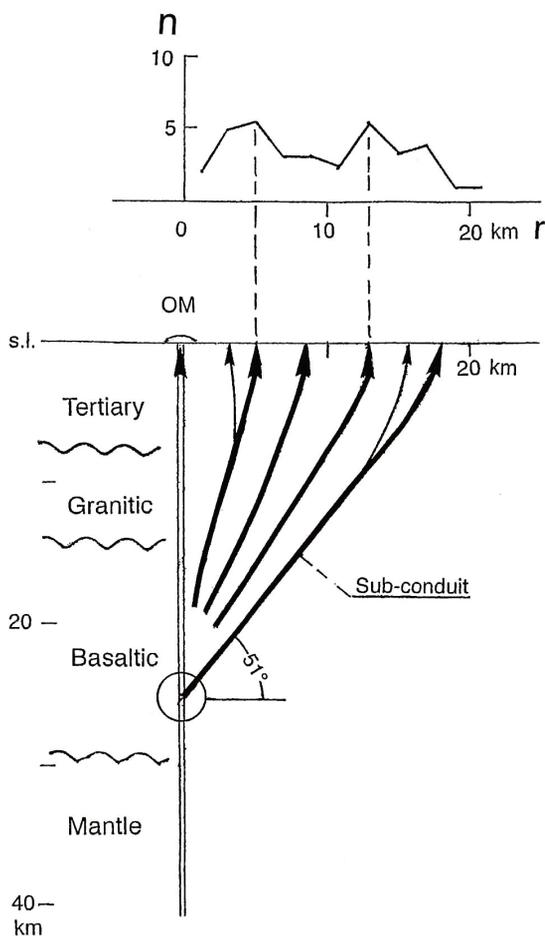

FIGURE 7. A conceptual model of monogenetic cones in the East–Izu area. (Top): Radial distribution of the cones around OM, similar to Fig. 5. n: number of cones per $\Delta r = 2$ km. (Bottom): A hypothetical image of magma conduits toward the component cones. The geologi–cal section is approximate.

Figure 6) amounting to 0.93 km^3, and the followings are 0.28, 0.26, 0.23, 0.12 km^3 and so on, smaller ones. The total volume of the volcanic ejecta from all the vents amounts to 2.5 km^3.

The distribution of monogenetic vents formed in the East-Izu area is shown in Figure 6 where five marine cones located at the E offshore from the peninsula are included because Hamuro et al. [1980] determined these to be similar age and rock type with the East-Izu group located on land. Thus, the group is composed of 70 cones on land and 5 beneath the sea as shown in Figure 6 where the dots denote locations of monogenetic cones and differences of their diameters are disregarded.

It is remarkable that OM Volcano is the largest and located approximately at the center of the monogenetic cluster. The activities of OM prevailed around 3700 ± 100 YBP [Saito et al., 2003] and after that, a cluster has been formed with smaller monogenetic cones. After the birth of Paricutin in Mexico, Kuno [1954] studied OM Volcano from the standpoint of its physiographic feature and structure, and mentioned that it closely resembles Paricutin in Mexico. He stressed that the petrographic character of OM lava is similar to that of the earlier lavas of Paricutin. In the following discussion, the present author assumes that OM is the center of the cluster formed directly through the main conduit from magma sources of the East-Izu area. Then the radial distribution of monogenetic cones at every 2 km intervals around OM is shown in Figure 7 (top), where there are no particular trends. Hence, sub-conduits of magma must be distributed rather uniformly around OM. The most distant parasitic cone is located at about 20 km distance from OM. In the shear fracture model, the sub-conduit reaching this point branched from the main conduit at a depth of 24 km (20 km × 1.2), in basaltic layer. This branch point may be a "magma stop" and the magma reservoirs should be located deeper in the mantle that is bounded by the crust at 30 ~ 35 km depth in this area. The sub-conduits may have been rather thin, characteristically for monogenetic volcanoes [De la Cruz-Reyna and Yokoyama, 2011]. As well as Figure 5, simplified images of magma conduits beneath the East-Izu area are shown in Figure 7.

2.2.1 RECENT SEISMIC ACTIVITIES IN AND AROUND THIS AREA

In March ~ May of 1930, earthquake swarms were felt around Itō Spa (Figures 6 and 8). And in November of the same year, the North-Izu Earthquake (Ms 7.3) occurred, though its epicentral area was outside of the monogenetic cluster.

2.2.2 THE 1975 ~ 1977 EARTHQUAKE SWARMS IN THE EAST-IZU CLUSTER

According to Tsumura et al. [1977], shallow microearthquakes began to occur in August 1975, and activity continued into the following year and finally ended in the summer of 1977. Their epicenters migrated in the cluster area as shown in Figure 8 which covers the period from Nov. 20, 1975 to Dec. 31, 1976 and their number totaled to 1872. The earthquakes were of maximum magnitude of 2.6 and their depths ranged 4 ~ 7 km b.s.l. (Figure 8 b). Coinciding with the seismic activity, local crustal uplift amounting to 15 cm was observed. This was centered at Togasa-yama Volcano, about 5 km W from OM. Any crustal deformations under the sea were not reported. The earthquake swarm was not accompanied by any surface eruptions after all. In Figure 8 b,

along a vertical E-W trending profile, temporal migration of the hypocenters cannot be traced but their linear trend of the distribution shown by red lines corresponds partly to failure developments. This trend coincides approximately with vertical profile of the outermost "sub-conduit" in Figure 7 (bottom) with elevation angle of 51 degrees. This supports validity of the shear fracture model for formation of parasitic vents.

Similar distribution of the hypocenters related to dike emplacement in 2006 near Paricutin, one of "the proper monogenetic volcanoes", was reported by Gardine et al. [2011] who presented a conceptual model of a propagating dike: the vertical angle of the hypocenter distribution is roughly 45 degrees and the bottom of the hypocentral zone is around 10 km b.s.l.
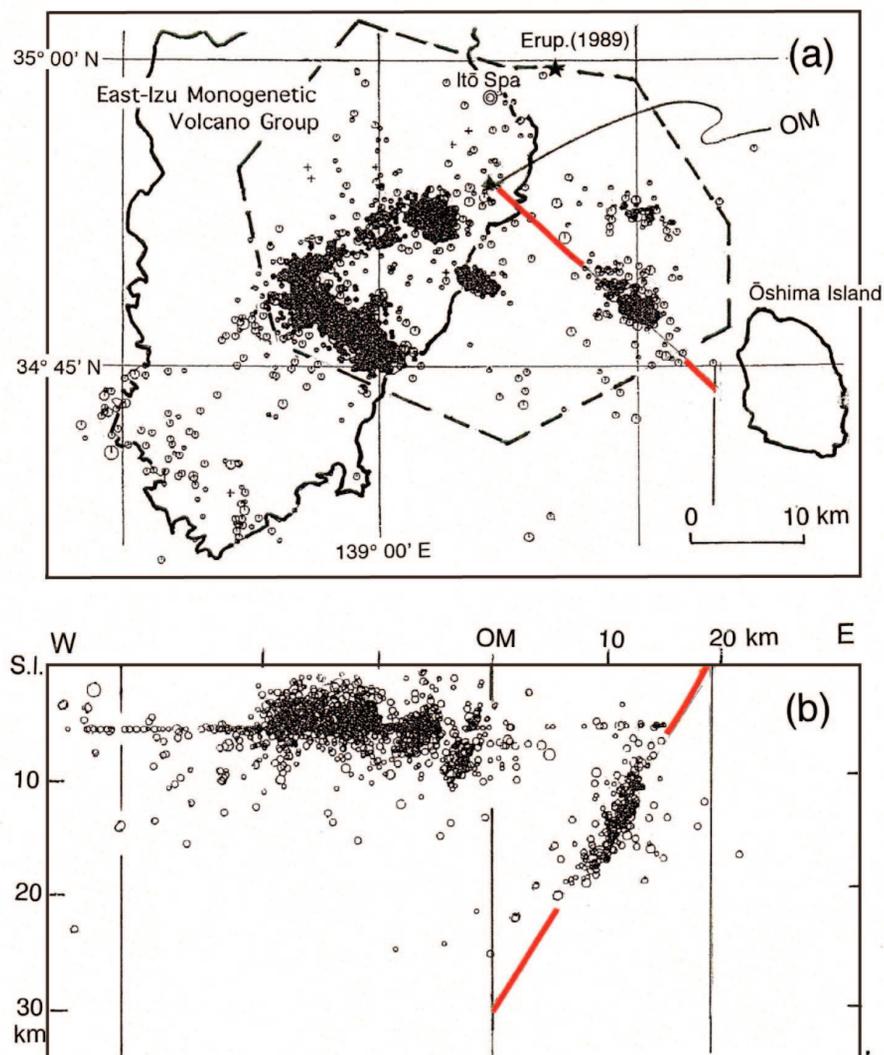
As for magma feeding system beneath Paricutin, we

FIGURE 8. Hypocenter distribution of the 1975 – 1976 earthquake swarms in the Izu Peninsula after Tsumura et al. (1977). The red lines show a conceptual line of stress migration started from a point beneath OM.

have no observational evidence for the magma reservoir: Yokoyama and De la Cruz-Reyna [1990] assumed its depth as the bottom of the crust from seismometric observations, And De la Cruz-Reyna and Yokoyama [2011] noted that the Paricutin magma reservoir might be significantly deeper than 8 km discussing surface deformations caused in 1943. Beneath the East-Izu area in 1976 and the Paricutin areas in 2006, their starting locations of upward trend of hypocenters were accidentally similar in depth, around 10 km. Here these locations are tentatively named "magma stops" where a particular stress should act to cause the upward migration of the hypocenters.

2.2.3 A SUBMARINE ERUPTION IN 1989 AT THE N PART OF THE CLUSTER ZONE

In July 1989, earthquake swarms started. On July 13, a minor submarine eruption occurred with very small amount of ejecta at the northernmost part of the group about 3 km N of Itō Spa. The eruption site (a star symbol near the top of Figure 8 a coincides with the epicentral area of the 1930 earthquake swarms. This is the first historically recorded eruption in this area. Okada and Yamamoto [1991] studied this event using seismometric and geodetic data obtained around Itō Spa and adjacent offshore areas. The hypocenters of the earthquake swarms around Itō Spa were determined to be at the maximum depth of 20 km. Finally, they proposed a dyke intrusion model for the submarine eruption.

2.2.4 CRUSTAL STRUCTURE OF THE IZU PENINSULA

Asano et al. [1982] studied underground structure of the Izu Peninsula in the N to S direction using the method of explosion seismology. We may extrapolate structure of the East-Izu area from their results and obtain the depth of the basaltic layer to be about 15 km beneath the area. We then know that the main conduit of OM originated from a deep part of the basaltic layer (Figure 7 bottom).

2.3 THE WUDALIANCHI PSEUDO-CLUSTER, THE NE CHINA

The basements of the Wudalianchi area are lavas of Lower Pleistocene age. At present, we do not find any noticeable volcanic edifices around this area. However, at a distance of 600 km S, there is Ma-On-Shan Volcano (Tertiary) and 590 km SE, Jingpo Crater-lake (Recent) as shown in Figure 3. The active volcanic area is the Changbaishan Mountains at a distance of about 750 km S.

In the Wudalianchi area of about 600 km^2 (= 30 km×20 km), there are 14 monogenetic volcanic cones as shown in Figure 9 [Feng and Whitford-Stark,1986, modified]. In the present paper, this area is named "pseudo-cluster" because the component cones are not numerous comparing with the above two areas.

The five lakes are characteristic of this area. The cones seem to be located on two parallel lines in the direction of N 40° E, except for 3 or 4 cones. The two lines are separated by about 15 km and the intervals between the cones range 5 ~ 7.5 km along each line. It has not been proved that these two lines are structural. In fact, linear structures are not always consistent with mass production of cluster cones by the shear fracture model.

Of the 14 monogenetic cones in this area, two cones along the westerly line, Laoheishan and Huoshaoshan cones are known to have erupted in 1719 ~ 1720: In fact, the activity of Laoheishan cone is reported to have been violent for the period mainly in June and July 1720. According to Yunpeng et al. [1996], Laoheishan cone erupted about several hundred years before the 1719 ~ 1720 eruption, and the volcanism along the line has shown a tendency of migrating from the SW to the NE. As for the eruption activities of Laoheishan cone, they classified those into two stages, and discussed them in detail. In short, Laoheishan cone had erupted twice. If the two eruptions are surely verified to have derived from the same magma source, they may be classified into monogenetic cones. The distribution of cones shown in Figure 9 seems to be a sparse cluster. Thus, at the moment, we cannot clearly define this group as "cluster" but tentatively classify this group into "pseudo-cluster".

Yunpeng et al. [1996] reported that earthquakes of M 0.5 ~ 1.0 and about 8 km in hypocentral depth occurred around Wohushan and Nangelaqiushan cones in the SW and W parts of the area. These are notable events suggesting volcano-tectonic activities in this area. They also tabulated geomorphlogical specifications of the Wudalianchi monogenetic cones. All cones are small, as well as the clusters in the Jeju Island area and the East-Izu area: their relative heights range from 60.8 to 165.9 m. The largest cone is Laoheishan having a volume of about 0.09 km^3 and the three smallest cones are each roughly 0.01 km^3 in volume. The total volume of 14 cones amount to 0.5 km^3. Possibly these may be in the early stage of development in formation of clustery monogenetic cones.

All rocks of the Wudalianchi cones are classified as alkaline basalts containing about 5 % of potassium according to Feng and Whitford-Stark [1986] and Yunpeng et al. [1996]. The latter authors conclude that the Quaternary in the Wudalianchi area is composed of vol-
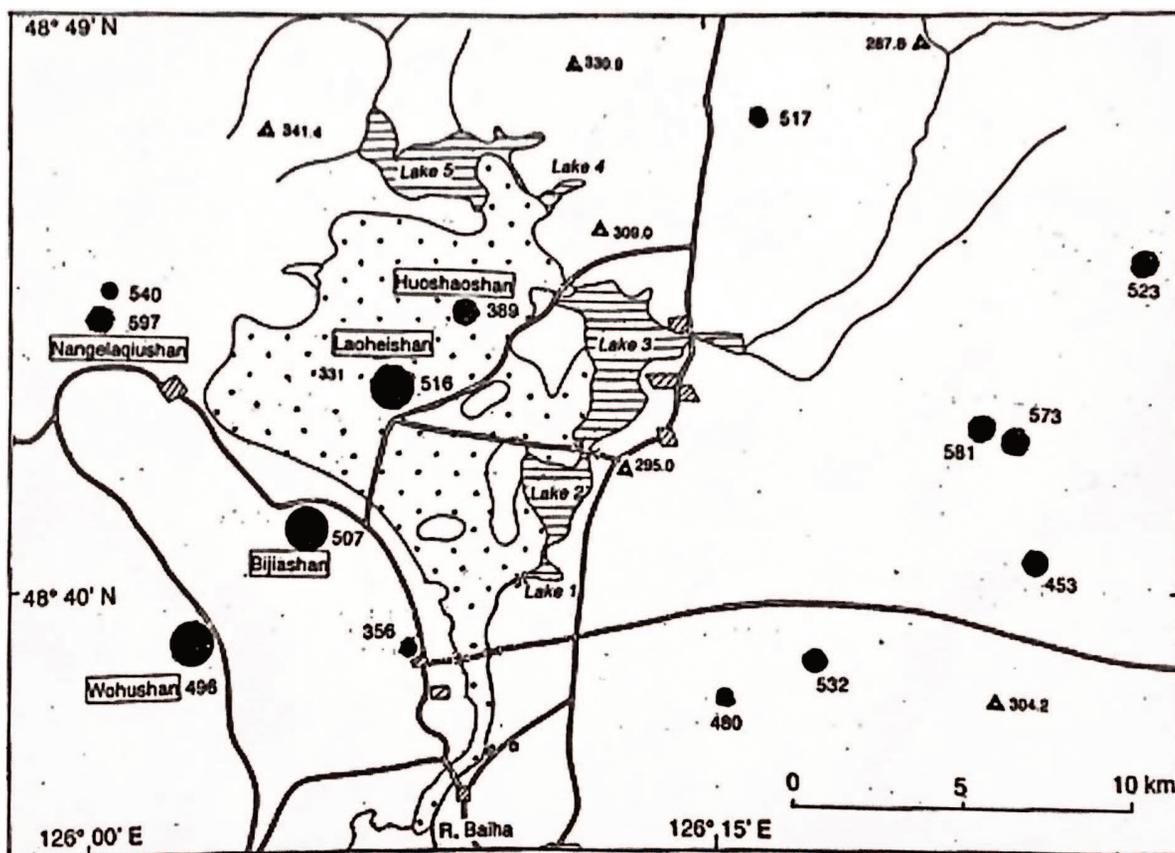
FIGURE 9. Topographic sketch map of the Wudalianchi volcanic group (after Yunpeng et al., 1996, partly modified). The group is composed of 14 volcanic cones marked by black circles, big and small, and attached by altitudes a.s.l. in meter. Dotted parts outline the 1719 – 1721 lava field issued from Huoshaoshan and Laoheishan volcanoes. The five lakes are marked by numerals 1 ~ 5.
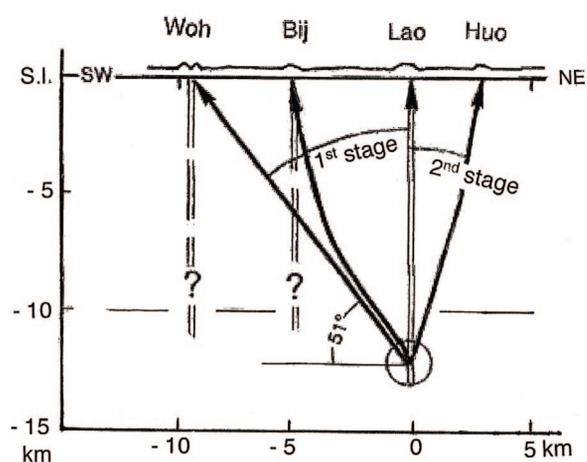

FIGURE 10. A conceptual model of the Wudalianchi volcanic group.

canic lavas, and the oldest is Lower Pleistocene (2.1 Ma). In Figure 10, the past magmatic activities in the SW part of the Wudalianchi pseudo-cluster are qualitatively and conceptually illustrated. Magmas are transported from the source through the main conduit to a shallow depth where the shear fracture model applies for distribution of magma to many vents.

On the other hand, in relation with the Wudalianchi area, an adjacent region between Qiqihacr and Harbin, was included in the research project of Jin et al. [1997] in 1992. They studied geothermal structure along a line from Manzhouli to Suifenhe, about 4000 km in length in the NE China. Along this profile, they found an area of high values in both the crustal and mantle geothermal heat-flows. This area is about 200 km from the Wudalianchi volcano area. Then, we may assume that the Wudalianchi area belongs to a relatively high heat-flow area. Ehara and Jin [1997] showed schematic diagrams of magma production and geothermal systems in the NE China. And Qiu Jiarang et al. [1991] concluded that the magmas were produced at a depth between 80 ~ 90 km in the NE China, after their petrographic studies.

2.4 SUMMARY OF THE PECULIAR CHARACTERISTICS OF THE MONOGENETIC CONES IN TWO CLUSTERS AND ONE PSEUDO-CLUSTER

In the previous sections, tectonic characteristics of the three areas are discussed respectively. In the present section, peculiar characteristics of monogenetic cones are summarized from the previous sections.

a) **Tectonic locations:**

Jeju Island area: Monogenetic cones are almost uniformly distributed over the slope of an existing volcanogenetic plateau around the central cone, Halla Volcano.

East-Izu area: Monogenetic cones are located over and among extinct stratovolcanoes.

Wudalianchi area: Two groups of monogenetic cluster cones are along the two parallel structural lines, almost independently of the pre-existing volcanoes.

In short, there are no tectonic characteristics common to the three areas.

b) **Actual volcanic activities:**

The ages of the first and the last eruptions of monogenetic cones are reported as shown in Table 1. The present volcanic activity of the three clusters are briefly summarized from each section as follows:

Jeju Island area: Historical documents mention that eruptions in 1002 and 1007 formed Piyang Island and Gun-san cone in the W part of the island and the last eruption was in 1570. At present no volcanic activity or fumaroles are observed on the island.

East-Izu area: This area has frequently experienced tectonic earthquake swarms. Both the 1975~1977 and the 1989 earthquake swarms were related to dike emplacement and the latter resulted in a small submarine eruption at the northernmost part of the area.

Wudalianchi area: The last volcanic eruptions occurred in 1721, around the SW part of this area. At the present time, earthquakes of M 0.5 ~ 1.0 at about 8 km in hypocentral depth occur sometimes around Wohushan and Nangelaqiushan volcanoes in the SW part of the area (Fig. 9). Such seismic activity suggests possibility of future eruptive activity in this area.

Of the three areas, with some uncertainty, only the Jeju Island cluster may have completed its volcanic activity.

c) **Dimension of clusters:**

Each cluster occupies an area of 600 ~ 900 km^2 while proper monogenetic volcanoes such as Jorullo and Paricutin occupy areas of 100 and 50 km^2, respectively. Average area of component cones of the Jeju cluster is estimated at 800 km^2 / 318 cones = 2.5 km^2 / cone, and similarly that of the East-Izu area is 12 km^2/ cone. In the Wudalianchi area, the cones are distributed linearly with a separation distance of about 5 km, and the area of a cluster-cone is about 43 km^2 / cone, pronouncedly sparse than that of a normal monogenetic volcano.

Clusters	Nos. of cones	First eruption	Last eruption	Ref.
Jeju	318	0.2~1 Ma	11th cent.	(1)
East-Izu	75	0.04 Ma	20th cent.	(2)
Wudal.	14	2.1 Ma	18th cent.	(3)

(1) Hasenaka et al. [1998 b] (2) Aramaki and Hamuro [1977] (3) Yunpeng et al. [1996]

TABLE 1. Eruption activities of the three clusters.

2.5 GEOMORPHOLOGICAL PARAMETERS OF THE CLUSTERS AND THE PROPER MONOGENETIC CONES

Monogenetic cones have been characterized by their small volumes: Smith and Németh (2019) mentioned that small-scale basaltic volcanic systems were the most widespread form of magmatism on planet Earth. Here, geomorphological characteristics of two clusters of monogenetic cones, one pseudo-cluster and the two "proper monogenetic cones", Jorullo and Paricutin, are tabulated in Table 2.

Firstly we should remember that volume estimation of volcanic edifices, and especially their ejecta are very uncertain and the errors are uncountable quantitatively. In this table, "Average volume of single cone" in the last column shows that the volume of the two clusters and the pseudo-one in the Far East is small, about 2 % of those of the proper monogenetic cones in Mexico. Considering the accuracy of the volume estimate, their volumes may differ by 2 orders of magnitude. "An outstanding characteristic of the cluster is the small volume

Clusters or proper monog. volcano	Total area (km²)	Num. of cones	Num. per Area (n / km²)	Vol. of largest cone (km³)	Total vol. of cones & ejecta (km³)	Avg. vol. of single cone (km³)	Ref.
Jeju	800	318	0.40	0.3	4	0.01	(1)
East Izu	900	75	0.10	0.83	2.5	0.03	(2)
Wudal.	600	14	0.02	0.09	0.46	0.03	(3)
Jorullo	100	---	---	---	2.05	0.9 DRE	(4)
Paricutin	50	---	---	---	3.6	1.6	(4)

(1) Hasenaka et al. [1998 b] and this paper   (2) Aramaki and Hamuro [1977]   (3) Yunpeng et al. [1996]   (4) Luhr and Simkin [1993]

TABLE 2. Geomorphological parameters of the three clusters and the two "proper monogenetic volcanoes".

of individual volcanic cone." This qualitative conclusion was obtained by the above quantitative discussion. Here we remember the words "Umschlagen von Quantität in Qualität".

Now we will try to find characteristic qualities of the monogenetic clusters, in contrast to "the proper monogenetic cones". At present, we have no sufficient observational data of subsurface structure relating to the formation mechanisms of the two clusters and the pseudo-cluster. Any qualitative differences of formation mechanism between the clusters and the "proper monogenetic group" should be one of the prime essentials.

3. QUALITATIVE COMMENTS ON THE CLUSTERS OF MONOGENETIC CONES

Formation mechanism of the clusters of monogenetic cones shall be qualitatively commented, especially on their magmatic behaviors. It may be different from that of the two "proper monogenetic cones", Jorullo and Paricutin, formed before our eyes. The following two items are approximate knowledge about formation of the clusters.

a) **Location of the magma sources of the clusters:** In the preceding chapters, we drew configurations of magma conduits forming monogenetic cones at the two areas, Jeju and East-Izu. The depths of branching points along the main conduits are determined to be 45 and 25 km, respectively. We are not sure whether these points are located in

magma reservoirs or not. On the other hand, in the Wudalianchi area (pseudo-cluster), petrological study indicates that the magmas are produced at a depth between 70 ~ 90 km, and as mentioned in Sec. 2.3, Jin et al. [1997] concluded that a region between Qiqihacr and Harbin, adjacent to the Wudalianchi area, belongs to a relatively high heat-flow region. Accordingly, this requires the magmas to be produced at a depth between 70 ~ 90 km. Hence an aggregate length of conduits from the magma source to the vents of each cluster may be considerably great. Through such long conduits, a small quantity of magmas can be redirected from encountering variation in tectonic stress and magmatic pressure, and distributed to many cones. This suggests that such magmas must be fluid or basaltic.

b) **Emplacement of magmas in the monogenetic volcanoes of the clusters:** We assume that the magmas start from the mantle depth. If a large amount of magma arrives near the surface, the shear fracture model can be applied to distribute magmas among numerous vents in the cluster, as illustrated in Figures 5 and 7. The cones are densely distributed in a cluster, and so they must be branched at rather shallow depths because dense distribution of long conduits should be unnatural.

In turn, the shear fracture model prescribes that the outermost sub-conduits branch from the main conduit at 51° in vertical angle. Such configurations of the sub-

conduits have been observed during an earthquake swarm in the East-Izu area (Figure 8), and a dike emplacement near Paricutin Gardine et al., [2011, Figure 9]. Furthermore, to interpret very dense distribution of the vents, corresponding branch-conduits are assumed in the above model as indicated in Figure 5 (bottom). In the case of the Jeju Island area, the branch at the main conduit may have been at a depth of around 50 km, and accordingly, the magma source may have been in the upper mantle.

4. CONCLUDING REMARKS

In the present paper, a new type of monogenetic volcanoes is introduced from three areas in the Far East: these are the Jeju Island area composed of 318 cones, the East-Izu area consisting of 75 cones, and the Wudalianchi area containing 14 cones. The last has smaller number of cones than the other two and is named "pseudo-cluster".

a) **Cluster of small monogenetic volcanoes:** An outstanding characteristic of the clusters is the small volume of individual volcanic cone. Their volumes are roughly $1/10^2$ of "proper monogenetic volcanoes" such as Jorullo and Paricutin. This fact suggests that the primary cause of the clusters should be different from the proper monogenetic ones. We may interpret the three clusters to be qualitatively different from the two Mexican proper monogenetic cones as follows. The present author prefers the shear fracture model for the formation of parasitic vents. Magmas ascend from the sources through the "main conduit", several "sub-conduits" and many "branch-conduits", and reach the surface forming many small cones. The shear fracture model can be effectively applied to interpret the formation mechanism of the clusters of cones.

In comparison with the above volcanic cones, formation mechanism of "proper monogenetic volcanoes" and polygenetic volcanoes are mentioned as follows:

b) **Proper monogenetic volcanoes:** De la Cruz-Reyna and Yokoyama [2011] have briefly summarized that their deep sub-crustal magma sources have a limited volume and no capability of refilling, at least in the time scale of the duration of single monogenetic eruptions. Such magmas directly reach the surface through a conduit system. When the eruption ends, magmas filling the conduits and cracks would solidify increasing the strength of the crust around the conduits. Consequently,

magmas of the following eruption would select different paths to reach the surface.

c) **Polygenetic volcanoes:** Magmas usually stop at reservoirs in the crust and ascend through central conduits that may remain open after magmas are ejected or drained back. And the magmas are also capable of forming new vents to produce parasites.

As for the future prospects of the three clusters' activity, we may tentatively assume as follows: the Jeju Island area has almost ended its activity in the historical time (the 11th century), the East-Izu area is near the end of its activity still inducing visible residual activity. A pseudo-cluster, the Wudalianchi area may have future volcanic activities forming more monogenetic cones in a wider area to form a larger cluster.

We should apply more quantitative methods to study further the characteristic activities of the clusters, and their deep structures. At the same time, it is important to search for similar clusters in the other parts of the world.

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