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Formation processes of the 1909 Tarumai and the 1944 Usu lava domes in Hokkaido, Japan

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Abstract
The formation of the two particular lava domes in Hokkaido, Japan is described and interpreted mainly from geophysical viewpoints. The 1909 eruption of Tarumai volcano was not violent but produced a lava dome over four days. The growth rate of the dome is discussed under the assumption that the lava flow was viscous and plastic fluid during its effusion. By Hagen-Poiseuille's Law, the length of the conduit of the lava dome is rather ambiguously determined as a function of viscosity of the magma and diameter of the conduit. The 1944 Usu dome extruded as a parasitic cone of Usu volcano, not in the crater, but in a flat cornfield at the foot of the volcano. From the beginning to the end for more than 17 months, seismometric and geodetic observations of the dome activity were carried out by several pioneering geophysicists. Utilizing their data, pseudo growth curves of the dome at each stage can be drawn. The lava ascended rather uniformly, causing uplift of the ground surface until half-solidified lava reached the surface six months after the deformation began. Thereafter, the lava dome added lateral displacements and finally achieved its onion structure. These two lava domes are of contrasting character, one is andesitic and formed quickly while the other is dacitic and formed slowly, but both of them behaved as viscous and plastic flows during effusion. It is concluded that both the lava domes formed by uplift of magma forced to flow through the conduits, analogous to squeezing toothpaste out of a tube.

Key words *lava domes – Tarumai volcano – Usu volcano – squeeze of magma – growth rate of domes – Hagen-Poiseuille's Law*

1. Introduction

The 1909 lava dome of Tarumai volcano, Hokkaido is a typical example of an andesite lava dome formed within its crater. The dome, measuring 1.5×10^7 m^3 in volume, was built probably in four days. This was typically formed by squeezing of magma or forced extrusion of magma through a narrow opening similar to a tube of toothpaste. Such a behavior is a characteristic of the Bingham fluids. The formation process of this lava dome is assumed to be viscous and plastic flows, and its controlling factors are discussed in reference to the reports of eyewitnesses. After the cooling of the dome, people had access to the top of the dome to observe its interior. The lava dome has not been remarkably changed by the later activity of the volcano. The formation of this lava dome has been scarcely discussed quantitatively.

Usu volcano, a neighbor of Tarumai volcano, formed a lava dome during 13 months in 1944 and 1945. This dome is unique in that it was formed at the base of a volcano, on flat ground, not within a crater. The magma pushed up the ground forming a mound and finally a half-solidified lava extruded from the mound and grew to a lava dome measuring 2.2×10^7 m^3 in volume above the mound. Its dacite magma

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is more viscous than the Tarumai magma, andesite. The formation of the 1944 lava dome was observed instrumentally from beginning to end by geodetic and seismometric methods. The results of precise levels carried out at the foot of the dome enable us to depict its pseudo growth curves, which indicate forced extrusion of half-solidified magma to form the lava dome. In 1952~1954, after its formation, the dome was explored with geophysical and geochemical methods, and the results provide some useful additional knowledge even though they are not satisfactory.

The two lava domes differ in the quality and quantity of their information. One formed in the early period of the 20th century at the summit of the volcano, with no instrumental data, while the other formed 35 years later, near villages and was observed instrumentally from beginning to end. At present, if dome-forming activity began at any volcano, modern techniques could be applied to monitor the growth of the dome with high accuracy and safety using the global positioning system, synthetic aperture radar and airborne laser digital mapping.

In the following, the sequential process of each dome first will be introduced and followed by some quantitative interpretations of their formation processes.

2. The 1909 lava dome of Tarumai volcano

Tarumai volcano located approximately 40 km south of Sapporo City (fig. 1) is one of the post-caldera volcanoes of Shikotsu caldera, whose structure was geophysically studied by Yokoyama and Aota (1965). On the summit of Tarumai volcano is a flat crater measuring 1.3 km in diameter. The 1909 eruption produced a 450-m-basal diameter and 134-m-high lava dome within the summit center. The highest point is the top of the lava dome, 1041 m above sea level (a.s.l.) as of 1996 (fig. 1-plan).

Historical records of the eruptions of Tarumai volcano go back to 1667, and are generally scanty. The 1874 eruption was violent and destroyed the pre-existing lava dome (I) which is believed to have been slightly smaller than the 1909 lava dome (II). For the period between 1874 and 1909, small eruptions were repeated at the summit within an inner craterlet of approximately 400-m-diameter and 60-m-depth.

Tarumai volcano has not manifested intensive activity since the 1909 eruption. At present, the activity of Tarumai volcano is continuously monitored by the Usu Volcano Observatory of Hokkaido University at a distance of 50 km, using various telemetering geophysical methods.

2.1. *The 1909 eruption of Tarumai volcano and formation of the lava dome*

The 1909 eruption was described by Oinouye (1909). In those days, this area was sparsely populated and the available information on the eruption was limited; the activity began in January 1909, and magmatic explosions took place at the summit craterlet from March 30 to April 12. The March 30 explosion formed an explosion pit approximately 15 m in diameter within the craterlet. The April 12 explosion at the same pit was much stronger and diameter of the pit may have been enlarged to nearly 30 m (*cf*. Photo 2). From Tomakomai City approximately 20 km SE of the volcano, no dome was seen at the summit on April 17, and it was cloudy on April 18. On the afternoon of the next day, the new lava dome (II) was recognized through the clouds. The lava dome was approximately 120 m high over the rim of the summit crater (fig. 1). The new lava dome could be found over the summit crater rim from Tomakomai City because it grew up from the bottom of the summit craterlet. In such a situation, we cannot uniquely determine the duration of lava dome formation: it may have ranged from two days (April 17~19) to six days (April 13~19); we take their average, four days. Growth of the lava dome was unaccompanied by any noticeable explosions, and lava extruded through the explosion pit referred to above. The lava filled the preexisting craterlet, and further accumulated to a height of 134 m above the craterlet rim or 194 m above its base. The total volume of the dome is estimated at 1.5×10^7 m^3 on the basis of the present topographic map, and the effusion rate of lava as 3.8×10^6 m^3/day. Oinouye (1909) witnessed the new dome with a round top on

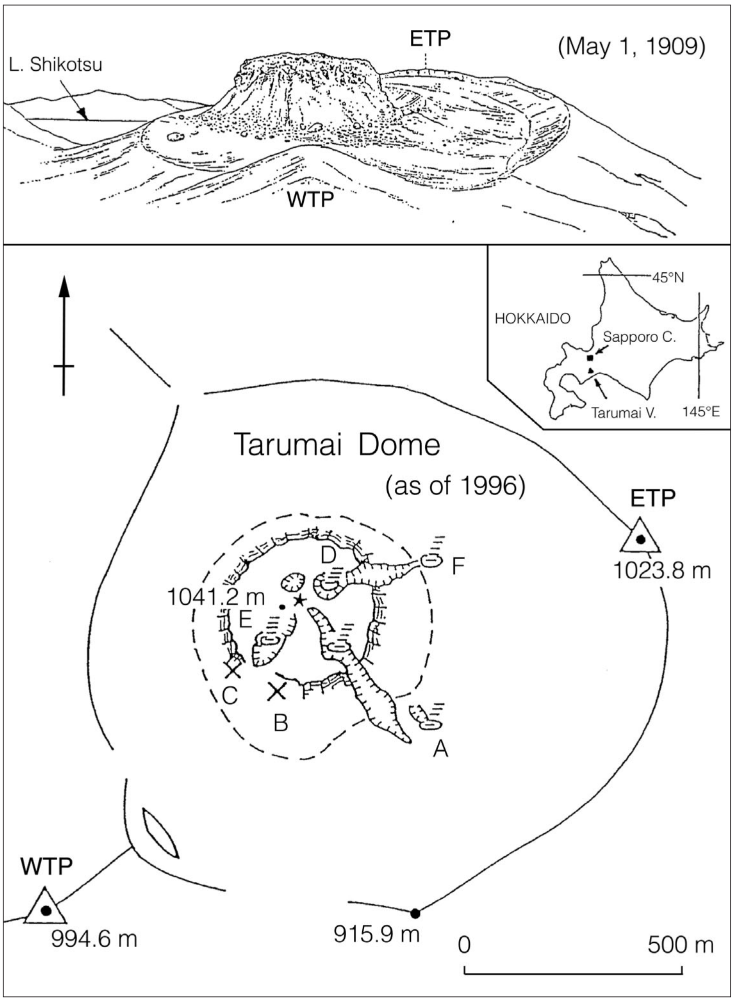

Fig. 1. A topographic sketch map of the 1909 Tarumai lava dome as of 1996. Letters A~F denote fumaroles, and ETP and WTP triangulation and GPS points as of 2000. The scenery at the asterisk point on the dome is shown by photo 2. The top is a sketch of the dome viewed from WTP as of May 1, 1909 (Oinouye, 1909).

April 23; by May 1, the top part of the dome had flattened, causing fractures due to cooling or withdrawal of magma. A sketch of the dome as of May 1 is shown in fig. 1 (elevation). We know a historical episode that Jaggar (1956) visited the new lava dome on May 10 and measured the temperature 457°C with a thermocouple in sulfur-covered cracks on the face of the lava dome. At that time, the lava dome was already covered with crust and accessible at some parts, but the inside may have been kept at high temperature. On May 15, a small explosion occurred, forming a fissure at the southern part of the dome.

To the discussion of formation processes of lava domes, knowledge on probable temperature and viscosity of the lava are indispensable. In general, magmas at depths have a high temperature around 1200°C or higher, and the eruptive temperature must be lower around 1000°C. As shall be mentioned in Section 3.4, the temperature of the 1944 Usu lava dome is estimated at approximately 1000°C. Similarly we may assume the same temperature for the 1909 Tarumai lava dome.

The dome lava is andesite of SiO_2 content 60% (Oinouye, 1909). The viscosity of its melt was measured in the laboratory at $10^{4.7}$ Pa·s at a temperature of 1100°C by Kani and Hosokawa (1936), who used the rotating cylinder method for temperature range 1100~1400°C. We estimate the viscosity at 1000°C, and refer to the experimental results obtained by Goto (1997) who measured viscosities of silicate melts from some Japanese volcanoes by the fiber-elongation method for a temperature range lower than 950°C and the counter-balanced sphere method for a temperature range higher than 1150°C. Goto (1997, fig. 11) showed that viscosities of melts of igneous rocks increase roughly 10 times with a temperature decrease of 100°C in a temperature range around 1000°C. By this relationship, we may assume the viscosity of the Tarumai dome at 1000°C to be approximately $10^{5.7}$ Pa·s.

At present we have access to the top of the dome and can study its internal structure at the opening of «D» fumarole in fig. 1 (plan). The cross section (photo 1) is similar to that of the model assumed in the experiments with putty by Reyer (1888) shown in fig. 2a. We recognize some slickensides (photo 2) at the point marked by an asterisk in fig. 1 (plan). They probably indicate a mold of the vent through which half-solidified lava squeezed up. We estimate the vent at the bottom of the dome is roughly 30 m in diameter.

A sketch of the structural model of the dome deduced from photos 1 and 2 is shown in fig. 2b, which is similar to one presented by Soya (1963) in another cross section. The 1909 Tarumai lava dome formed by magma squeezing through the vent. The magma may have risen as a viscous flow through a deep conduit, approached the vent, and squeezed out as a Bingham plastic flow. This is strongly supported by the internal structure shown in photos 1 and 2.

The effusion rate is 3.8×10^6 m^3/day and the vent measures 30 m in the effective diameter ($2a$); the flow velocity in the conduit (v) is estimated at approximately 0.06 m/s and the

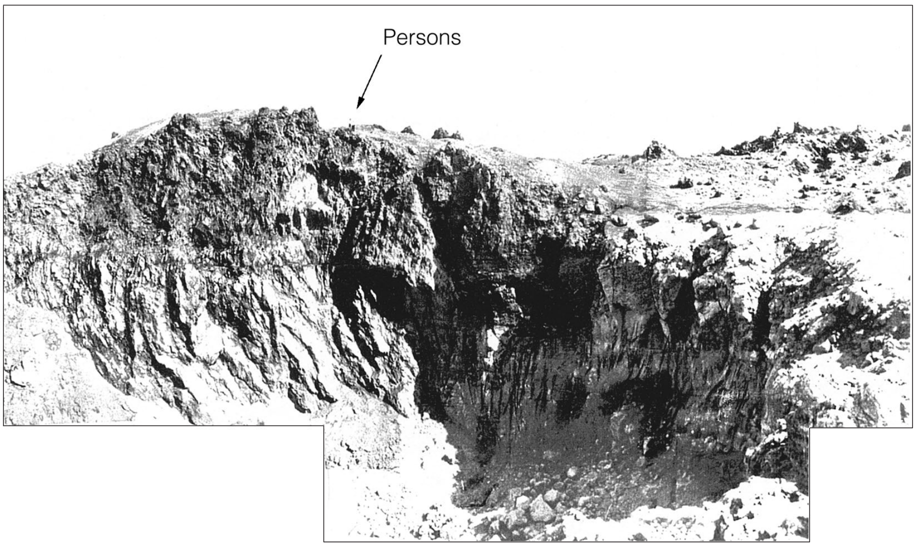

Photo 1. An eastward inside view of «D» fumarole (fig. 1) on the top of the Turumai dome as of 1960.

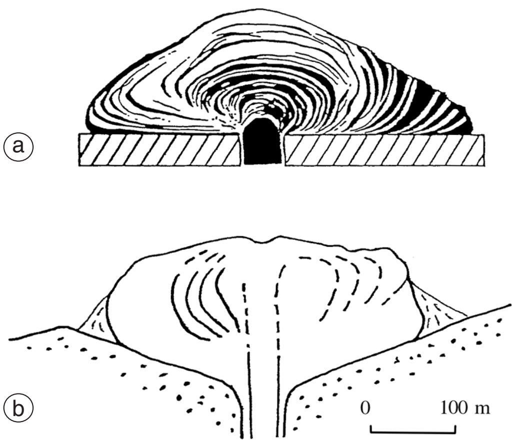

Fig. 2a,b. a) A squeeze experiment with putty by Reyer (1888); b) a model of the 1909 Tarumai dome (*cf.* photos 1 and 2).

Photo 2. Slickensides at the center of the Tarumai dome (asterisk in fig. 1) as of 1960.

Reynolds number ($R = av\rho/\eta$) is 10^{-3} in order of magnitude, proving that it was a laminar flow. For reference, Moore (1987) stated that the 1984 Mauna Loa lava flow was laminar but unsteady, with surges and ebbs; he estimated typical flow velocities in the range of 0.1~0.3 m/s, larger than that of the Tarumai dome because the Hawaiian lavas are more fluid.

If we assume a conduit of 30 m in diameter, connected with the Tarumai dome, a length of 21 km full of magma can supply the total lava of the dome. However, it is more probable that the conduit was connected to a magma reservoir at a shallower depth.

2.2. *Growth process of the 1909 Tarumai lava dome*

In general, magmas at depth have a high temperature around 1200°C or higher, and may be Newtonian viscous fluids. When they cool, they harden with time and change to non-Newtonian viscous fluids. With more cooling, their viscosities increase exponentially, and plastic behaviors predominate. After squeezes, the Tarumai lava accumulated on the crater and did not notably deform. In the following, we assume that the Tarumai magma flowed viscously throughout dome formation even though its viscosity changed with time. Laminar lava flows through a conduit should obey the Hagen-Poiseuille's Law. Then flow rate Q is expressed as

$$Q = \frac{\pi}{8}\frac{r^4}{\eta}\left(\frac{\Delta p}{l} - \rho g\right) \tag{2.1}$$

where r denotes the radius of the vent, Δp the driving pressure, l the vertical length of the vent, ρ the density of magma, g gravitational acceleration and η the viscosity of lava. Here, strictly speaking, η is different from the viscosity of dry melts measured in the laboratory; it is influenced by such factors as chemical components (mainly SiO_2 and water), degree of crystallization, temperature distribution, and their changes with time and space during formation of lava domes. It is almost impossible to know the true viscosity of juvenile lava *in situ*; the

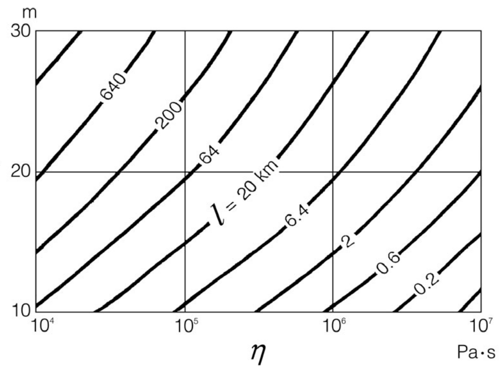

Fig. 3. Flow rate Q is estimated at 7.5×10^6 m^3/day. By means of the Hagen-Poiseuille's Law, length of conduit l is plotted with two parameters, radius of vent r (m) and macroscopic viscosity η (Pa·s). l is expressed in km logarithmically.

next best estimates in our discussion depend on laboratory measurements of dry melts.

The viscous lava flow gradually stiffen with decreasing temperature, and plastic behavior is enhanced, sometimes becoming a kind of Bingham flow which behaves analogously to squeezing toothpaste out of a tube. We see several flow lines of lava at the front o f the dome in photo 1 and a plug flow of lava at the vent in photo 2. This means that the lava was fluidal in the early stage and hardened in the last stage as its temperature dropped.

If lava successively wells up beneath existing lava in the same way as in the experiment by Reyer (1888) shown in fig. 2a, the maximum value of Δp is equal to the highest hydrostatic pressure of the lava column, *i.e.* $(l+\underline{134+60})\rho g$. Then, eq. (2.1) becomes

$$Q=\frac{\pi}{8}\frac{r^4}{\eta}\rho g\left(\frac{l+194}{l}-1\right)=\frac{\pi}{8}\frac{r^4}{\eta}\rho g\,\frac{194}{l}. \tag{2.2}$$

The flow rate Q is estimated at 3.8×10^6 m^3/day by knowing the total volume of the dome and the duration of the dome formation. By means of eq. (2.2), length of the conduit l is plotted with two parameters, radius of the vent r (m) and viscosity η (Pa·s), in fig. 3, where ρ is assumed to be 2.5×10^3 kg/m^3 and l is expressed in km logarithmically. Resolvability of l is rather low in the diagram. We adopt probable values of r and η to infer the probable range of l in order of magnitude; $r=15$ m on an average and $\eta=10^{5.7}$ Pa·s of the dry melt at 1000°C as mentioned in the previous section. In fig. 3, we get a rough idea of the value l in a rather wide range 2~20 km, and probably around 10 km. At a depth of l, the conduit is connected with a magma source whose volume is sufficiently large to be not affected by squeezes of the dome magma. In the above discussion, we simplified some parameters such as uniform cross section of the conduit, uniform viscosity and pressure gradient of the magma throughout the conduit. At present, we have no data to independently confirm the value of l.

3. The 1944 lava dome of Usu volcano

Usu volcano is located 70 km south west of Sapporo City and 50 km west of Tarumai volcano. The volcano has three lava domes, two of the summit formed in 1663 or 1769 and 1853, and one at the eastern foot formed in 1944. Besides the lava domes, a mound 100 m high formed at the eastern foot by the 1910 eruption. A topographic sketch map of Usu volcano is shown in fig. 4. The dome magmas are all relatively viscous dacite containing 69% SiO_2 content (Oba, 1966).

It has erupted four times in the 20th century – 1910, 1944, 1977 and 2000 – and each eruption was observed with standard instruments. Of these eruptions, only the 1944 eruption produced a lava dome, a parasitic cone of Usu volcano called «Showa-shinzan» (new lava dome born in the Showa era). A geophysical comparison of these eruptions except the last was discussed by Yokoyama and Seino (2000). The last eruption in 2000 was magmatophreatic and formed several craterlets at the northwestern foot of the volcano (N and K in fig. 4). The activity of Usu volcano has been monitored since 1977 by the Usu Volcano Observatory of Hokkaido University using various geophysical means.

The formation of the 1944 lava dome seems to be a fundamental example to discuss dome formations generally, because it extruded on ap-

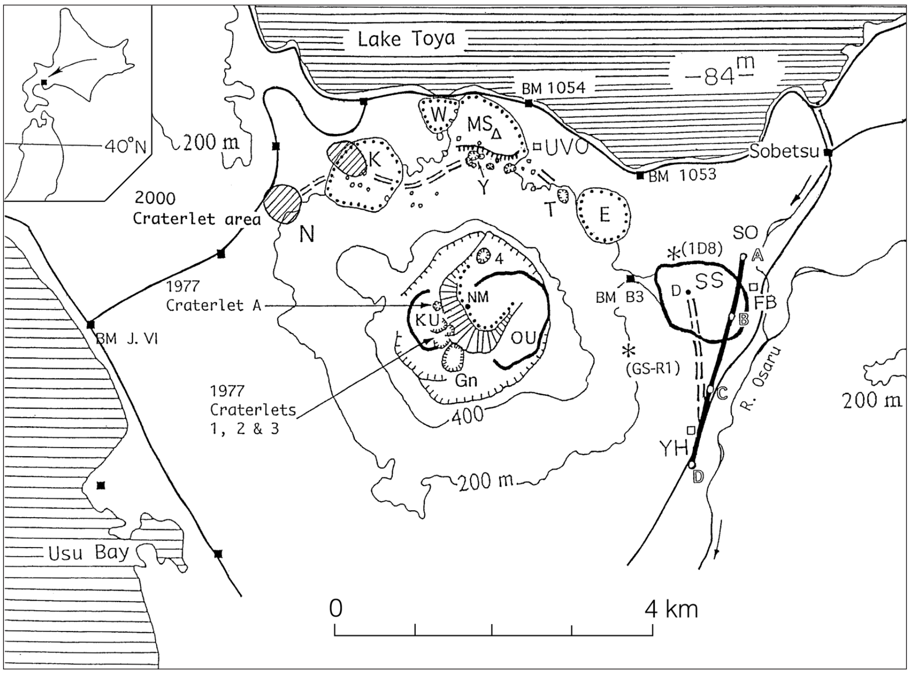

Fig. 4. Topographic sketch map of Usu volcano as of 2002. Thick contours show lava domes and those with dots volcanic mounds. SS – the 1944 lava dome (Showa-shinzan); MS – the 1910 mound; KU – the 1663 or 1769 lava dome; OU – the 1853 lava dome. A thick line A-B-C-D shows route of precise levels. Double broken lines indicate migration trend of volcanic activity. YH – Yanagihara village; SO – Sobetsu village; (GS-R1), (1D8) – test wells; Y and T – craterlets of the 1910 eruption; E and W – mounds formed in the prehistoric times; K and N – explosion areas of the 2000 eruption.

parently virgin ground where there was no sign of former craters, and its growth was observed instrumentally though not perfectly. The observational data of the 1944 lava dome, the present author believes, must give us important information for model experiments and theoretical simulations for crustal deformation. A preliminary report on the growth mechanism of the dome was published by Yokoyama (2002). In the present paper, more detailed discussion is made.

3.1. *The 1944 eruption of Usu volcano*

An earthquake swarm began on the last day of 1943 at the eastern foot of the volcano, and lava dome activity began in May 1944 and migrated approximately 1 km northward. The ascending magma first uplifted the ground, forming a mound, and contacted the aquifer in June, causing violent explosions. Finally the magma extruded through the mound to form a lava dome in November 1944 and completed its uplift around October 1945. The lava dome and mound seen from the eastern slope of Usu volcano, as of 1958 is shown in photo 3. The eruption activity can be divided into four stages: precursory earthquakes, migration of activity, eruptions, and doming. Such activity was observed from start to finish by geodetic and seismometric methods. Yokoyama and Seino (2000, fig. 7) presented a diagram of magma ascent in relation to the 1944 eruption. We can still utilize the data to discuss formation mechanism of the dome.

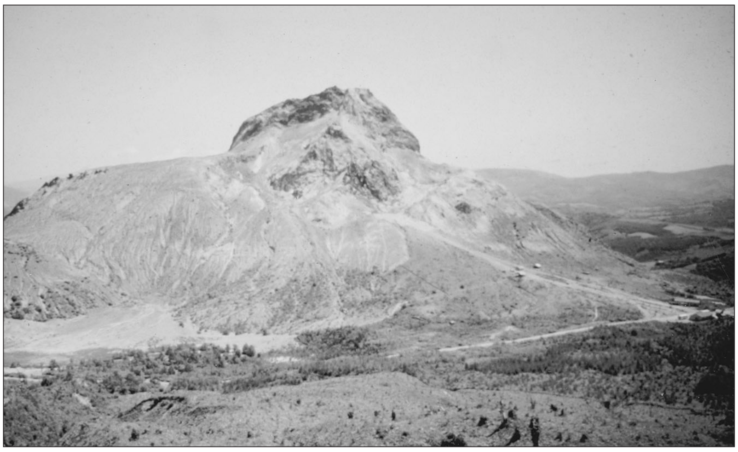

Photo 3. The 1944 Usu lava dome and mound (Showa-shinzan) seen from the eastern summit rim of Usu volcano, as of 1958. The relative height of the summit is *ca.* 300 m on this side. The left-hand low hill preexists, indicated by M in fig. 5.

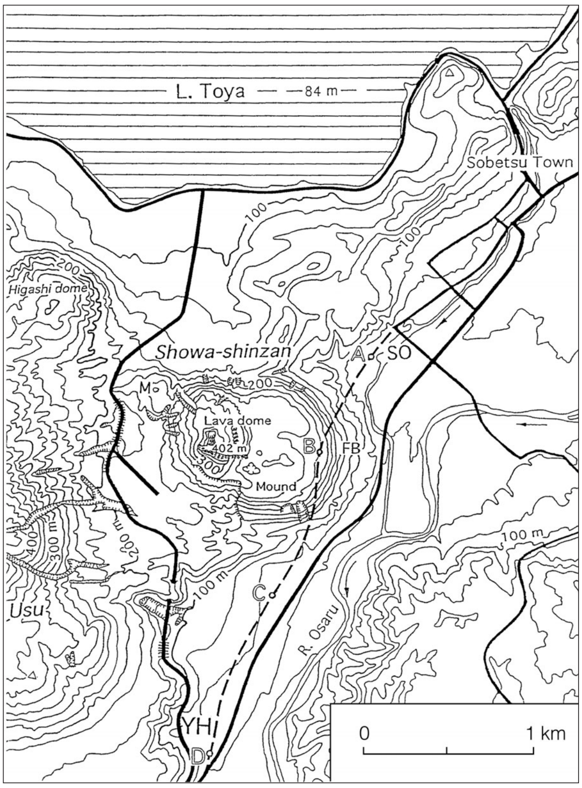

Fig. 5. Topographic sketch map of the 1944 lava dome area as of 2002. Contour interval, 25 m. Thick broken line indicates route of precise levels in 1944, projected on map of 2002; M, preexisting hill.

3.2. *Pseudo growth curves of the 1944 lava dome*

We find in a few papers, *e.g.,* Fukutomi (1946) and Minakami *et al.* (1951), the observational reports of seismicity and deformation that accompanied the 1944 eruption. In the following, a pseudo growth curve of the lava dome will be discussed on the basis of these papers.

Minakami (1947) repeated precise levels along the road traversing the eastern foot of Usu volcano, from SO to YH, about 3 km in distance (𝔸-𝔹-ℂ-𝔻 in figs. 4 and 5). The leveling route is projected on the 1996 topographic map around the dome by a thick broken line in fig. 5. The first survey was on March 29, 1944 and was repeated seven times with averaged intervals of two months. The last survey was on May 19, 1945 when the maximum upheaval of the route reached about 60 m and the road was abandoned. The leveling route grazed the deformed area at a distance of approximately 500 m from the center of the dome. In this paper, the

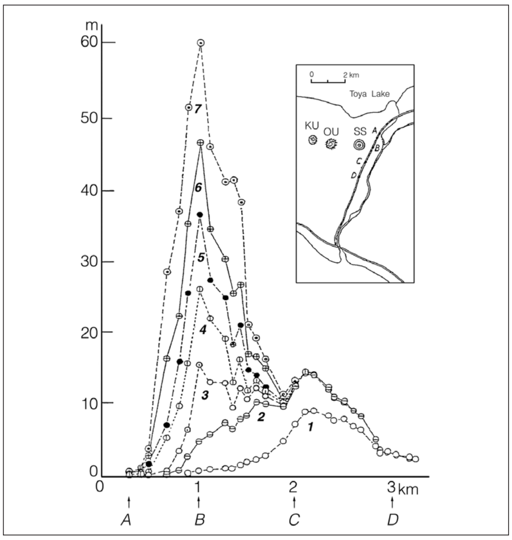

Fig. 6. Results of repeated precise levels at the eastern base of the 1944 dome (SS) after Minakami (1947). The periods of the surveys 1~7 are indicated in fig. 7.

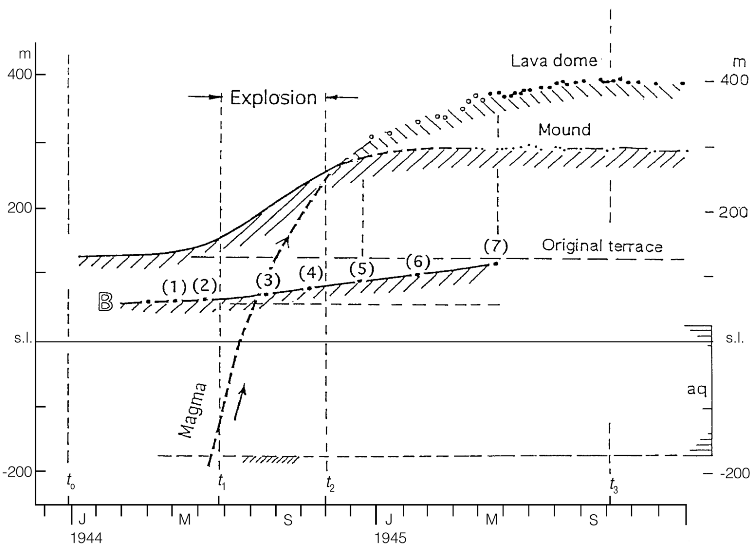

Fig. 7. Magma ascent in the 1943 eruption (thick broken line is assumptive) and growth of lava dome and mound (Yokoyama and Seino, 2000). Hollow circles indicate visual observations and solid ones instrumental determination after Fukutomi (1946). Upheaval of point 𝔹, the nearest benchmark to the center of lava dome on leveling route, is shown by a thick line with parenthesized numerals (1~7) denoting surveying periods after Minakami *et al.* (1951); aq, denotes the aquifer.

results of the precise levels shall be utilized to figure growth curves of the 1944 lava dome itself. The results of the precise levels are shown in fig. 6, where the errors of the surveys were within 1 cm. In the figure, the deformation first took place at Yanagihara (YH in fig. 4) at the southern part of the route and migrated toward the north. Fukaba (FB) or 𝔹 point became the center of inflation from survey no. 3 until the end of the observations.

To successfully depict the growth curves for the dome, we need to know the relationship between the true height of the surface upheavals and the vertical displacement of the leveling route. Yokoyama and Seino (2000) discussed the magma movement in the 1943 eruption and their result is partly reproduced in fig. 7 where the surface upheaval curve is composed of the two parts divided by the lava extrusion, earlier the mound and later the lava dome. The lava dome extruded in November 1944 (a little later than t_2 in fig. 7). The true heights of the lava dome at surveys nos. 5 and 6 were visually determined and those at and after no. 7 were observed using a transit compass at a distance of 2.5 km NE of the volcano (Fukutomi, 1946). Survey nos. 2~4 are linearly interpolated. We notice that the surface upheaved smoothly in general. The relationship is determined by least squares: 1 m of upheaval along the route corresponds to approximately 4.2 m upheaval of the mound or the lava dome.

If we assume that the upheaval of the dome takes the form of a circular cone with its vertical axis at the center of the dome, the vertical sections of the dome at any distance should be similar to each other and roughly triangular. In the case of the 1944 dome, the ratio of the similarity between the dome top and the leveling route was 4.2. In fig. 5, the 1944 lava dome is slightly asymmetric. However, it had grown up taking the form of a circular cone as a whole.

Pseudo profiles of the growing mound and lava dome are obtained by magnifying by 4.2 times the displacements of the road (fig. 6) as shown in fig. 8 where the magma column at each stage and the aquifer levels at drilling 1D8 (fig. 4) are indicated. Here, we name the curve in fig. 8 «pseudo» growth curves, because true curves should be observed along the route passing the highest point of the dome. Actually such a survey was impossible.

In fig. 8, we do not know the exact diameter of the vent at each stage, but the past explosion craters of this volcano are suggestive of this problem; the space among the four craterlets before the dome extrusion was roughly 60 m (Minakami *et al.*, 1951, fig. 8). And the opening of no. 4 craterlet of the 1977 eruption formed by a single violent explosion was approximately 100 m across (Yokoyama and Seino, 2000, photo 1), and its vent diameter must be much smaller than

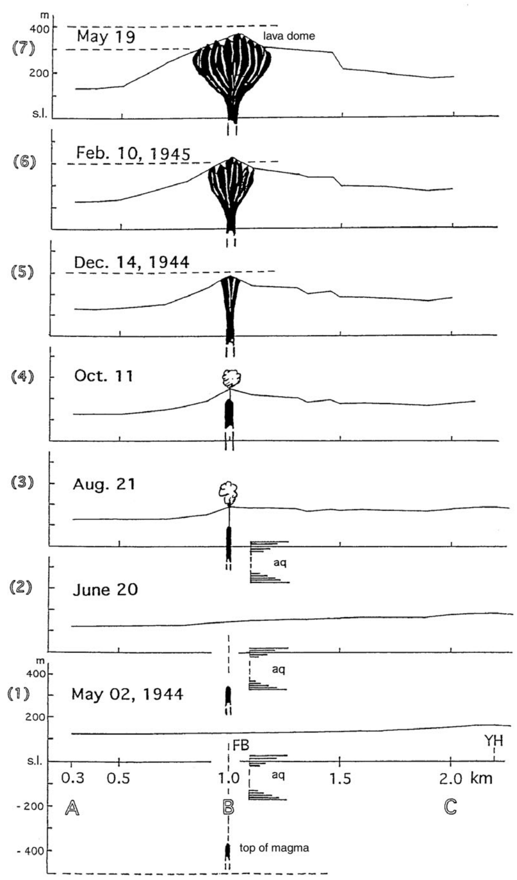

Fig. 8. Pseudo growth curves of the 1944 dome. The benchmarks on the abscissa are distributed at an interval of approximately 100 m as the same as fig. 6. Explosion activity was high between survey nos. 2 and 3. aq – aquifer; FB – Fukaba; YH – Yanagihara.

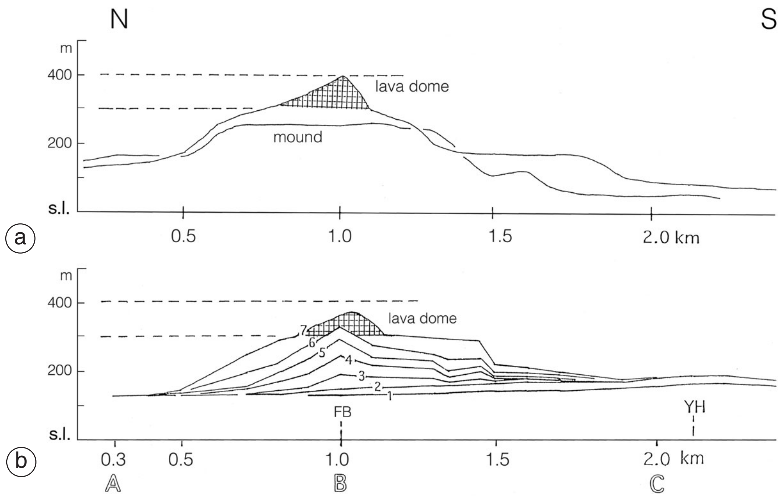

Fig. 9a,b. Comparison of pseudo growth curves and actual topographic profiles. a) Topographic profiles of the 1944 dome passing lava dome and mound; b) successive profiles of the pseudo growth curves. In fact, dome continued to grow five months more.

100 m. Thus we may assume the diameter of the magma column was nearly 60 m. On the other hand, seismic activity was rather low during the dome formation (Yokoyama and Seino, 2000, fig. 7a). This implies that the magma ascended without much working for the vent which must have been rather small in diameter.

Resemblance between the pseudo growth curves and the true ones may be confirmed by comparison of the last stage (survey no. 7) of fig. 8 with the parallel profile of the existing dome. Two actual profiles, one passing the lava dome (hatched part) and the other passing only the mound, are shown in fig. 9a. All the profiles in fig. 8 are shown together in fig. 9b where the last profile is survey no. 7 (May 19, 1945). We may say that the resemblance is surprisingly good considering that the growth was not complete by survey no. 7 but continued until October 1945, and that the surveys did not cross the region of maximum deformation.

As seen in fig. 9b, the mound expanded laterally in proportion as it uplifted vertically until survey no. 6, and did so noticeably before survey no. 7. To confirm this aspect, only the northern half of profiles 2~7 are shown in fig. 10, because

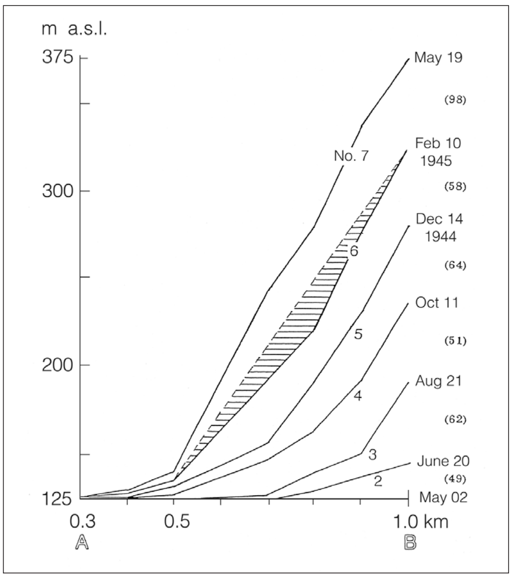

Fig. 10. Northern half of pseudo growth curves. Letter 𝔹 is the center of dome. Hatched part indicates the excess expansion of dome between survey nos. 6 and 7. Parenthesized numerals indicate the intervals in day between the surveys; the magma ascended rather smoothly until survey no. 6.

the deformation of the southern half of the pseudo growth curves are disturbed by the earlier activity. In fig. 10, the respective curve is the total result of irreversible deformation due to an ascending source, integrated from the beginning to that period. In the figure, the profile of no. 1 is almost flat, and the eruption began three days after profile no. 2. The deformation due to magma intrusion is focused prominently in the range of 0.5 km from the center (𝔹). In other words, the 250 m upheaval was achieved roughly in a range 1 km in diameter. Profiles nos. 2~6 are concave upward, but profile no. 7 changes to roughly straight. The dome had increased its height roughly uniformly until no. 6, as shown by the right-hand ordinate in fig. 10, where the survey interval is roughly 60 days in an average; this means that the magma smoothly ascended through a rather narrow conduit until that period. After profile no. 6, the lateral expansion of the upper part took place. In fig. 10, hatching approximately indicates the lateral expansion of the dome. At the last stage, no. 7 in fig. 8, the dome increased its volume by lateral expansion or by actual accumulation of lava. This is closely related to the growth mechanism of the lava dome.

In this case, a point source model was not applicable to the ground deformation, because the medium deformed beyond its elastic limit and the deformations are irreversible.

3.3. *Significance of the pseudo growth curves in relation to volcanic activity*

The growth profiles at each survey period and their relations with the volcanic activity are discussed in the following:

No. 1 (May 2) – The top of the magma may have been below the aquifer, whose depth is approximately 170 m below sea level at a testing well shown in fig. 7 (Yokoyama and Seino, 2000).

No. 2 (June 20) – The magma approached the base of the aquifer. The first explosion occurred on June 23, before the uplift was clear. Prior to the outburst, seismic activity increased a little.

No. 3 (August 21) – The explosions were continuing but not so strong. The craterlets had increased to four in number. The uplift profile seems clearly to be a conical hill with approximately 65 m upheaval. By this time, the top of the magma may have reached a depth between the ground surface (180 m a.s.l.) and the aquifer top (30 m a.s.l. in fig. 7). If we adopt the curve of magma ascent shown in fig. 7, the depth should be approximately 100 m beneath the surface.

No. 4 (October 11) – The explosions were continuing at a low level, and the crater had been enlarged. The upheavals in nos. 3 and 4 were taking the form of a mound or bulge that was not underlain by any «cryptodomes». The mound is composed of somma lava of Usu volcano.

No. 5 (December 14) – At the end of November, the top of the solidified magma gradually emerged among the four craterlets on the summit of the mound. At this stage, the top may have appeared to be a lava spine, but later was followed by several spinescent lava blocks and finally the dome achieved an onion structure. No more explosions occurred after October, probably because the magma was protected from contacts with the aquifer by the solidified inner wall of the conduit, or because the water dried up. On the other hand, seismic activity increased afterward, and the earthquake family of C-type appeared (*cf.* Yokoyama and Seino, 2000, fig. 7a). Minakami *et al.* (1951) attributed the origin of the family to repetition of the same mechanism for production of the seismic waves at the same location of hypocenters, nearly 0.5 km beneath the surface. It may have been caused by some disturbances in magma ascent.

No. 6 (February 10, 1945) – The dome was growing over the mound, which had attained its maximum height, approximately 300 m a.s.l. The craterlets amalgamated into one crater, and a large volume of lava accumulated there.

No. 7 (May 19) – The lava dome had increased its volume laterally by continued feeding of magma through the conduit and approached its final shape. The seismicity was continually high. After survey no. 7, the lava dome still uplifted a little and finally attained a height of approximately 400 m a.s.l., and the seismicity lowered in October 1945.

Summarizing the activity in each stage, we may say that these results are a fact of fundamental significance in discussion of ground deformation, and they may be used as a criticism of the methods using theoretical calculations and numerical or model experiments, all of which require the assumption of source models and material constants. It is notable that the ground surface was uplifted far in advance of magma extrusion.

3.4. *Growth process of the 1944 Usu lava dome*

For discussion of the growth mechanism of lava domes, knowledge of the temperature and viscosity of lavas are indispensable.

On the 1944 lava dome of Usu volcano, which was completed in 1945, there were a few strong fumaroles issuing gas. Some of them became accessible around 1946. The temperature of one of the strong fumaroles (named «K») has been periodically measured by a thermocouple. Extrapolation of secular changes over 50 years (Yokoyama and Seino, 2000, fig. 13) indicates that the original temperature of the fumarole was approximately 1000°C. Dacitic magma is viscous and takes much time to move from the vent, and has a lower temperature. In this fumarole, heat is supplied by high temperature gas emission from depths.

Goto (1997) measured viscosities of silicate melts from some Japanese volcanoes including the Usu lava dome, by the fiber-elongation method for a temperature range lower than 950°C and the counter-balanced sphere method for a temperature range higher than 1150°C. The viscosity of the Usu lava dome at 1000°C is interpolated to be roughly $10^{6.8}$ Pa·s between the two temperatures.

When we try to apply Hagen-Poiseuille's Law (eq. (2.1)) to the 1944 lava dome, we have no clue to estimate the pressure gradient beneath the volcano.

As for the apparent structure of the 1944 dome, the mound measures approximately 200-m-relative height and 1-km-basal diameter, and the lava dome approximately 100-m-high above the mound and 300-m-basal diameter on the mound (fig. 9). Minakami *et al.* (1951) reported the morphological and geological structure of the newly formed mound and dome correctly.

Hayakawa *et al.* (1957) applied various methods to explore the underground structure of the dome in 1952~1954. By seismic explorations, they confirmed that the upper part of the lava dome is approximately 400 m in diameter at a depth of 200 m below the top (200 m a.s.l.). They could not detect the deeper part, including the conduit, probably because the deeper part was not voluminous and the conduit was narrow. As discussed earlier about fig. 8 in Sections 3.2, we may assume the diameter of the original vent was nearly 60 m. The lower part of the lava dome must be linked to a narrow conduit. If we adopt these results, we may assume that the total volume of the lava dome is approximately twice the protruded volume in the order of magnitude.

Eyewitnesses of the dome formation reported the sequence as follows: a spinescent lava block first emerged among four explosion craterlets at the western part of the mound at the end of November 1944 (roughly survey no. 5) and gradually inclined westward as it rose. The eastern side of the dome grew to a semidome, and the western side became steep in early February 1945 (roughly survey no. 6). Simultaneously a few slab-like lava masses emerged along the sides of the first lava spine. On the surface of lava masses, we find many long striations arranged in parallel rows caused by intense friction during the ascent, and no regular joints because the lava did not solidify *in situ* there. In such a way, the dome was formed by the coalescing of several spinescent lava blocks. Finally the dome achieved its onion structure.

The summit of the dome is covered by gravel layers, approximately 2 m in thickness, composed of pebbles of granitic, andesitic, and sedimentary rocks. The pebbles are water-worn river gravel of various sizes ranging from a fist to a head, and all are red colored and sometimes cracked by heat from the new lava. In the eastern base of Usu volcano, the gravel layer is overlaid by pumice flow deposits (25000 years BP) from Toya caldera, originally deposited in riverbeds. The same gravel is found in the drill cores of test well (GS-R1 in fig. 4), approximately 1 km SW of the dome, at a level of approximately 50 m a.s.l. This means that the magma had already solidified before it reached the surface and could transport the gravel on it. Similar gravel is also found on the summits of Oo-Usu and Ko-Usu lava domes in fig. 4 as reported by Friedländer (1912) and Powers (1916), which may have been formed by the same mechanism as the 1944 dome.

In summary, we infer that the 1944 magma ascended in half-solidified state through the conduit, and that the lava dome grew laterally by lava supply at the later stage after it reached the crater. As a result, the dome completed an onion structure. This is in contrast to the 1909 Tarumai dome and the 1902 Mt. Pelée spine; the former formed by squeezes of viscous lava from the vent in four days, and the latter extruded on the earth's surface taking a form of solidified lava spine of more than 300 m high with the maximum growth rate of 10 m/day (Lacroix, 1904).

The volume of the 1944 Usu lava dome above the surrounding terrace is estimated at 2.2×10^7 m^3 on the basis of a topographic map. If we adopt the equal subsurface volume as an onion shape, the total volume is 4.4×10^7 m^3. The dome grew up rather uniformly for the early 13 months, while the activity continued for approximately 17 months. Hence, the typical effusion rate of magma is obtained as 4.4×10^7 m^3/13 months $=1.1\times10^5$ m^3/day on the average, which is remarkably small in comparison with that of the 1909 Tarumai dome (3.8×10^6 m^3/day). If the mean diameter of the conduit is assumed to be 60 m, the flow velocity of magma is 43 m/day, and the Reynolds number of the flow is 10^{-5} in order of magnitude. A length of 16 km full of magma can supply the total lava of the dome, but in fact the conduit may reach a reservoir at a depth shallower than 16 km.

4. Concluding remarks

Features of lava dome formation change with the viscosity of the magma, which increases with increasing silica content. Thus, dome formation is likely for dacites and rather rare for basalts. The 1909 Tarumai lava is andesite while the 1944 Usu lava is dacite. Both the 1909 Tarumai and the 1944 Usu lava domes were formed by squeeze out of magma forced to flow through the vents. However, it is difficult to say collectively about the viscosities of both the magmas because they change with time and space: ascending magmas become lower in temperature, gas and water contents, and increase in degree of crystallization. Accordingly their rheologic behaviors should change from Newtonian viscous flows to Bingham plastic flows. In fact, the lava domes assumed different features of effusions due to differences in viscosities of their magmas, endogenous pressure and size of vents.

During the formation of the 1909 Tarumai dome, the motive pressure may have been roughly constant and the magma did not contact the aquifer because the formation did not accompany noticeable explosions. As seen in an exposed cross section of the dome, the magma behaved as viscous Newtonian flow at the early stage, and was successively squeezed out beneath the preceding lava. According to lowering of the temperature, the lava moved as Bingham plastic flow forming slickensides near the vent. Thus, some qualitative interpretations on the process are successful while some quantitative analyses are accompanied with little confidence because some parameters remain indeterminable.

As for the 1944 Usu dome, pseudo growth curves of the dome are constructed from the results of repeated precise levels along a route crossing the base of the dome. Based on the curves, we can infer the formation processes. The half-solidified dacitic magma ascended as viscous Newtonian flow through a conduit accompanied by earthquakes and surface uplift. When the magma contacted the aquifer, it caused violent explosions. Furthermore, the magma continued to uplift and extruded the mound, and grew laterally as well as upward as Bingham plastic flow, and finally formed an onion structure. The half-solidified plastic flow could lift pebbles from a level of approximately 50 m a.s.l. through the conduit at the last stage. In the discussion of the 1944 Usu dome, it became clear that mounds or bulges are not always underlain by cryptodomes.

The growth rates of the Tarumai dome is roughly 35 times larger than that of the Usu dome. Growth rate Q is a function of r, η, $\Delta p/l$ and ρ as shown by the Hagen-Poiseuille's Law. The viscosities of the dry melts of the two lava domes measured in laboratory are reduced to $10^{5.7}$ and $10^{6.8}$ Pa·s at 1000°C, respectively. The difference of the growth rates between both the domes can be partly explained by the difference of their viscosities; the other parameters should be considered to get a better understanding.

The formation of the 1909 Tarumai dome was not observed instrumentally; nevertheless we can discuss its process with some inevitable ambiguity because it still conserves its original morphology. That of the 1944 Usu dome was observed with the standard instruments, and consequently we can analyze its activity and interpret its formation process to a certain extent.

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