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FORMATION OF FRACTURES IN KOMAGATAKE VOLCANO, HOKKAIDO

by

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(with 9 text-figures and 1 plate)

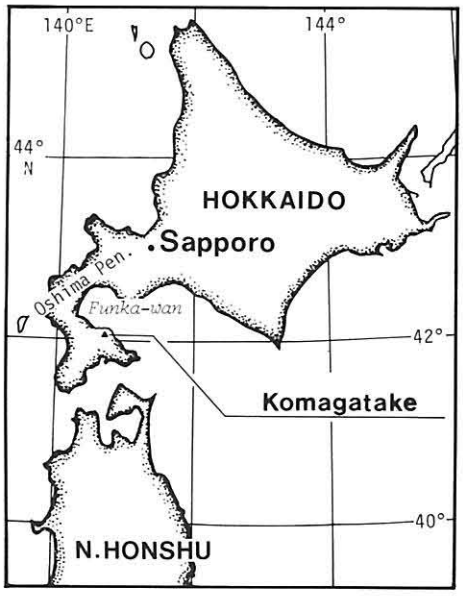
Abstract

Fractures developed in the atrio of Komagatake Volcano, Hokkaido, are classified into three main types. 1) 1929 fractures along the atrio margin, 2) 1929 concentric fractures, and 3) the 1942 major fissure. The former two fractures were formed by settling and compaction due to welding as well as settling of the 1929 pyroclastic deposits, respectively. These fractures were strongly controlled by the older topography. The 1942 major fissure extending across the atrio for 1.6 km in NW-SE, was initially produced by doming due to the excess magma pressure, and enlarged by explosions and subsequent collapse of the wall.

Introduction

Komagatake, Hokkaido, one of the most active volcanoes in Japan, is situated on the southern coast of Funka-wan (Volcano Bay) in the Oshima Peninsula (Text-fig. 1). It is a truncated stratovolcano (1133 m a.s.l.) crowned with a horseshoe-shaped crater or caldera about 2 km across at the summit.

Although the atrio (floor of the horseshoe-shaped crater) of Komagatake is rather



Text-fig. 1 Location of Komagatake Volcano in Hokkaido.

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flat, a number of craters and fractures of various sizes, which have formed accompanying recent eruptions in 1929 and 1942, are developed here (Text-fig. 2). The fractures appear to have formed from either doming of the atrio or compaction and creeping of the thick pyroclastic deposits which burried the atrio.

Our particular interest is in the development of the fractures. This paper describes and discusses this development.

Komagatake and its Historic Eruptions

The volcanic edifice of Komagatake consists of lavas and pyroclastics of pyroxene andesite of the calc-alkalic rock series. The formation of the stratovolcano started in late Pleistocene, but the type of eruption has changed to more explosive since early Holocene. Thus, eruptions of the Plinian type have intermittently occurred in this stage, often with accompanying pumice flows. Destruction of the summit by sector collapse has rarely occurred (Katsui et al., 1975).

In bulk chemical composition, the pumice and ash produced by the Plinian eruptions at Komagatake are intermediate andesite. However, the composition of groundmass, which represents the residual liquid composition of magma is highly silicic, 71.67-75.97% SiO_2. The explosive type of eruptions may be ascribed to such highly silicic liquid magma (Katsui et al., 1978).

Text-fig. 2 An aeroview of the summit area of Komagatake from the eastern sky.

Since the first recorded activity in 1640, similar explosive eruptions have been repeated at Komagatake. Old documents related to the activities of Komagatake have been collected and interpreted in reference to the detailed tephro-chronological studies of the pyroclastic deposits (Katsui et al., 1975, 1978; Katsui and Ishikawa, 1981). The results are shown in Table 1.

The 1640 Plinian eruption was preceded by phreatic explosions which triggered a sector collapse of the summit to produce a large, dry debris avalanche, leaving a horseshoe-shaped crater opening to the east. The debris avalanche entered the sea and caused a destructive tsunami, by which more than 700 people were drowned along the Funka-wan coast. Plinian eruptions occurred in 1694 and 1856 were accompanied by pumice flows. More than 20 people were killed by the 1856 pumice flow on the southern foot.

Similar Plinian eruption accompanied by pumice flows occurred in 1929. This eruption started on June 17 at ca. 0:30 with a mild explosion, then reached the culminant phase at ca. 10:00 which continued for about 14 hours, yielding a large amount of pumice fall and flow deposits as much as ca. 0.5 km^3 in total volume (Tsuya, 1930: Kozu, 1934: Katsui et al., 1975). In 1942, notable phreatic explosions occurred and a fissure 1.6 km long opened (Ishikawa and Hashimoto, 1943). Since then, no activity has been recorded except for weak fumaroles and seismicity.

Table 1 Historic eruptions of Komagatake, Hokkaido

Year (AD)	Main activity expressed by IAVCEI's symbols*	Tephra	Remarks
1640	○ ⇑ → *(g)* ≈ ↑ *(g)* † 700+ killed by tsunami	Ko-d	Debris avalanche caused tsunami, which was followed by Plinian eruption.
1694	○ ↑ *(g)* → *(g)*	Ko-c_2	Plinian eruption accompanied by pumice flow.
1765	○ ⇑ ? *(l)*		Minor eruption? No reliable record.
1784	○ ⇑ *(l?)*		Minor eruption.
1856	○ ↑ *(g)* → *(g)* ⌂ *(m)* † 20+ killed by pumice flow	Ko-c_1	Plinian eruption accompanied by pumice flow. A small lava dome was built in the Ansei crater.
1888	○ ⇑ *(m?)*		Minor eruption.
1905	○ ⇑ → *(m or g)*	Ko-b	Moderate phereatic eruption accompanied by mudflow.
1919-24	○ ⇑ *(m?)*		Minor phreatic explosions.
1929	○ ↑ *(g)* → *(g)* → ⊠ † 2 killed by pyroclastic fall	Ko-a	Plinian eruption accompanied by pumice flow. 1929 major crater formed.
1935-38	○ ⇑ *(m?)*		Minor phreatic eruptions.
1942	○ ⇑ *(g)* A fissure 1.6 km long opened		Notable phreatic explosion. 1942 major fissure opened.

Compiled from Katsui et al.(1975) and Katsui and Ishikawa(1981)

* ○ eruption in the central crater, ↑ normal explosions, ⇑ phreatic explosions, → pyroclastic flows, → mudflows, ⌂ extrusion of a lava dome, ≈ tsunamis, ⊠ destruction of arable land, † casualties.
Volume of erupted materials: *(l)* <1 x 10^4m^3 <*(m)*<1 x 10^7m^3<*(g)*

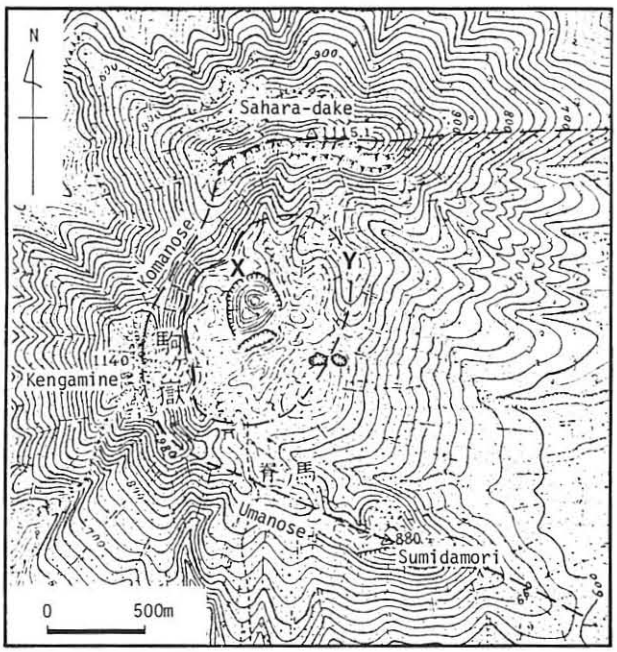
Changes in Topography of the Atrio

The present topography of the atrio is largely built by historic eruptions, especially by the 1929 and 1942 activities.

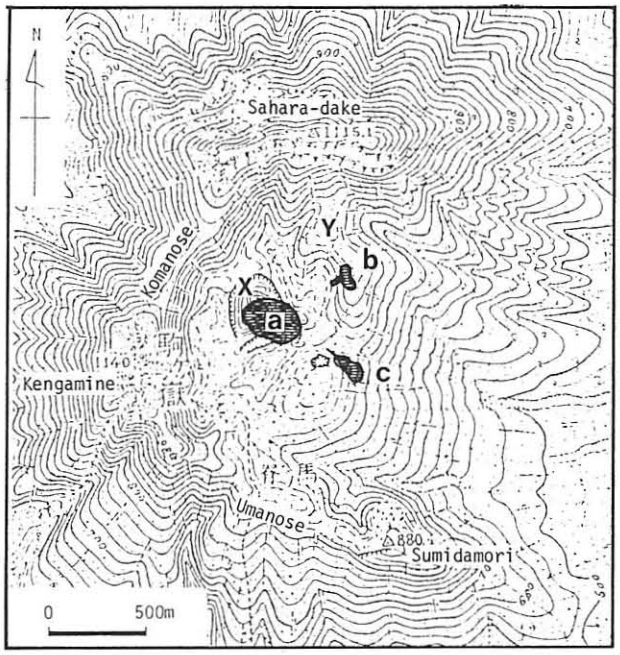
The Horseshoe-shaped crater rim involving Sahara-dake, Kengamine and Sumidamori peaks, and Komanose and Umanose ridges (Text-fig. 3), was formed by destruction of the summit not only in the 1640 activity but also in pre-historic eruptions. Subsequent to the 1640 activity, however, such destruction of the summit has not occurred, but the topography of the atrio has been conspicuously changed by the historic eruptions.

As a result of the Plinian eruptions in 1640, 1694 and 1856, Elliptic (Da'enkei) crater was formed in the atrio (Text-fig. 3). The eastern rim or bank of the crater was called Nakamo-yama (Y in Text-fig. 3) which was possibly formed by a thick pile of pyroclastic materials. In the Elliptic crater, there was the Ansei crater, 300 m across and 50 m deep (X in Text-fig. 3), from which the 1856 Plinian eruption occurred. A small lava dome, which was extruded in the later stage of the 1856 eruption, existed on the bottom of the Ansei crater before the 1929 eruption (Kato, 1909; Tanakadate, 1918).

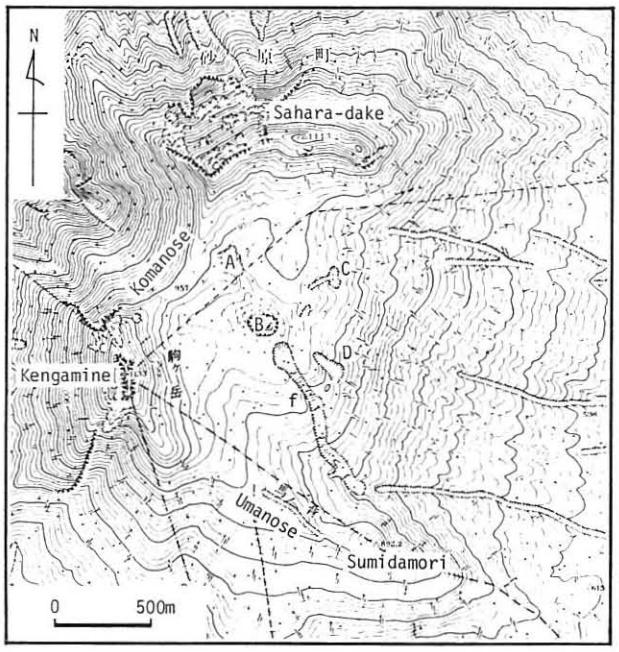
The Plinian eruption in 1929 occurred mainly from the 1929 major crater, 230 m across and 50 m deep. Its location coincides with the center of the Elliptic crater, but it is slightly deviated from the Ansei crater as shown by "a" in Text-fig. 4 (Atumi and Kishinouye, 1931). During the 1929 eruption, two other subsidiary craters, Mayu-gata and Hisago-gata craters, opened inside and outside Namako-yama ("b" and "c" in



Text-fig. 3 Map showing the topography of the summit area of Komagatake before the 1929 eruption (Land Survey Department, 1915). Horseshoe-shaped crater rim and Elliptic crater are shown by dashed lines. X: Ansei crater (1856) with a small lava dome on the bottom, and Y: Namako-yama.



Text-fig. 4 Location of the 1929 craters superimposed on the older map of Land Survey Department (1915). a: 1929 major crater, b: Mayu-gata crater, c: Hisago-gata crater, and X: Ansei crater (1856).



Text-fig. 5 Contour map of the summit area of Komagatake (Geographical Survey Institute, 1957). A: 1942 crater, B: 1929 major crater, C: Mayu-gata crater, D: Hisago-gata crater, f: 1942 major fissure.

Text-fig. 4, respectively).

The Elliptic crater, embracing the Ansei crater and a small lava dome, has been buried by a large amount of the 1929 pumice and other pyroclastic materials to form a

shallow flat atrio (Text-fig. 5). The amount of increase in height reached about 130 m at the bottom of the Elliptic crater, and about 115 m on its eastern rim or Namako-yama (Watanabe, 1932). The height of the southern rim of the Horseshoe-shaped crater was also increased, 50-60 m at Umanose and 12.65 m at Sumidamori (Atumi and Kishinouye, 1931). A number of fractures from which steam was emitting were observed in the atrio after the eruption.

In 1942, a major fissure trending NW-SE for a length of 1.6 km, opened in the atrio at the time of phreatic explosion on November 16. Phreatic explosions occurred along the fissure cutting the 1929 major crater which has been considerably deepened, about 80 m in depth. Many new craters or craterlets are aligned along the fissure. The crater that opened at the northern end of the fissure is named the 1942 crater ("A" in Text-fig. 5).

Fractures on the Atrio

Fractures on the atrio of Komagatake are shown in Text-figs. 6 and 7. They are classified into three main types: fractures along the atrio margin, concentric fractures, and the 1942 major fissure.

Fractures along the atrio margin ("m" in Text-fig. 6)

These fractures extend from Sahara-dake to Sumidamori along the horseshoe-shaped crater rim. They are not found at the eastern margin of the atrio. Along ridges, for example Komanose and Umanose, they are extension fractures which are open to widths of a few meters. Their vertical displacement is little or zero. However, at the foot of Kengamine, dip slip faults are dominant and extension fractures are rare. The faults dip toward the center of the atrio and their maximum vertical displacements amount to more than 5 m.

Concentric fractures ("c" in Text-fig. 6)

These fractures are distributed to the northeast of the 1929 major crater and to the east of Mayu-gata (cocoon-shaped) crater. They were produced during the 1929 eruption. The center of concentric fractures around the 1929 major crater does not coincide with that of the crater. It is situated at the northwestern point of the crater, where Ansei crater was opened before the 1929 eruption. Fault topography is unclear due to subsequent weathering. Though it is now barely recognized as a gentle undulation with a wave length of 10 to 20 m, it clearly showed topography of a ring fracture system just after the 1929 eruption (Atumi and Kishinouye, 1939). The flat top of undulation inclines slightly toward the center.

1942 major fissure ("f" in Text-fig. 6)

This fissure, produced by the 1942 eruption, is 1.6 km long and extends from NW to SE cutting through the 1929 major crater. The vertical section of the fissure crops out on the wall of the 1929 crater, which has a depth of 80 m. The vertical displacement

of the fissure is not observed, but a 2 m horizontal opening is observed in the welded tuff comprising the major part of the 1929 deposits (Text-fig. 8). At the upper part of the 1929 deposits, the opening of the fissure is greatly enlarged and attains widths of 50 to 100 m. It shows up as a chain of circles or ellipses in plan view. The bottom of the enlarged fissure is shallow compared to its width and is buried by collapsed blocks from the fissure wall.

Others

Radial fractures ("r" in Text-fig. 6) are distributed in the southwestern part of the atrio. On a small dome, they extend from the center to the north and the southeast. They are extension fractures with openings of 1 to 2 m and have no vertical displacement. This small dome appears a structural one in the development of radial fractures. Before the 1929 eruption, here was a small ridge extended from the horseshoe crater rim (Text-fig. 3). Accordingly, it is suggested that the dome structure was produced by a small compaction of the 1929 deposits relative to the peripheral area, rather than uplifting.

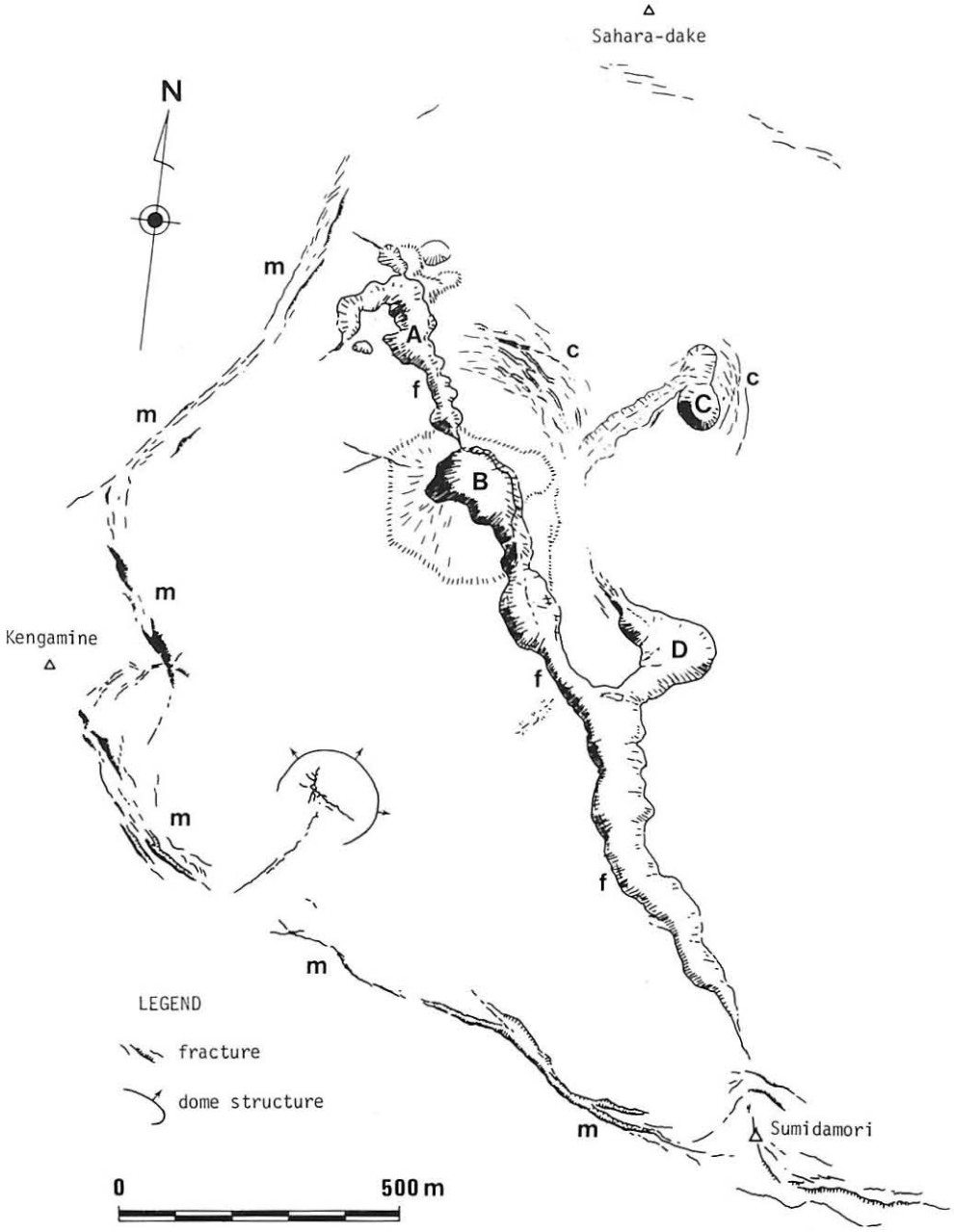
A fracture zone extends from the Hisago-gata crater to the NNW and an elongated depression extends from the Mayu-gata crater to the NW. These are fracture zones which were produced from the 1929 eruption (Atumi and Kishinouye, 1931). In the fracture zone which extends from the Hisago-gata crater, the form of the fractures is well preserved and steam emanates from them. Fractures, which are in right-handed en echelon arrangement along this fracture zone, show a left-lateral slip. Some of the fractures are regarded to have slipped in recent years inferred from their fresh appearance.

Origin of Fractures

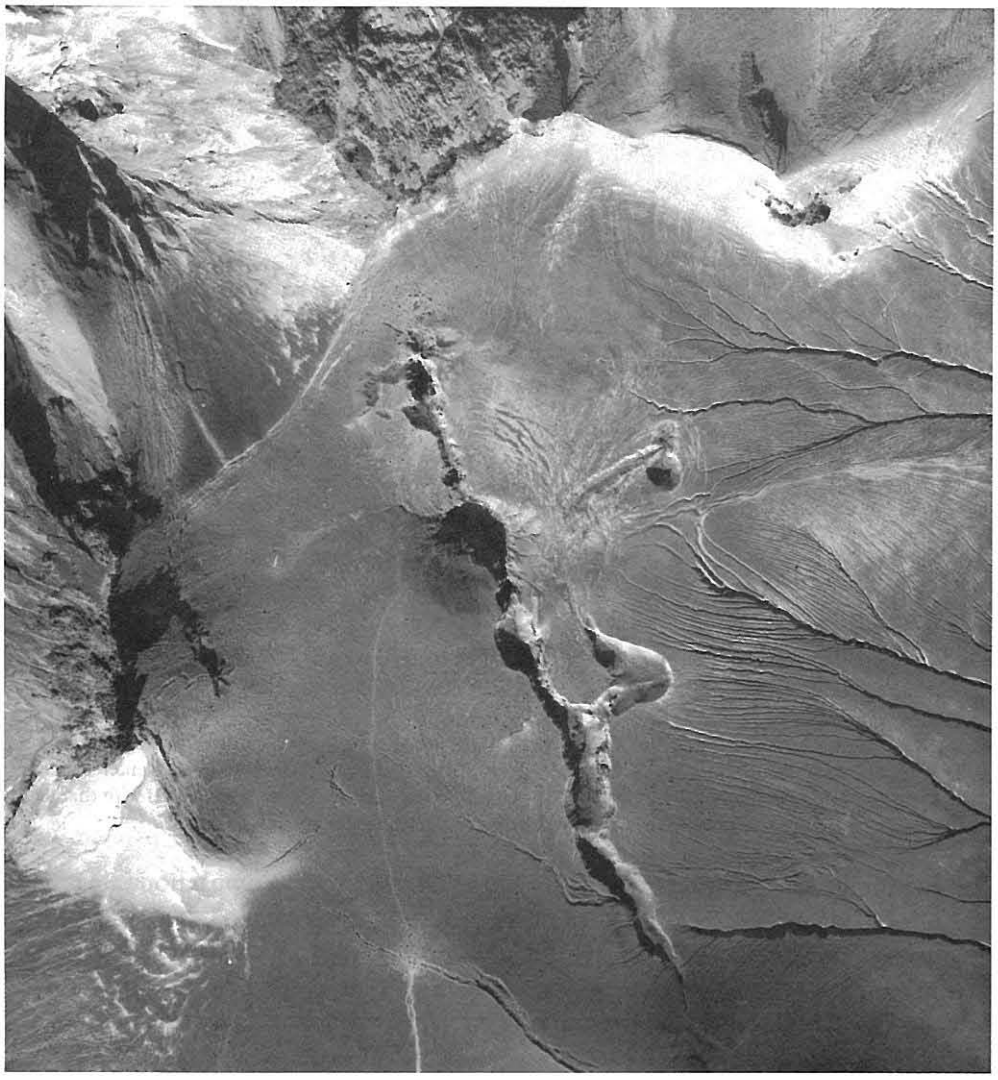
Fractures along the atrio margin and concentric fractures

Two months after the 1929 eruption of Komagatake, H. Nemoto of the Hakodate Ocean Meteorological Station made a reconnaissance of the atrio which was filled up by the new pyroclastic deposits. He observed many fractures cutting the deposits as well as the 1929 crater, although vigorous steaming from the crater and fractures made it impossible to carry out observations in detail. However, general topographic features of the atrio at this time were similar to those described in topographic surveys by Atumi and Kishinouye (1931) and Watanabe (1932) in the next summer. Miyabe (1930) and others also observed the atrio in this period.

Miyabe (1930) considered that the fractures around Sumidamori had been produced by down-slipping of the 1929 deposits, while fractures along the atrio margin, especially from the foot of Kengamine to Sahara-dake, and concentric fractures around the 1929 major crater had been formed by settling of the piled ejecta. Afterward, opening of the 1942 major fissure made it possible to observe the internal state of the 1929 pyroclastic deposits in the atrio. According to Katsui et al. (1975), the deposits are fairly welded in the middle to lower part. Therefore, compaction as well as settling due to welding of the deposits must play an important role in development of the frac-



Text-fig. 6 Map showing craters and fractures in the atrio of Komagatake. A: 1942 crater, B: 1929 major crater, C: Mayu-gata crater, D: Hisago-gata crater, m: fractures along the atrio margin, c: concentric fractures, f: 1942 major fissure, r: radial fractures.



Text-fig. 7 Vertical aerial photograph of the summit area of Komagatake (Geographical Survey Institute, 1982). Explanation of craters and fractures is given in Text-fig. 6.

tures.

Atumi and Kishinouye (1931) showed that the geometric center of the concentric fractures around the 1929 major crater coincides with the center of the crater. However, strictly speaking, it is offset slightly from the above center and is situated at the center of the Ansei crater, as shown in Text-fig. 6. It is suggested that the 1929 pyroclastic deposits are piled most thickly at the depression of the Ansei crater which was 50 m in depth. Therefore, the amount of compaction of the 1929 deposits probably attains the maximum here. As the ratio of long to short axes of pumice included

Text-fig. 8 The southern wall of the 1929 major crater. A thick welded tuff sheet produced by the 1929 eruption is exposed on the crater wall. The crater is cut by the 1942 major fissure at the center of this photograph. Note small amounts of opening of the fissure in the welded tuff sheet compared with the surface where the fissure has been enlarged by explosions and subsequent collapse.

in the lower part of welded tuff is 5 to 6 (Katsui et al., 1975), the compaction rate is 0.2 — 0.16 if the original shape of pumice is assumed to be spherical and their horizontal axes are constant in length. Therefore, the surface of the 1929 deposits above the Ansei crater must have subsided 40 to 42 m more than other parts of the atrio. If the horizontal axes of pumice expanded freely at welding, the compaction rate is calculated as 0.3 to 0.5, which corresponds to the relative subsidence of 35 to 25 m. It is considered that the geometric center of the concentric fractures is at the Ansei crater, near the 1929 major crater.

Around the Mayu-gata crater concentric fractures are also formed, where the 1929 deposits are accumulated thickly. On the contrary, no concentric fracture is observed around the Hisago-gata crater, because the deposits have not been piled as thickly.

The origin of ring fractures or ring dykes has drawn the attention of many researchers. Anderson (1924, 1937) pointed out that ring dykes intrude into shear fractures when magma pressure is reduced. Robson and Barr (1964), however, argued that ring fractures are produced by tensile failure. Roberts (1970) objected to the point force solution of Anderson. He showed that some ring dykes occupy tesile fractures formed under excess magma pressure whereas other ring dykes occupy shear fractures formed under reduced magma pressure.

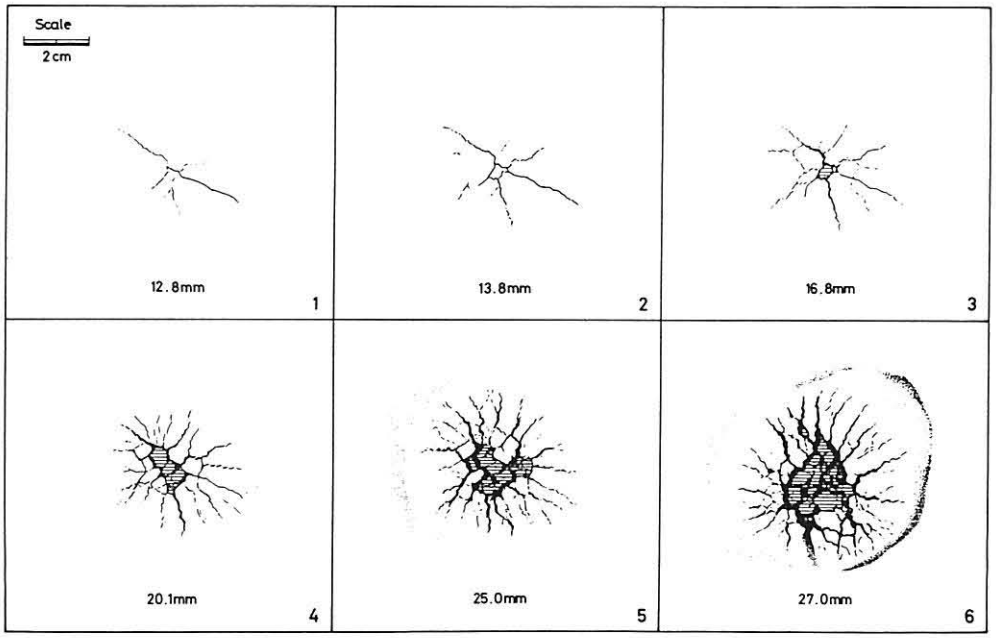
It is inappropriate that they discussed the three-dimensional structure based on two-dimensional analyses. Parker and Mcdowell (1955) performed scale model experiments about the formation of salt domes and discussed the influence of subsurface solution of the upper part of the salt dome. Their experiments showed that the surface manifestation of this is collapse with reverse faulting dominant in the collapsed area. This model can be applied to the collapse caused by reduced magma pressure, though they did not discuss the fault pattern in plan view or ring fractures per se.

In some three-dimensional models (Parker and Mcdowell, 1956; Koide and Bhattacharji, 1975; Komuro and Fujita, 1980) the formation of fractures due to excess magma pressure was discussed, but the case of reduced magma pressure or withdrawal of magma column was scarcely discussed. Ring fractures are probably produced under the conditions of the latter case. The concentric fractures of Komagatake are obviously formed by the compaction of deposits. The formation mechanism of the concentric fractures may be analogous to the reduced magma pressure model.

The 1942 major fissures

The 1942 major fissure is enlarged at the surface by explosion and subsequent collapse, though it is scarcely open in the lower part of the 1929 deposits. The fissure must have been formed just before the phreatic explosion by the excess magma pressure.

The magma reservoir can be assumed to be a sphere in model experiments (Komuro



Text-fig. 9 An experiment demonstrates formation of a dome of particle material layer in the process of rising of a rigid sphere, 2 cm in size and 7.5 cm in depth. The amount of rise of the sphere is given in mm (after Komuro and Fujita, 1980). Note a straight fracture which formed in the early stage.

and Fujita, 1980). A domal uplift of overburden, associated with radial fractures, results from upward pressure on the sphere (Text-fig. 9). These results are essentially identical to those of Parker and Mcdowell (1955). In these experiments, it is noticed that in the early stage of upwarping radial fractures don't develop equally in all directions but develop in a preferred orientation (Stage 1 in Text-fig. 9).

According to Ishikawa and Hashimoto (1943), a fracture that connects the 1929 major crater and the Mayu-gata crater was opened slightly in the 1942 explosion. The development of the 1942 major fissure, with a minor fracture, may represent the early stage of the above model experiments. The azimuth of the fissure may have been controlled mainly by the direction of the maximum harizontal stress (σ_{Hmax}) in this region, as discussed by Nakamura (1975).

Concluding Remarks

The fractures developed in the atrio of Komagatake were examined. All of the fractures have been formed by the 1929 Plinian eruption and the 1942 phreatic explosion.

They are classified into three main types: 1) 1929 fractures along the atrio margin and 2) concentric fractures, and 3) the 1942 major fissure.

1) The 1929 fractures along the atrio margin were formed by settling of thick pile of the 1929 pyroclastic deposits.

2) The 1929 concentric fractures were produced by compaction due to welding as well as settling of the 1929 deposits. The geometric center of the concentric fractures around the 1929 major crater is offset from the center of the crater and coincides with that of the Ansei crater. This is interpreted in terms of difference in the amount of compaction related to the older topography of the atrio. A similarity between the concentric fractures and the ring fractures and dykes is suggested in their origin. Furthermore, a small dome with radial fractures was formed in the atrio by a small compaction of the deposits relative to the peripheral area.

3) The 1942 major fissure, 1.6 km long, was opened possibly by doming due to the excess magma pressure, and enlarged by explosions and subsequent colalpse of the wall. Model experiments support the above origin. The azimuth of the fissure appears to have been determined by the direction of the horizontal maximum stress in this region.

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