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DEVELOPMENT OF FAULTS AND GROWTH OF USU-SHINZAN CRYPTODOME IN 1977-1982 AT USU VOLCANO, NORTH JAPAN

by

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(with 21 text-figures)

Abstract

Usu-Shinzan, a cryptodome uplifted about 180 m, was built on the summit of Usu Volcano during the 1977-1978 dacite eruption and subsequent activity until spring 1982. Numerous faults have developed associated with the growth of Usu-Shinzan, but their development was restricted to the northern harlf area of the volcano, possibly being controlled by the structure of the southern wall of Toya caldera which is overlain by the volcano. In the summit area, typical synthetic and antithetic faults were formed, which resulted in development of an asymmetric graben. The main fault coupled with hinge faults grew up to form a U-shaped fault block. Due to NE upward movement of the U-shaped block, the northern somma was cut by many strike-slip faults and pushed outward, and on the northern foot a number of strike-slip faults showing radial arrangement have been formed. Re-activation of some of the 1910 faults were observed. The development of these faults can be interpreted by means of intrusion of the dacite magma along the steep southern wall of the caldera under the volcano. Changes of fault activity with time suggest that the magma column expanded not only at the upper part but also notably inflated at the lower part after November 1977.

Introduction

During the 1910 activity that occurred on the northern foot of Usu Volcano, notable crustal movement, with accompanying earthquakes and development of faults and fissures, continued for more than three months after the strong phreatic explosions (Text-fig. 1). This movement resulted in the formation of Meiji-Shinzan, a new mountain born in Meiji Era. The 1910 activity has been thoroughly studied by Omori (1911, 1912 and 1920), Sato (1913) and others. Omori (1920) confirmed that Meiji-Shinzan was uplifted as high as 155 m with an average amount of upheaval 1.55 m per day, and that another unnamed subsidiary hill, uplifted about 75 m, was also built simultaneously.

Although neither essential ejecta nor new lava appeared in this activity, it is apparent that the phreatic explosions were caused by intrusion of an acid magma which contacted with plentiful groundwater. Omori (1912) considered that Meiji-Shinzan was formed by shallow intrusion of a dome lava similar to Ko-Usu and O-Usu lava domes on the summit of this volcano. Further, he mentioned that the older parasitic hills, Higashi-maruyama and Nishi-maruyama on the northern foot, were possibly formed through the same process. Subsequently, Tanakadate (1926, 1929) named "roof mountain" for such uplifted hills, and "cryptodome" for lava columns that intruded at shallow depth to form roof mountains. Since then, the term cryptodome has been

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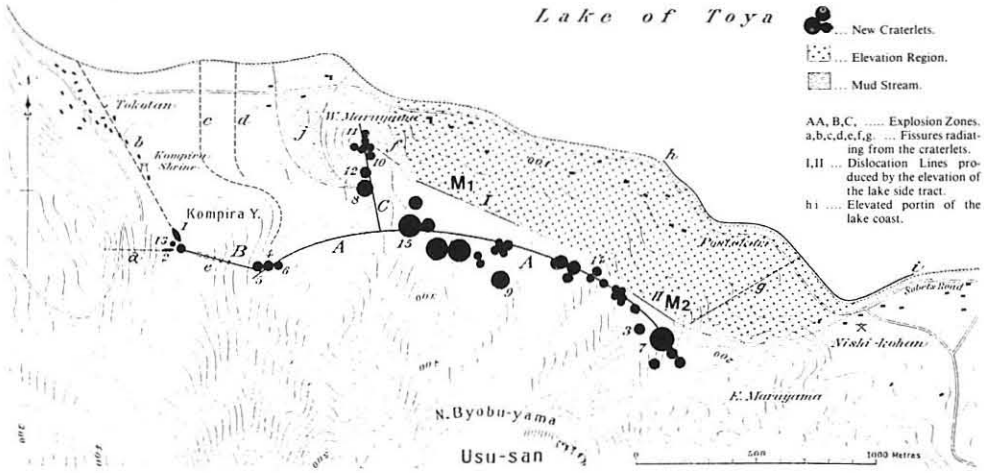


Text-fig. 1 Craterlets, fissures and faults formed by the 1910 activity which occurred on the northern foot of USU Volcano (Omori, 1911). The sites M1 and M2 subsequently uplifted to form Meiji-Shinzan and the subsidiary cryptodome, respectively. Note the fissures "a and b" and "g", where intensive fault activities occurred again during the 1977-1982 activity.

widely used, e.g. a new dacite cryptodome emplaced just before the great 1980 eruption of Mt. St. Helens (Moore and Albee, 1981).

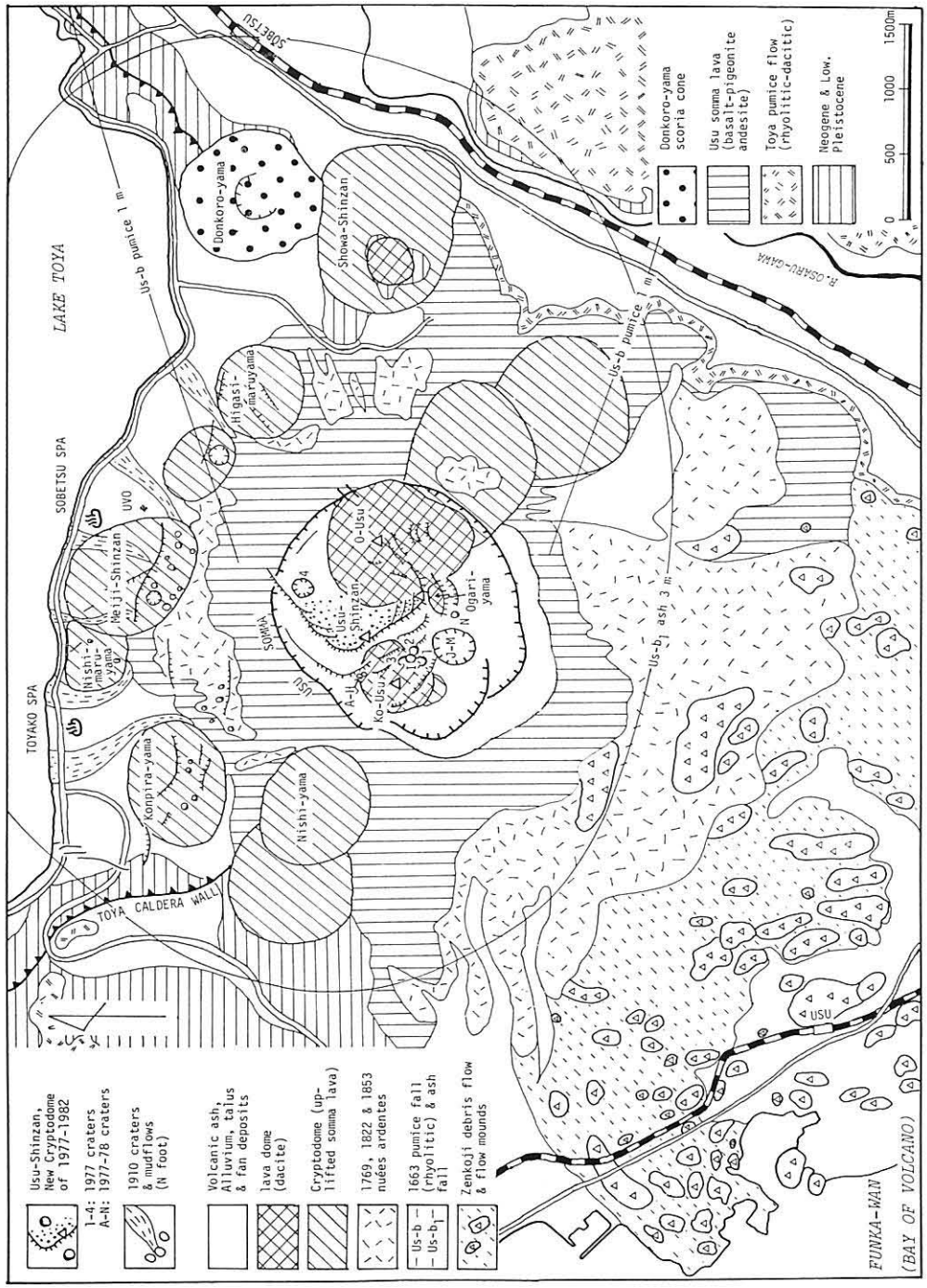
After 32 years of dormancy since the formation of Meiji-Shinzan, a similar roof mountin was built on the eastern foot of Usu during the 1943-1945 activity. This roof mountain, Showa-Shinzan, accompanies a dacite plug dome which extruded above the roof mountain in the later stage of this activity (Minakami et al., 1951; Mimatsu, 1962).

Recently, during the 1977-1978 eruption and subsequent activity, Usu Volcano has produced another new roof mountain, Usu-Shinzan on the summit, with accompanying earthquake swarms as in the previous historic activities of the volcano. Such types of activities of Usu Volcano may be interpreted as due to the high viscosity of magma as already pointed by Minakami et al. (1951).

In the recent activity, a number of faults associated with the growth of Usu-Shinzan have developed, but their development was restricted to the northern half area of the volcano, possibly being controlled by the structure of the basement. The process of development of these faults has been continuously observed since the beginning of the recent activity. On the basis of detailed analysis of these faults, the mechanism of the formation of Usu-Shinzan cryptodome is considered in this paper.

Outline of Geology of Usu Volcano

Usu Volcano is situated on the southern rim of the Toya Caldera in southwest Hokkaido, and consists of a somma volcano and a number of lava domes and cryptodomes (Katsui et al., 1981; Soya et al., 1981; Text-figure 2).



Text-fig. 2 Geologic map of Usu Volcano (compiled from the 1:25,000 geologic map of Katsui and Oba in Yokoyama et al., 1973, and that of Soya et al., 1981)

The somma volcano is a truncated stratovolcano crowned with a small caldera, 1.8 km across and ca. 500 m high, and it covers a circular area 7 to 8 km across at the base. This main volcanic edifice was formed in early Holocene by repeated eruption of lava flows and scoria of basalt and mafic andesite of the low-K tholeiitic rock series (Ōba, 1966). After the completion of a stratovolcano, several thousand years ago, its summit was broken by a phreatic explosion accompanied by a large debris avalanche. The destruction of the summit possibly resulted in the formation of a small horseshoe-shaped caldera, but its southern opening was buried by subsequent eruptions to form the present somma.

After a long period of quiescence, the historic activities commenced in 1663 with a Plinian eruption of rhyolite pumice. Then explosive activites have been recorded in 1769, 1822, 1853, 1910, 1943-1945, and 1977-1978. These activities are either pumice eruptions or phreatic-phreatomagmatic ones, sometimes accompanied by pyroclastic flows, surges or mudflows. Occurrence of conspicuous ground deformations with earthquake swarms and formation of lava domes or cryptodomes are the characteristic feature of the historic activites of Usu. During the historic times, three dacite lava domes (Ko-Usu, O-Usu, and Showa-Shinzan) and seven cryptodomes (Nishi-yama, Konpira-yama, Nishi-maruyama, Meiji-Shinzan, Higashi-maruyama, Ogari-yama, and Usu-shinzan) were formed, though the dates of some domes are uncertain. It is worthy to note that these domes are aligned in two parallel zones running NW-SE through the summit and the northern foot, and are probably controlled by the structure of the southern wall of Toya Caldera which is overlain by Usu Volcano.

The historic volcanic products consist of typical low-K acid rocks which varied with time from rhyolite to dacite decreasing in silica from 73.29 to 67.70%. This variation is possibly ascribed to a compositionally zoned magma chamber (Ōba and Katsui, 1983; Ōba et al., 1983). In this connection, a mechanism involving injection of andesitic magma into rhyolitic magma prior to the historic eruption has been proposed (Okumura et al., 1981).

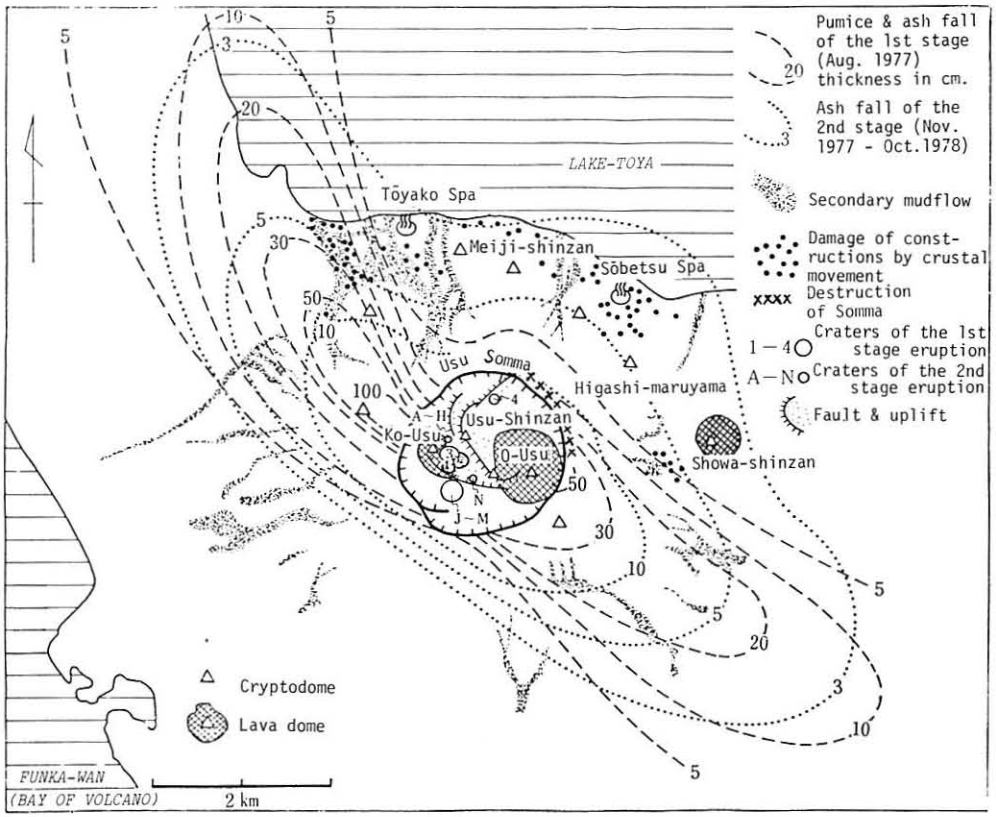
Brief history of the 1977-1978 Eruption

On August 6, 1977, Usu Volcano renewed its activity with local earthquakes. On August 7, 32 hours after the beginning of the preceding earthquake swarms, a major pumice eruption of hypersthene dacite occurred from the summit, producing an eruption cloud 12 km high. Paroxysmal eruptions of the first stage lasted for a week from August 7 to 14, opening Craters 1-4, each about 100 m across. The total volume of the ejected pumice and ash amounted to as much as 8.3×10^{13} cm^3. Toward the end of the eruptions, the vesiculation of pumice decreased notably, suggesting that the upper part of the dacite magma enriched in water discharged in this stage. Then, the residual magma which was depleted in water and highly viscous, ascended gradually to form a new cryptodome (Katsui et al., 1978b; Niida et al., 1982; Suzuki et al., 1982).

Due to continuous shallow intrusion of the magma, the second stage eruptions started on November 16, 1977, with a minor phreatic explosion, then the explosive ac-

tivities much increased with time. Thus, moderate phreatomagmatic explosions occurred frequently from late April to early September, and the eruption stopped on October 28, 1978. During the second stage, Craters A-N, several to 130 m across, were formed along the southwestern foot of the newly growing cryptodome, and Gin-numa Crater, a large depression about 400 m across, was built by coalescence of Craters J, K, L, and M. The total volume of the ejecta of the second stage amounts to 7.5×10^{12} cm^3 (Niida et al., 1980).

The growth of the new cryptodome, with accompanying earthquake swarms, continued after the eruption, and it reached a maximum upheaval of about 180 m in Feb.-March 1982. The norhtern part of the somma was cut by numerous faults and moved outward about 190 m. The crustal movements also had influence upon the northern foot (Text-fig. 3). In March 1982, earthquakes and crustal movements ceased rather abruply, but gas emissions persistently continue (Katsui and Yokoyama, 1979; Katusi et al. 1981; Okada et al., 1981; Yokoyama et al., 1981; Yokoyama et al., 1983) The present pumice and ash showers, mudflows triggered by rainfalls, and ground deformations cused severe damage around the volcano (Seki ed., 1978; Katsui, 1980;



Text-fig. 3 Usu Volcano after the 1977-1978 eruption. Pyroclastic fall deposits are expressed by thickness contour lines in cm (Katsui, 1980).

Kadomura ed., 1982, 1984; Kadomura et al., 1983; Yamagishi et al., 1982).

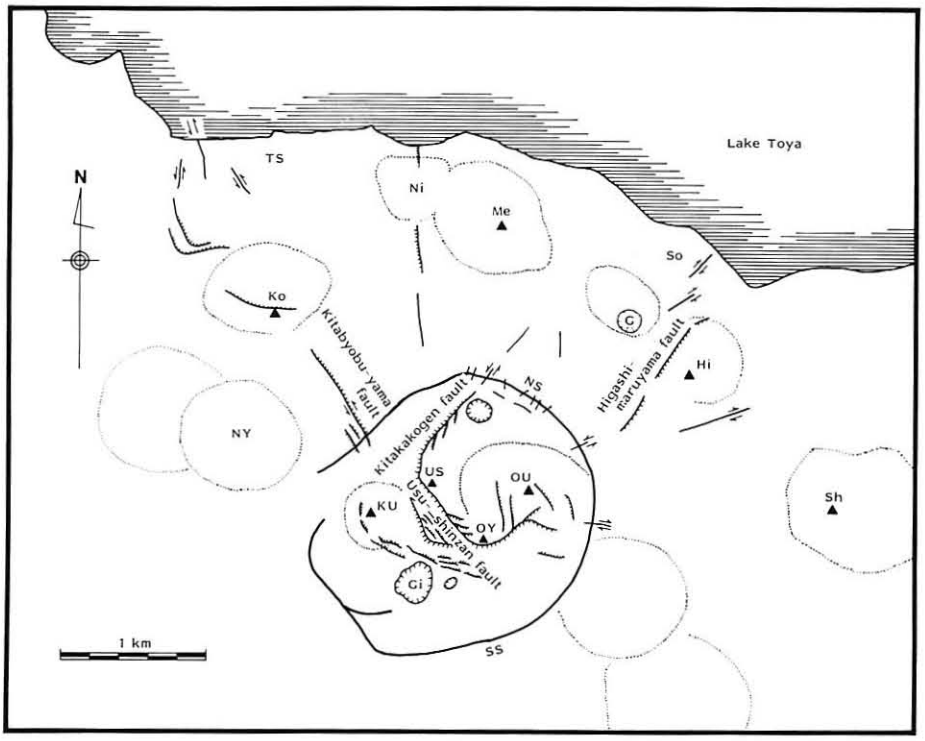
Development of New Faults

The major faults produced during the 1977-1982 activity of Usu Volcano are shown in Text-fig. 4. The sequence of the development of new faults in the summit area is illustrated by Text-fig. 5.

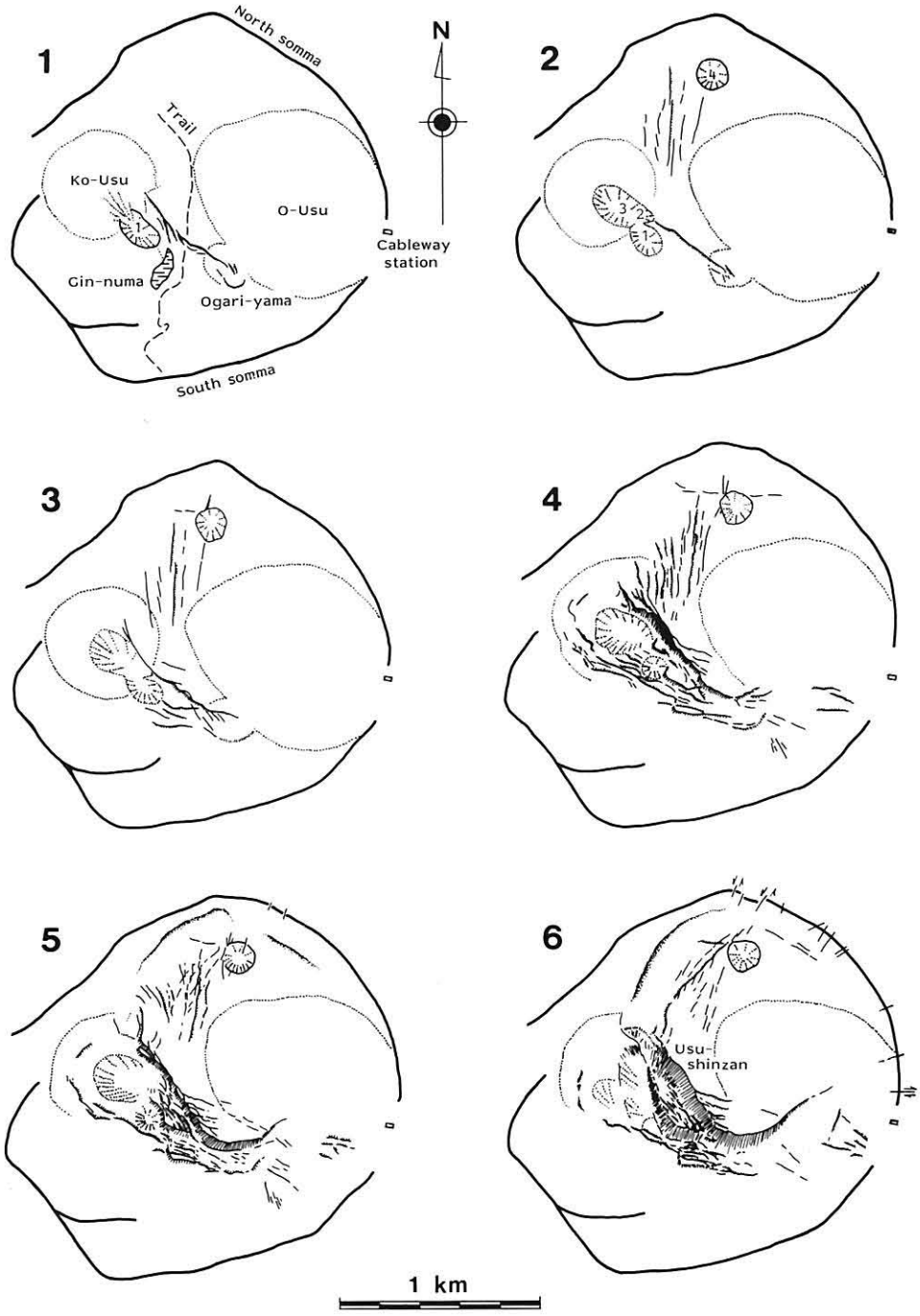
Summit area

At 0850 (JST) on August 7, 1977, just 20 min. before the first pumice eruption, a normal fault, dipping south with a vertical displacement of ca. 40 cm, was found on the eastern foot of the Ko-Usu dome (oral communication from Ishibashi in 1977; Text-fig. 6). This is the first indication of the fault which has subsequently developed into the main fault (Usu-Shinzan fault).

On the next morning, August 8, after the first pumice eruption from Crater 1, it



Text-fig. 4 Major faults produced during the 1977-1982 activity.
Ko: Konpira-yama, TS: Toyako Spa, Ni: Nishi-maruyama, Me: Meiji-Shinzan, So: Sobetsu Spa, G: Genta-ana crater, Hi: Higashi-maruyama, Sh: Showa-Shinzan, NS: North somma, SS: South somma, KU: Ko-Usu, US: Usu-Shinzan, OY: Ogari-yama, OU: O-Usu, Gi: Ginnuma crater, and dotted lines: cryptodomes and lava domes. The name of faults referred to Yamagishi et al. (1982).



Text-fig. 5 Sequence of the development of faults in the summit area of Usu from August to November 1977. Illustration from aerial photographs.
1: August 8, 1977, 2: August 10, 3: Augut 12, 4: August 23, 5: September 25, and 6: November 29.

Text-fig. 6 A normal fault cutting a trail in the atrio, observed at 0850, 20 min. before the beginning of eruption on August 7, 1977. (photo by courtesy of Mr. Ishibashi)

was observed from the air that the main fault has extended along a NW-SE ridge from the eastern foot of Ko-Usu to the Ogari-yama dome (Text-fig. 5-1). The main fault was not yet large in displacement and was accompanied by several branch faults. On the southern side of the main fault, Crater 1 opened.

On August 10, four new craters had already opened and many right-handed en echelon faults were observed from Ko-Usu to Crater 4 (Text-fit. 5-2). On August 12, the main fault had developed considerably and began to cut the Ko-Use dome. Several normal faults whose senses were the same as that of the main fault, dipping south, were also formed on the southern side of the main fault. These faults appear to be step faults (Text-fig. 5-3).

On August 23, the vertical displacement of the main fault amounted to about 50 m (Katsui et al., 1978b). Another group of notable faults which run also from NW to SE but dip to the north in opposite sense to the main fault, developed in the south (Text-fig. 5-4). These faults cut the prexisting normal faults which dipped south. As a result, an asymmetric graben was formed from Ko-Usu to Ogari-yama dome. The summit of Ko-Usu, situated in the graben, began to subside with development of the graben (Katsui et al., 1978b). It is noticed that the location of the new craters, Craters 1 to 3, coincides with the graben. In the northern atrio, the normal faults which were arranged en echelon began to form minor horst-grabens.

On September 25, several faults with NE-SW strike appeared in the area from Ko-Usu to Crater 4 (Text-fig. 5-5). They began to cut the pre-existing echelon faults which stopped development. The southern normal faults opposed to the main fault notably increased, and the blocks bounded by these faults tilted to the south (Text-fig. 7-1). The main fault turned to NE at Ogari-yama and began to cut the O-Usu dome. Branch faults along the main fault increase showing a right-handed en echelon arrangement.

The norhtern atrio began to swell in proportion to the uplift of Usu-Shinzan, so that buckles by compression and low angle thrust faults were formed at the boundary between the somma and the atrio (Text-fig. 7-2). No evidence showing compression has been found in other areas of the atrio. The northern part of the somma was cut by a

Text-fig. 7 Various types of faults developed on the summit of Usu (October 23, 1977).
1. The southern normal faults (antithetic faults) developed in the asymmetric graben. The main fault scarp on the left. 2. Low-angle thrust faults on the northern atrio. The swelling front shoved to the north somma. 3. A right-handed strike slip fault cutting the northeastern somma. The building in the background is the cableway station. 4. Numerous minor faults produced by right-handed simple shear near the cableway station. Note the shifted benches.

number of short strike-slip faults.

By November 29, the whole fault system on the summit area was observed (Text-fig. 5-6). A hinge fault (Kita-kakogen fault of Yamagishi et al., 1982) whose displacement was larger toward SW appeared from near Ko-Usu to Crater 4 and connected with the main fault. As a result of development of these faults, a U-shaped fault block was revealed. This fault block continued to uplift, so that many short left-handed strike-slip faults with large displacement cut the northern somma near Crater 4. On the contrary, near the cableway station on the eastern part of the somma, right-handed displacement was observed (Text-fig. 7-3 & 4)

The northern part of the somma was thrust out to NE, so that the outer slope of the somma changed steeply and began to break down.

After the formation of the U-shaped fault block, the fault movement has been localized to this block, which uplifted notably, and other faults became rather inactive. Destruction of the O-Usu and Ko-Usu lava domes continued with the movement of the

Text-fig. 8 The summit of Usu viewed from the southeastern sky on November 4, 1977 (cfr. Text-fig. 5-6). Note uplifting Usu-Shinzan (center) and sinking Ko-Usu in the asymmetric graben. A number of antithetic faults can be seen in the graben. (photo by Japan Defence Force)

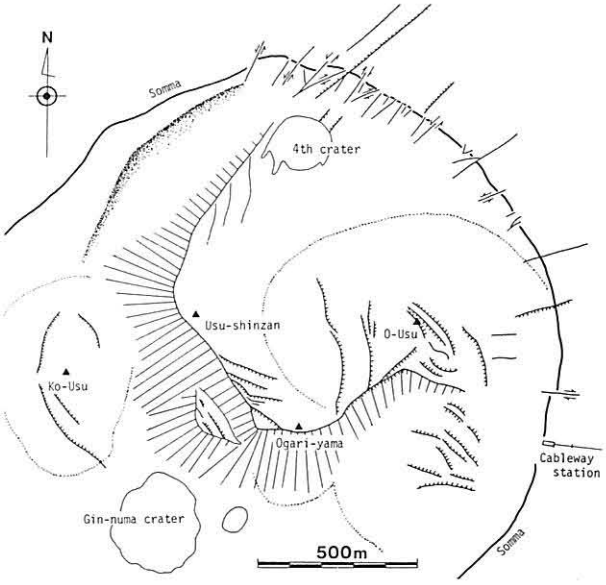
block. (Text-figs. 8 and 9).

The faults which dipped north within the asymmetric graben were partially destroyed by the second stage eruption, especially by the opening of the Gin-numa crater in 1978. The northern atrio continued to uplift, so that its height became the same level as that of the northern somma by the end of 1980, though before the eruption it had been about 60 m lower than the somma. (Text-fig. 10).

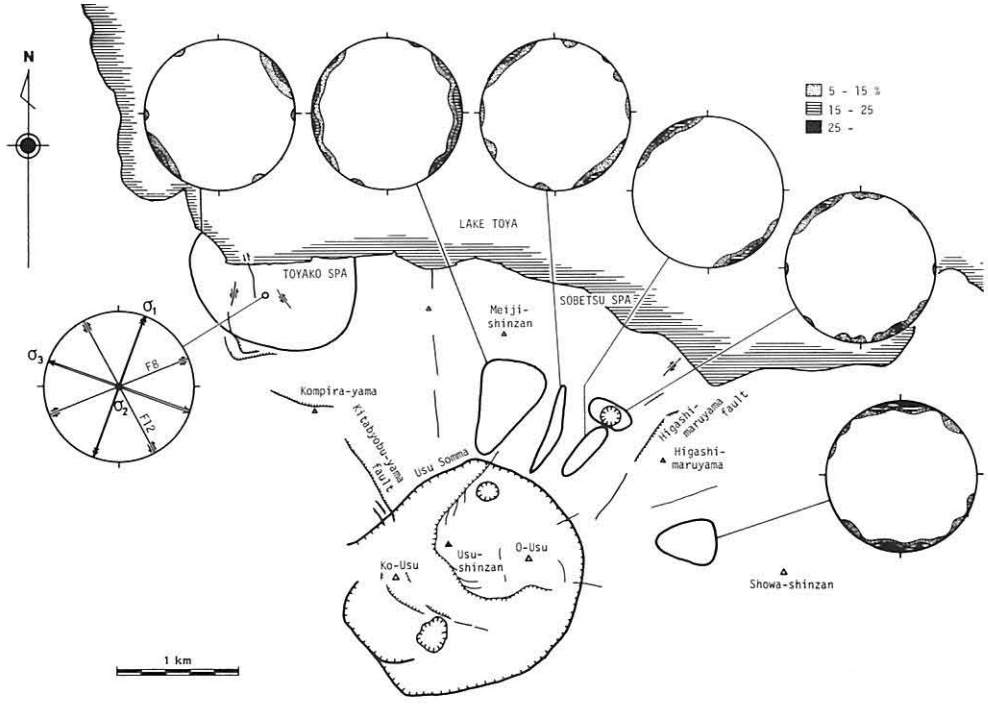
Northern foot of Usu Volcano

A number of new faults have been formed at the northern foot of Usu Volcano, but no faults were found at the southern foot (Text-fig. 11). This evidence may be ascribed to the presence of the Toya caldera wall beneath the volcano (Katsui et al., 1978b). Text-fig. 11 shows the equal area projections (lower hemisphere projection) of poles of minor fault planes which were formed during the period from August 1977 to May 1978. This figure also shows major faults around the volcano and the stress analysis at a certain point of Toyako Spa. Minor faults strike E-W in the eastern area, ENE to N-S on the northern slope, and NW in Toyako Spa, indicating that they form a radial fault system. The strikes of major faults. e.g. the Higashi-maruyama and the Kitabyobu-yama faults agree with those of minor faults in each area. In the area to the west of

Text-fig. 9 The summit of Usu viewed from the northeastern sky on November 29, 1977 (cfr. Text-fig. 5-6). Note Kita-kakogen fault, a hinge fault cutting echelon faults (center). Low-angle thrust faults along the north somma, and Crater 4 in foreground. (photo by Japan Defence Force)



Text-fig. 10 Map showing growth of the U-shaped fault block and destruction of the lava domes and the northern somma. July 1979.



Text-fig. 11 Map showing new faults around Usu Volcano. Contour diagrams show the lower hemisphere projection of minor faults in the areas enclosed by solid lines. Stress analysis is obtained by means of strike-slip faults, F8 and F12 in Toyako Spa (Text-fig. 14). Tensile stress is positive. Note the radial arrangement of the major and minor faults on the northern foot of the volcano.

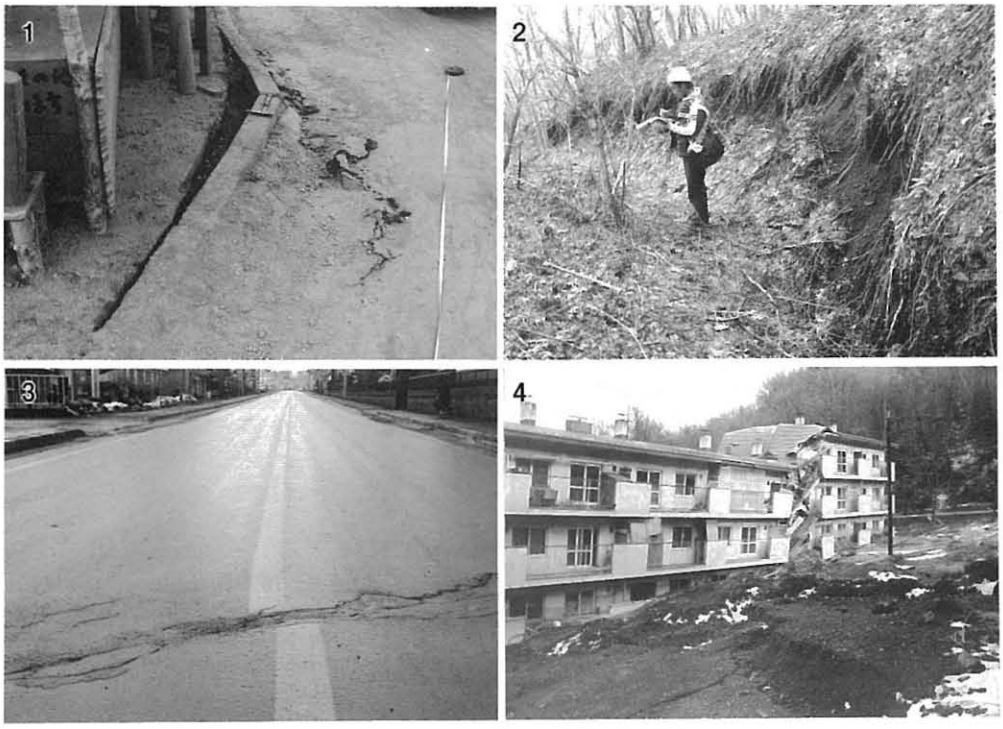
Showa-Shinzan and northwest of Higashi-maruyama, many right-handed strike-slip faults are observed. On the other hand, there are many left-handed strike-slip faults in the Toyako Spa area.

Eastern side of Usu Volcano

Many right-handed strike-slip faults developed, and the road from Sobetsu Spa to Showa-Shinzan was cut by them. The fault activity and ground deformation on the foot of Usu Volcano was first observed in this area. On Autgust 7, 1977, just before the eruption, the tension of the cableway wires had already loosened due to E-W shortening of ground. On August 15, edge stones of a road began to be destroyed at the western foot of Showa-Shinzan (Katsui et al., 1978b; Text-fit. 12-1). In this region, the fault activity and ground deformation have decreased earlier than other regions, and almost ceased by the beginning of 1979.

Higashi-maruyama and NE-N side of Usu Volcano

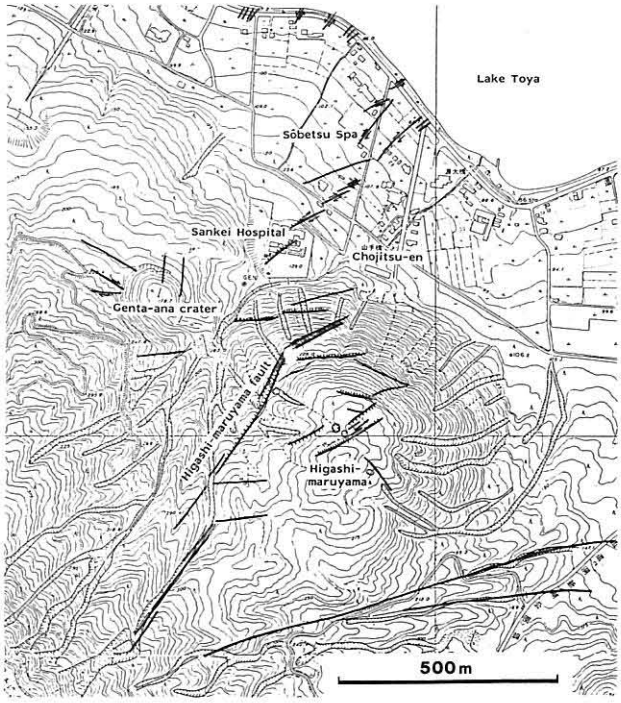
Many short faults have developed in this area, and their strikes tend to change from NE to N (Text-fig. 11). The vertical displacement of these faults commonly ranges 10 to 20 cm and rarely attains 1 or 2 m. The Higashi-maruyama fault, a new fault, strikes NNE-SSW and cuts the western side of Higashi-maruyama where it constitutes a minor



Text-fig. 12 Ground deformation and faults on the foot of Usu Volcano.
1. Edge stones buckled due to horizontal compression at the Showa-Shinzan street on the eastern foot of Usu (August 20, 1977). 2. A re-activated fault on the top of Higashi-maruyama (April 29, 1978). 3 A left-handed strike-slip fault cutting Route 230 in Toyako Spa (Fl in Text-fig. 14) (November 22, 1977). The lateral displacement attained about 4 m by the spring of 1982 when the crustal movement ceased. 4. An apartment house damaged by a normal fault (F28 in Text-fig. 14). The fault scarp in foreground (December 1978).

graben (Text-fit. 13). Toward the northeast the graben bends to ENE. On the top of Higashi-maruyama, there is a minor graben formed possibly during the 1910 activity. It is bounded by the faults which had throws of 1 to 2 m before the recent eruption, but now have throws of 2 to 3.5 m. The lower 1 to 1.5 m of the fault scarps were newly formed during the present activity (Text-fig. 12-2).

A number of right-handed strike-slip faults were produced on the alluvial fan from the Sankei Hospital toward NE (Text-fig. 13). At the western part of the fan, however, minor left-handed strike-slip faults were formed. The shoreline road on the fan was cut by many short faults, and the shoreline has been thrust out into Lake Toya about 10 m by the end of 1979 (Yokoyama et al., 1981). In this area, many buildings were damaged. Sankei Hospital, for example, at the top of the fan began to be destroyed in early September 1977 and collapsed by the end of 1978. Another building, Chojitsu-en, which is located near the hospital was inclined about 6° to NNE and considerably damaged. Most of these destroyed buildings are located on or along the above mentioned right-handed strike-slip faults. It is noticed that the site of these faults coincides



Text-fig. 13 New faults on the northeastern side of Usu Volcano. Note the predominance of right-handed strike-slip faults in the Sobetsu Spa area.

well with that of the pre-existing faults which were formed by the 1910 activity (Omori, 1911; "g" in Text-fig. 1).

Northern side of Meiji-Shinzan and Nishi-maruyama

This area was scarcely damaged by fault activity. However the road along the shoreline of Lake Toya is cut by faults which strike N10°W with a vertical dip and the western block subsided with a throw of 20 cm (Text-fig. 4).

Kitabyobu-yama (NE part of the somma)

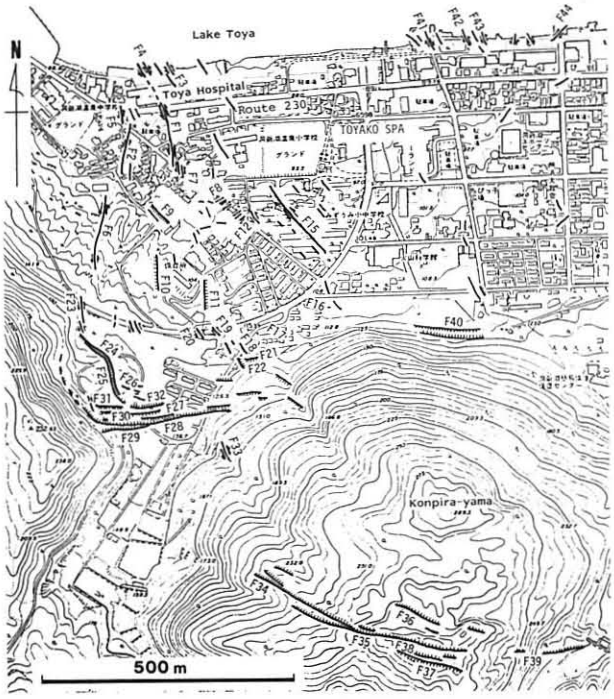
Kitabyobu-yama fault, a new fault which strikes NNW-SSE and whose northeast side subside 2 m, extends from the northwestern part of the somma to Kompira-yama (Text-fig. 11). It is an oblique slip fault as evidenced by striations developed on the fault plane which indicate left-normal slip (Yamagishi et al., 1982). The fault is situated on the NW extension of the Usu-Shinzan fault, but its sense is contrary to that of the latter fault. The sense of the Kitabyobu-yama fault is rather similar to that of F1 fault in Toyako Spa (Text-fig. 14).

Kompira-yama

In this area there are old E-W faults which were produced in the 1910 activity (Omori, 1911; Sato, 1913). The new faults F34 to F39 shown in Text-fig. 14 are of dip-slip type, which strike also E-W and dip north. These new faults are obviously reactivated old faults similar to those on Higashi-maruyama.

Toyako Spa

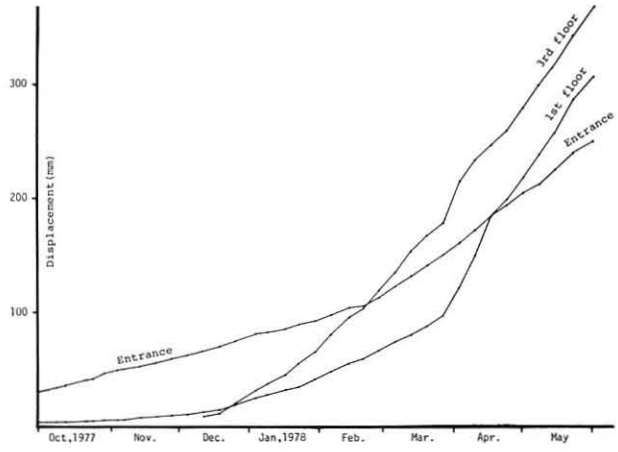
In Toyako Spa, the present fault movement caused severe damage to buildings,



Text-fig. 14 New faults on the northwestern side of Usu Volcano. Note the predominance of left-handed strike-slip fault in the Toyako Spa area.

roads and other constructions. At the time of the 1910 eruption, ground deformation and fault movement conspicuously occurred in this area (Omori, 1911). A left-handed strike-slip fault cut Route 230 in front of Toyako Kyokai Hospital (Text-fig. 12-3; F1 in Text-fig. 14). The lateral displacement attained about 4 m by the spring of 1982 when the crustal movement ceased. Other faults, e.g. F2, F6 and F23 shown in Text-fig. 14, are relatively large left-handed strike-slip faults.

The faults F24 to F32 are of dip-slip type. The northern side of these faults sub-



Text-fig. 15 Amount of displacement of the cracks at the building of Toyako Kyokai Hospital which was damaged by F1 fault. Note the displacement rate accelerated after February 1978.

sided, so that an apartment building standing across the faults was gradually cut and destroyed (Text-fig. 12-4).

The faults F8 and F12 seem to be a conjugate set, and stress analysis by means of these faults is shown in Text-fig. 11. The maximum tensile principal stress axis (σ_1) is horizontal NNE-SSW, the intermediate principal stress axis (σ_2) is vertical, and the minimum principal stress axis (σ_3) is horizontal WNW-ESE.

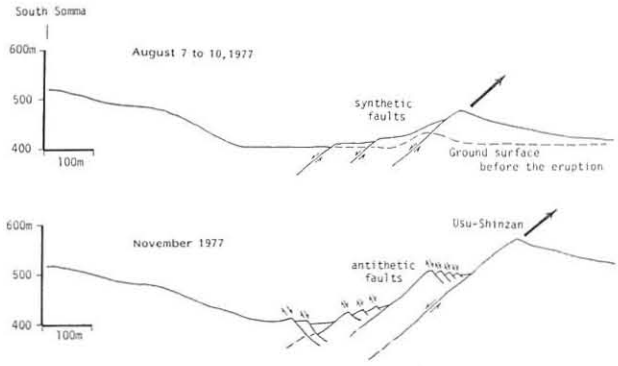
Text-fig. 15 shows the amount of displacement of cracks, which were formed by the movement of the strike-slip faults at the building of the Toyako Kyokai Hospital. The crack at the entrance of the building is extension of F1 fault as shown in Text-fig. 14. It is noticed that the displacement rate of these cracks accelerated after February 1978.

Discussion

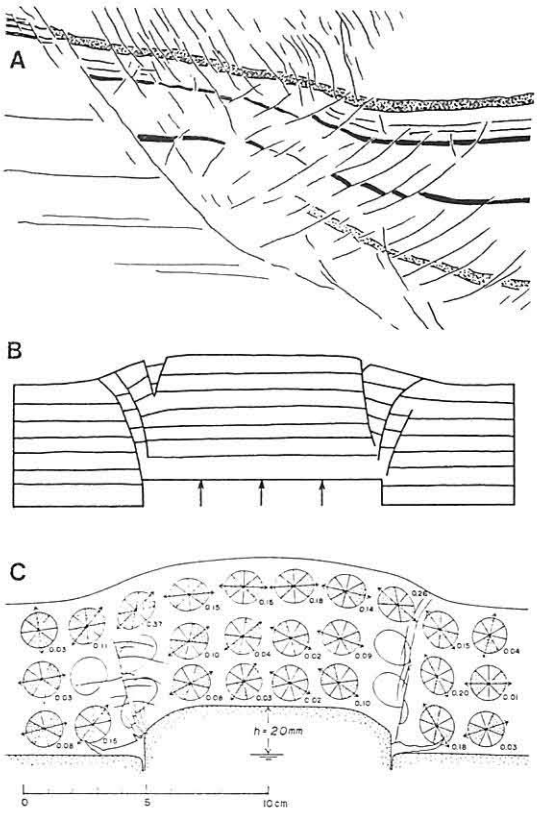
Faults on the summit

From September to November 1977, the new fault system in the atrio was able to be best observed (Text-fig. 5-5 & 6). Then however, these faults have been partially destroyed due to opening of the second stage craters, and obscured by covering of ash as well as subsequent erosion. During the early stage of the movement several normal faults dipping south were formed on the southern side of the Usu-Shinzan fault (Text-fig. 5-3). These faults are regarded as synthetic faults (Cloos, 1936). After August 12, 1977, however, no more synthetic faults have been produced, and in turn many normal faults dipping north have developed here. The ground surface of each block bounded by these normal faults tilted to the south, which indicates that these fault planes developed concavely under the ground (Text-figs. 5-4 & 5 and 7-1). Accordingly, these faults are identified as antithetic faults of Cloos (1936) (Text-fig. 16).

Cloos's (1936) experiments showed that antithetic faults are formed by the necking of a clay layer simulating the earth's crust which receives horizontal extension (Text-fig. 17-A). On the contrary, experiments and numerical analyses by Sanford (1959) and Kodama et al. (1974) showed that reverse faults are produed in front of a vertical rising block, where the horizontal compressive stress excels (Text-fig. 17-B & C). Therefore, it is considered that the displacement vectors of the Usu-Shinzan fault had



Text-fig. 16 Schematic diagrams showing development of synthetic faults (top) and antithetic faults (bottom) on the summit of Usu Volcano. The antithetic faults began to form after August 10, 1977. Note the large horizontal component of displacement vector of Usu-Shinzan.

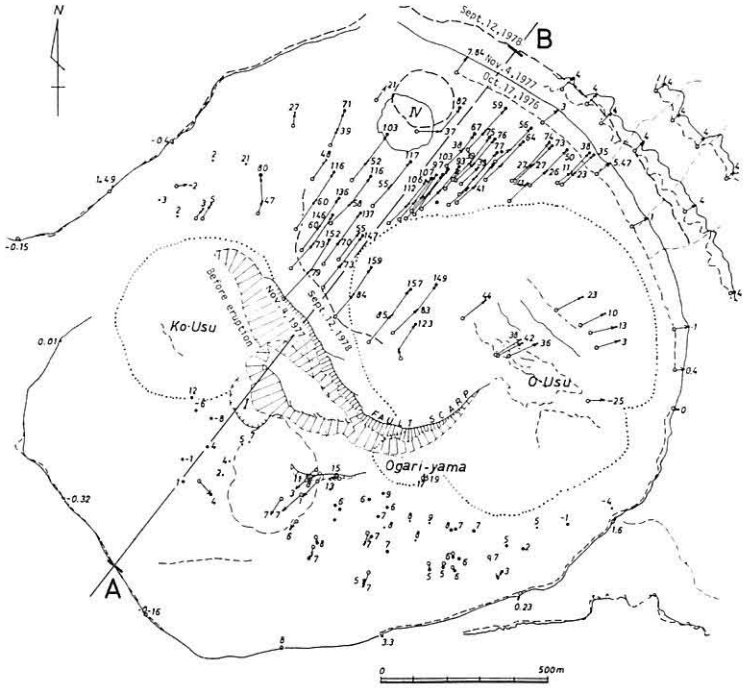


Text-fig. 17 Model experiments on horizontal extension and vertical uplift.
A: Antithetic faults produced by horizontal extension (simplified from Cloos, 1936).
B: Fault patterns produced by vertical rising of a rigid block (Sanford, 1959).
C: Strain distribution in a moist clay layer produced by a vertical raising rigid block (Kodama et al., 1974). Arrows show maximum extensile principal strains. No reverse faults are produced in the Cloos's experiment. On the other hand, in the latter two cases, horizontal contractile strain and reverse faults are formed at the surface in front of the uplifting block.

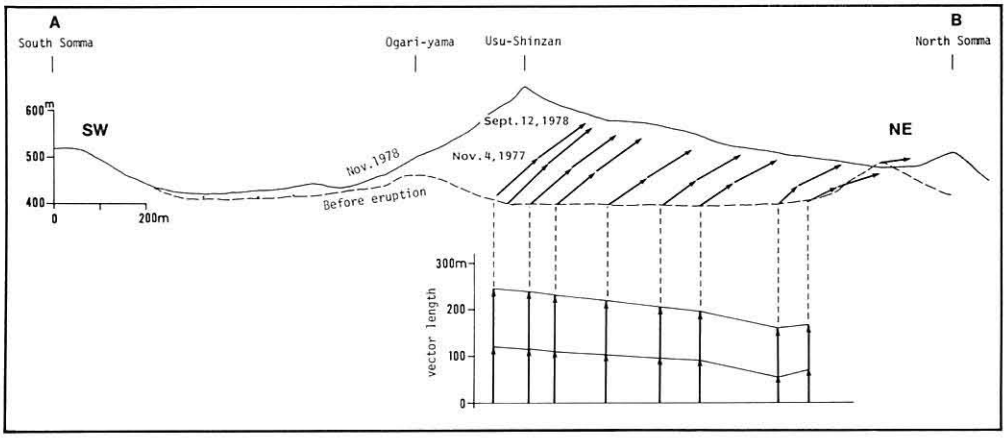
large horizontal components because no reverse faults were formed in front of this main fault. This anticipation can be confirmed by tracing of the displacement of many specified points in the atrio. Text-fig. 18 shows the displacement vectors in the atrio during the period from the beginning of activity to September 12, 1978, which were obtained from new contour maps and migration of the same trees identified on airphotos taken in this period (Tanaka, 1979). Elevation angles of the displacement vectors attain about 40° at the Usu-Shinzan fault, whereas they are almost horizontal at the northern part of the somma (Text-fig. 19).

Faults on the foot

The new faults on the foot of Usu Volcano show a radial arrangement (Text-fig. 11), but their distribution is restricted to the northern area of Usu Volcano. Yokoyama et al. (1973) and Katsui et al. (1978a) noted that the sites of all of the historic eruptions and ground deformations are also confined to the northern half area of the volcano. This evidence can be well interpreted based on the structure of Usu Volcano that is not symmetric north to south, because this volcano has been built on the southern wall of the Toya Caldera. The northern half of the volcanic edifice is situated on the steep wall inside of the caldera, whereas the southern half rests on the gentle slope outside of the



Text-fig. 18 Map showing displacement vectors of ground deformation in the summit area of Usu Volcano (after Tanaka, 1979). Figures are vertical displacement in meter.



Text-fig. 19 Cross section A-B showing the displacement vectors (cfr. Text-fig. 18). At the Usu-Shinzan fault, the elevation angles of the vectors attained about 40° before November 4, 1977, but subsequently they became slightly gentle. Note the nearly same vector length after November 4, 1977.

caldera.

Along the western border of Toyako Spa, there is a boundary between the Tertiary

basement rocks of the caldera wall and the volcanic edifice of Usu (Text-fig. 2), and many left-handed strike-slip faults are observed (Text-fig. 14). On the contrary, right-handed strike-slip faults are predominant on the eastern foot of the volcano (Text-fig. 13). A considerable amount of simple shear stress must have been produced due to maga intrusion between the rigid caldera wall and the radially inflating volcanic edifice causing these strike-slip movements.

Stress analysis by means of F8 and F12 faults in Toyako Spa indicates that the maximum tensile stress is horizontal NNE-SSW (Text-fig. 11). The faults F24 to F32 which destroyed apartment houses are located to the SSW from this point, and seem to have formed on the top of a landslide. The direction of the landslide is NNE which coincides with that of the maximum tensile stress. Therefore, it is inferred that the driving force of the fault system in Toyako Spa is composed of left-handed movements and associated landslide movements toward NNE. The faults F1 and F24 to F32 are larger than others in Toyako Spa. The site of these larger faults almost coincides with that of the 1910 faults (Omori, 1911; "a" and "b" in Text-fig. 1).

The Kitabyobu-yama fault may not be connected with the Usu-Shinzan fault because their senses are different from each other, but it may be related to F1 fault because of their similar strike and sense.

The movement of the Higashi-maruyama fault agrees with that of the U-shaped fault block. Dislocation of the right-handed strike-slip faults in the Sobetsu spa area also coincides with the movement of the fault block. It is noticed that these faults were formed in the same zone of the 1910 faults (Omori, 1911; "g" in Text-fig. 1).

Variation of fault activity with time

The growth rate of the Usu-Shinzan cryptodome was maximum in August 1977 and decreased exponentially with time, but increased temporarily in January-February 1978 (Yokoyama et al., 1981). Yokoyama and Seino (1979) interpreted this event as due to the energy supply because the seismic energy discharge followed the same pattern.

As previously noted, the fault activity on the foot of the volcano began in the eastern part, then the region of increased fault activity migrated with time counterclockwise to the northwest foot. The cracks related to the F1 fault movement in the northwest foot accelerated in displacement rate after February 1978 (Text-fig. 15). Such change of fault activity with time on the northern foot, may be associated with changes in the direction of displacement vector on the summit as well as with the above temporal increase of energy supply (magma intrusion). During the observation from September to December 1977, the displacement vector at Usu-Shinzan and Ogari-yama changed in rising angle from 50° to 30° and in direction from N60°E to N20°E (Niida et al., 1978). After January 1978, the direction of displacement vectors at the north somma changed from northeast to north (Umehara et al., 1982).

Emplacement of magma inferred from seismic evidence

According to Okada et al. (1981), the earthquake hypocenters under Usu Volcano showed an elliptic distribution with a NW long axis of 800 m in length. The earthquake

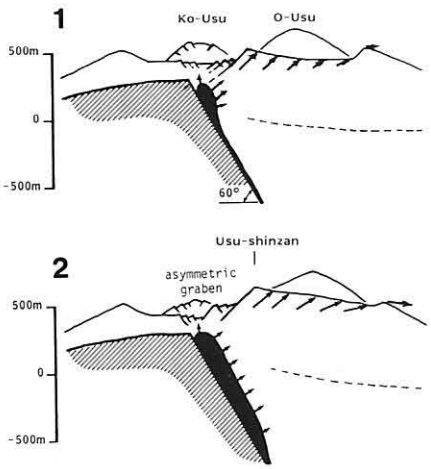
mechanism was mostly the normal dip-slip type except for the earthquake swarms of the reverse dip-slip type which occurred under Ko-Usu domes. The distribution of the earthquake foci was deeper toward northeast, forming a zone dipping about 60° NE. The compressive principal stress axes were NE upward. Configuration of the earthquake foci showed an earthquake-free zone at the central part of the foci zone. Reduced travel time anomalies were observed across the earthquake-free zone, and indicate that this earthquake-free zone may be filled with a magma (Moriya and Okada, 1980). Harada (1981) stated that the magma intruded along the Toya caldera wall which was assumed to dip 60°NE, because the earthquake zone inclined toward NE under Usu Volcano and the compressive principal axes were NE upward.

Intrusion of the dacite magma of high viscosity along the wall possibly pushed the volcanic body normal to the rigid caldera wall. Displacement vectors of the U-shaped block are consistent with this movement, because the maximum elevation angle is about 40° (Text-fig. 19), that is nearly equivalent to the complementary angle to the estimated dip of the caldera wall.

Intrusion process of magma

As shown in Text-fig. 19, the displacement vector lengths were markedly longer at Usu-Shinzan than in the northern somma until November 4, 1977, but, subsequently they became almost the same. This evidence indicates that the area of ground deformation expanded in the latter period, though the displacement rate was retarded.

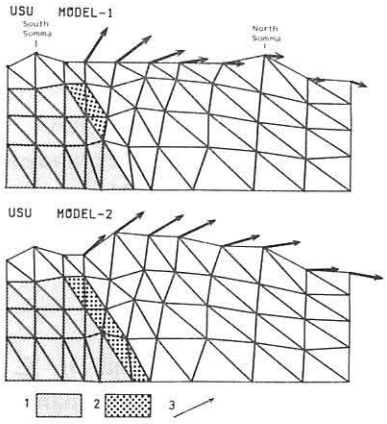
It is likely that in the early stage, the size of the magma column intruded along the caldera wall was relatively small. Expanding of the magma column pushed the volcanic edifice normal to the rigid caldera wall to form synthetic faults. This was followed by development of antithetic faults due to successive magma supply (Text-fig. 20-1). Then, the ground deformation area was enlarged especially at the time of the acceleration of magma intrusion in early 1978. This evidence may be accounted for by assuming a model of expanding of the lower part of the magma column (Text-fig. 20-2),



Text-fig. 20 Schematic profiles of magma intrusion.
1: August 7 to November 1977. A dacite magma intruded along the Toya cladera wall dipping 60° NE. The expanding magma body pushed the volcanic edifice normal to the rigid caldera wall to form synthetic faults. Then, antithetic faults developed on the SW side of the main fault.
2: after November 1977. Magma intrusion continued decreasing in rate with time, but temporarily increased in January-February 1978, and the magma body expanded possibly at the lower part as well as the upper part. The expansion of the magma body may be responsible for the change of displacement vectors as shown in Text-fig. 19.

though the apex of the column was possibly still ascending in this stage (Niida et al., 1980; Okada et al., 1981).

On the basis of the boundary conditions provided from the above considerations, elastic analyses of the present ground deformation of Usu Volcano were performed in terms of the finite element method. The analytical results of Model-1 (Text-fig. 21) coincide well with the configuration of displacement vector before November 4, 1977 (Text-fig. 19). Similarly, those of Model-2 (Tex-fig. 21) represent the subsequent stage and agree well with the displacement vector after November 4, 1977 (Text-fig. 19).



Text-fig. 21 Plane-stress elastic analyses by finite element method based on the schematic models of Text-fit. 20. Model-1 represents the crustal movement until November 1977, and model-2 that after November 1977 until September 1978. Both periods correspond to those of Text-fig. 19. Compare the displacement vectors of this figure with those of Text-fig. 19. Boundary forces are caused by increasing pressure along the boundary of the intrusive magma. Boundary conditions along the left side and the bottom of models are fixed. Vectors show relative length to the maximum vector. Young's modulus ratio between basement rocks and volcanic edifice = 10^3, Poisson's ratio = 0.25.
1: basement Tertiary rocks of the caldera wall, 2: intrusive magma, and 3: displacement vector.

The expanding of the magma column can be ascribed either to successive intrusion of new magma from deeper sources or to the gradual bubble growth in the magma which had been isolated from the deeper sources. The latter process is a possible cause especially for the long-lived activity more than 4 years, as recently discussed by Watanabe (1984). However, it must be taken into consideration that the ground deformation and seismicity increased temporarily in January-February 1978. This event as well as the activity of the early stage may be better explained by the former process than the latter one.

Concluding Remarks

During the 1977-1978 eruption of dacite pumice and ash and following activity until spring 1982, Usu volcano has produced Usu-Shinzan cryptodome, uplifted about 180 m on the summit. A number of faults have been developed associated with the growth of Usu-Shinzan, but their development was restricted to the northern half area of the volcano, possibly being controlled by the structure of the southern wall of Toya Caldera which is overlain by the volcano.

In the summit area, synthetic faults appeared first, then antithetic faults were formed, which resulted in development of an asymmetirc graben. The main fault

coupled with hinge faults grew up to form a U-shaped fault block.

Due to NE upward movement of the U-shaped block, the northern part of the volcano was considerably deformed. Thus the north somma was cut by many strike-slip faults, and on the northern foot a number of strike-slip faults showing radial arrangement have been developed. Left-handed strike-slp faults are prevalent in the NW foot, whereas right-handed ones predominate in the NE foot. Re-activation of some of the 1910 faults were observed in both areas, which is possibly ascribed to the underground structure as above mentioned.

Development of these faults may be interpreted by means of the dacite magma intrusion along the steep southern wall of Toya caldera under the volcano. Ascending and expanding of the magma column pushed the volcanic edifice normal to the rigid caldera wall and provided displacement vectors having large horizontal components to form the synthetic and antithetic faults above the magma column. On the contrary, to the northern foot a radial strike-slip fault system was formed due to compression.

Changes of the fault activity with time suggest that the magma column expanded not only at the upper part, but also notably inflated at the lower part after Nomveber 1977. This was tested, with satisfactory results, by means of plane-stress elastic analyses by finite element method based on the model above mentioned.

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