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Across-Arc Mineralogical and Geochemical Variations in Kirishima Volcano Group and its Implication in the Genesis of the Volcanism of the Ryukyu Arc (I)

By

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Abstract: Kirishima Volcano Group (KVG) lies at the northern end of the Ryukyu arc that extends discontinuously in a NNE direction from northern Taiwan to Kyushu Island of Japan. Within the KVG, three active stages are recognized on the basis of field geology and tephrochronology. The third stage volcanoes, the subject of this paper, comprises thirteen youngest volcanoes(< 18,000 years) and were erupted from a series of vents aligned NW-SE direction. The arrangement direction is oblique to the volcanic front of the arc and is parallel to the proceeding direction of the Philippine Sea plate.

In basalts or basaltic inclusions, olivine crystallization is followed either by plagioclase(the plagioclase basalt suites of Morrice and Gill(1986) : PBS) or augite(the augite basalt suites : ABS). PBS occur at the volcanic front side of the KVG and evolve to quartz-bearing pyroxene andesite. ABS occur behind the front side and evolve to hornblende-bearing pyroxene andesite, and have higher Al^{IV} contents in calcic pyroxene. All tholeiitic lavas and ejecta are confined to the low K_2O volcanic products near the volcanic front, while calc-alkaline materials are erupted more randomly. Regardless of their rocks series , the eruptive products near the volcanic front have low incompatible elements concentrations(average $K_{60}=1.7$) and low K_2O/Na_2O ratios. In contrast to this, the lavas behind the volcanic front have high incompatible elements concentrations(av. $K_{60}=2.25$), high K_2O/Na_2O ratio and higher modal clinopyroxene /plagioclase ratios. These results have clarified the lateral variations of magma compositions of the KVG, in which silica activity decreases, and incompatible elements and water contents increase away from the front. These variations are well correlated with the depth of Wadati-Benioff zone beneath the KVG, the depth of which abruptly changes from 110 to 170 km away from the front. Based on these facts, it is concluded that the lateral variations of the KVG in geochemistry represent the across-arc geochemical variations of the Ryukyu volcanic arc. Moreover, comparison of K_2O/Na_2O ratios in lavas from the KVG and N-type MORBs indicates that the above lateral variations are probably caused by the lateral heterogeneity of the mantle wedge beneath the KVG.

CONTENTS

I. Introduction

The Ryukyu arc shows a double arc structure, which is composed of one trench, one outer arc (presently non-volcanic), and one inner arc(presently volcanic) in the order arranged away from the ocean. Kirishima Volcano Group lies at the northern end of the Ryukyu arc that extends in a NNE direction from northern Taiwan to Kyushu Island (Fig.1). The Ryukyu arc has recently received considerable attention of earth scientists owing to the presence of the Okinawa Trough which is considered to be

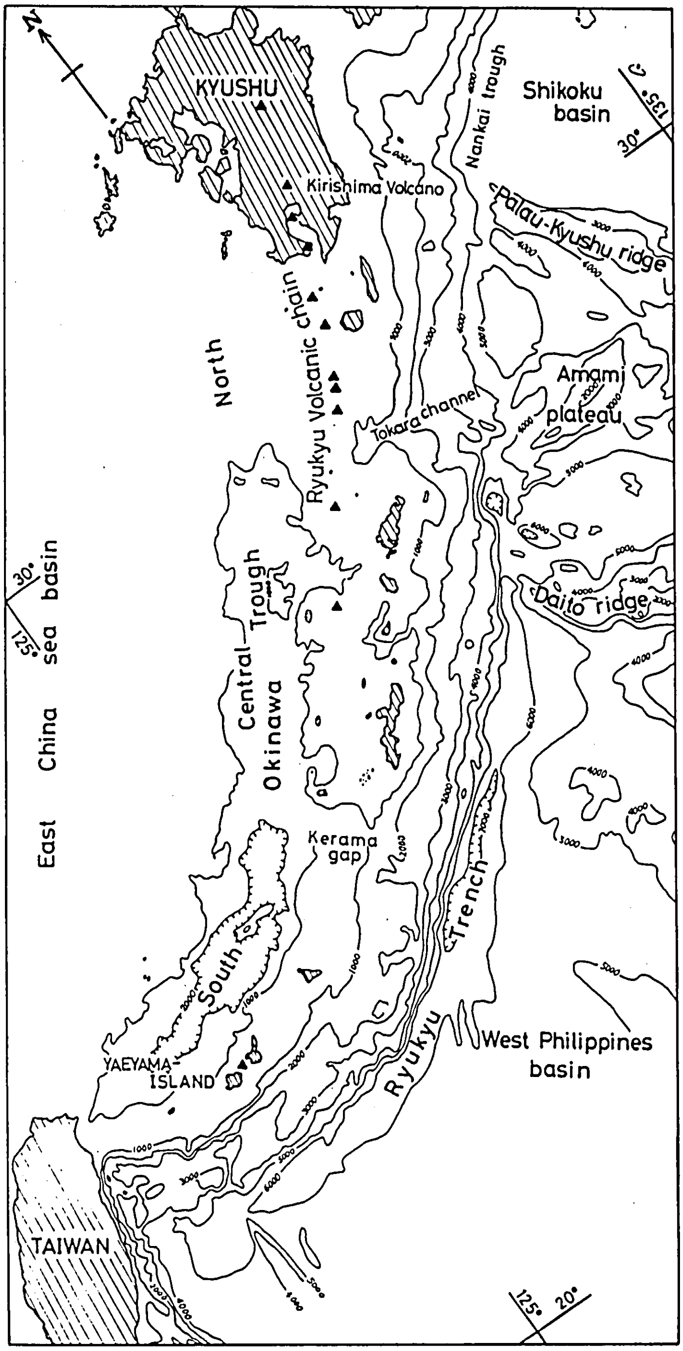

Fig. 1. Map of the Ryukyu arc region showing the position of the trench, the present-day active volcanoes( ) and the Okinawa Trough. Bathymetry is cited from Mammericks et al.(1976).

a back-arc basin of young stage developed along the Asian continental margin. Letouzey and Kimura(1986) and Sibuet et al.(1987) have pointed out that crustal separation and active spreading along the Okinawa Trough occur associating back arc volcanism. The Okinawa Trough is characterized by the development of en échelon depressions with elongated basaltic ridges of left hand(Kimura, 1983).

The volcanic activity along the Ryukyu arc occurs in the tectonic position located between the non-volcanic island arc and the deep Okinawa Trough (Fig.1). The distribution of active volcanoes in the tectonic position is not uniform along the Ryukyu arc. Most of these active volcanoes are in Kyushu and along the northern Okinawa Trough where the continental rifting is occurring in initial stage. The sizes of the active volcanoes decrease considerably from Kyushu Island to the latitude of Iwo-Torishima Volcano, associating that the arc volcanism terminates near the Iwo-Torishima area where Iwo-Torishima Volcano is placed. Only back arc volcanism, which is related to the spreading of the Okinawa Trough, exists in the area on the south of Iwo-Torishima Volcano, except one historical submarine eruption in the vicinity of Yaeyama islands which is placed at the southern end of the Ryukyu arc (Kato, 1982). Thus, the volcanism of the Ryukyu arc is explained in term of an alternation of arc volcanism and back arc volcanism, as previously remarked on by Honza(1983).

Recent trace elements studies on arc magmas erupted in the Ryukyu volcanic arc indicated that these magmas were generated from mantle sources metasomatically enriched in incompatible elements(Ujike et al., 1986; Nakada,1986), suggesting that volcanism of the Ryukyu volcanic arc is apparently correlated to the subducting slab(Philippine Sea plate). Sibuet et al.(1987) proposed that two types of volcanic activity such as arc volcanism and back arc volcanism might result from the slight difference in depth to the subducting slab, because it had been considered that the depth of the Wadati-Benioff zone increase from 80-120 km below the volcanic arc to 100-175 km below the back arc basin (Eguchi and Uyeda, 1983). However, Shiono et al.(1980) and Imagawa et al.(1985) revealed that the subducted slab penetrates down to the depth greater than 170 km beneath the Kirishima and Aso volcanic centers. From this fact it seems likely that there is little difference in the depth of the Wadati-Benioff zone beneath the both sites of volcanic activity. It has to be said that there still remains the question concerning how the difference in morphology between the arc volcanism and the back arc volcanism has occurred.

Spatial variations in the geochemistry and crystallization sequences of erupted lavas along the volcanic front of the Ryukyu arc have been recognized(Kobayashi, 1982 ; Aramaki and Ui, 1983 ; Nakada, 1986). For example, incompatible elements such as K, Rb, Sr increases from south to north along the volcanic front. Such spatial variations have been considered to be attributed to several factors as follows: (a) depths of magma genesis and degree of melting of a uniform source, (b) compositional variations of source rocks, (c) variation of volume of subducted continent-derived sediments, and (d) difference of role of continental crust played during fractional crystallization of magma. However, a clear distinction between the relative effects of these factors has not been yet clarified, because of a lack of the information as to across-arc variations in the petrography and geochemistry of the Ryukyu arc volcanic rocks.

The volcanoes in the Ryukyu volcanic arc form a single volcanic chain, so that it is difficult to demonstrate across-arc change of magma chemistry related to the subduction of the Philippine Sea plate. However, the Kirishima and Aso volcanic groups have a possibility that across-arc change of magma chemistry would be observed within themselves. Both volcano groups show across-arc wide distribution. The Philippine Sea plate is subducting with high angles(above 70°) beneath both volcano groups(Imagawa et al., 1985), and the depth of subducting slab beneath Kirishima Volcano Group varies from 100 km in the trench side to 170 km in the back arc side. Inoue(1985) has found in Kirishima Volcano Group that the K_2O content in volcanic rocks of fixed SiO_2 content gradually increases from the trench side towards the back arc side. These facts would give an important clue to clarify the across-arc features of magma chemistry related to subduction in the Ryukyu arc.

The primary aim of this paper is to provide a detailed geological and geochemical documentation of the volcanic products of Kirishima Volcano Group. Their geochemical characteristics represent an across-arc variation. The obtained results are available to understand geochemical characteristics for the other volcanoes of the Ryukyu volcanic arc, most of which lie at its volcanic front. On the basis of these comparisons, the magmagenetic and tectonic significance of the volcanic activity of the Ryukyu arc will be discussed.

II. Geological Outline of Kirishima Volcano Group

1. General statement

Kirishima Volcano Group(or KVG) is the name of a group of volcanic peaks which consist of more than 20 volcanic edifices, each of which is less than 3 km^3 in volume, and occupies an area of about 20X30 km elongated in the NW-SE direction. The bird's-eye view of KVG is strikingly similar to the moonscape. Judging from the results of Bouguer gravity anomaly, in the northern vicinity of the KVG there appear to be two Crater Lake type calderas, Kakuto and Kobayashi(Tajima and Aramaki, 1980). However, the genetic relation between these calderas and KVG is still ambiguous.

The volcanic activity of KVG began in the late Pleistocene and continues until now. Construction and destruction of volcanic edifices have repeatedly occurred. Most of them ceased their eruptive activity at present, though Sinmoe-dake and Ohachi Volcanoes have been active in historic times.

The volcanic activity of KVG can be divided into three stages on the basis of field geology and tephrochronology, first stage, second stage and third stage in ascending order. The first two stages are separated by the eruptive episode of the Kakuto pyroclastic flows(KPF), which is of late Pleistocene[ca., 0.1 Ma(Fukuoka, 1974; Nishimura and Miyachi, 1973,1976)] from the Kakuto caldera. On the other hand, the boundary between the second and third stage is shown by the long quieter period(Nakamura,1987). During this period of quiescence, a catastrophic eruption with large-scale pyroclastic flows (Ito pyroclastic flow deposit; 22.000 y.B.P.) occurred at the 50 km south of KVG being followed by the formation of caldera depression, so called Aira caldera(Matsumoto, 1943). KVG and its adjacent areas are covered by the Ito pyroclastic flow deposit(IPF) with great thickness.

The first two stages are described in detail in this chapter, while the third stage is briefly summarized, because its detail is described in Chapter III. A summary of the geologic history and simplified geological map of KVG are shown in Fig.2 and Fig.3, respectively.

2. Previous works

Besides the short descriptions of the explosive activities and the investigative reports of natural gas, only a few geological descriptions on the representative volcano of KVG are found among the literatures. The first paper on the geology of KVG had been published by Oda(1921), giving an outline of the geology of the volcanoes and petrographical description of some of their lavas. He also pointed out that the latest lava flow of Naka-dake Volcano, which is a member of KVG, is a product of the eruption in historic times.

Sawamura and Matsui(1957) performed the comprehensive study of the whole volcanoes of KVG, describing their general geology in more detail and chemical compositions of 18 lavas. They divided the history of the volcanic

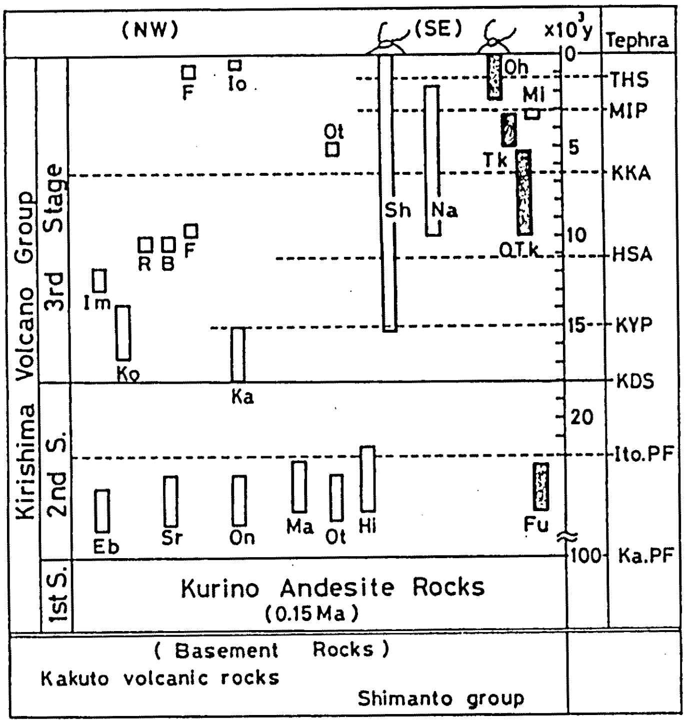

Fig. 2. Summary of the growth-history of Kirishima Volcano Group.

Eb: Ebino-dake, Sr: Shiratori-dake, On: Ohnamino-ike, Ma: Maruokayama, Ot: Ohhatayama, Hi: Hinamori-dake, Fu: Futagoish, Ka: Karakuni-dake, Ko: Koshiki-dake, Im: Iimoriyama, R: Rokkannon-miike, B: Byakushi-ike, F: Fudo-ike, Io: Iwo-yama, Sh: Shinmoe-dake, Na: Naka-dake, OTk: Old-Takachiho, Tk: Takachiho-no-mine, Oh: Ohachi, Ka.PF: Kakuto pyroclastic flow deposit, Ito: Ito pyroclastic flow deposit, KDS: Karakuni-dake scoria falls, KYP: Kobayashi pumice falls, STA: Satsuma tephra, K-Ah: Kikai-Akahoya, MIP: Miike pumice falls, THS: Takaharu scoria falls.

activity of KVG into three stages : Kurino andesite stage, Shiratori andesite stage and the stage of present volcanoes. The last stage was further subdivided into two groups with reference to the difference of the arrangement direction of volcanic centers : Karakuni group and Takachiho group. Afterwards this scheme of the growth-history of KVG has been accepted by most geologists. However, there are still many unsolved problems concerning in the growth-history of KVG. The most important one of them is that the growth-history of each volcanic center still remains an unknown. Moreover, the source of tephra distributed on the eastern foot of KVG is not determined at all. Therefore, the mutual relation among the volcanic centers of KVG has not been confirmed.

Sawamura and Matsui(1957) also pointed out that KVG is characterized by the association of Hypersthenic rock(H) series and Pigeonitic rock(P) series magma(Kuno,1950), and P-series lavas and ejecta are erupted only in southeast side of KVG while H-series materials are erupted more randomly. Kuno (1960) indicated the presence of high-alumina basalt in the rocks of KVG, which was described in term of P-series by Sawamura and Matsui(1957).

The first systematic petrological study on the volcanic rocks of KVG has performed by Shinno(1966) on the basis of chemical analyses of 15 lavas and 5 minerals. He divided the volcanic rocks of KVG into the following two groups according to the distinguishable relation between olivine and pyroxene : high aluminous rocks and calc-alkaline rocks. The high aluminous rocks are comparable with Kuno's high-alumina basalt. On the basis of the petrochemical and thermodynamic considerations, he concluded that the "high-alumina basalt magma" is not necessary to be primary magma.

After Sawamura and Matsui'(1957)s work, the study of the growth-history of KVG has long been suspended. In 1969, Endo and his colleagues group discussed the growth-history of KVG from the standpoint of tephrochronology, resulting in opinions a little different from the Sawamura and Matsui. An important result in their papers is that the stratigraphic relations among the volcanic centers of KVG has been confirmed to some extent using several air-fall tephra as useful key beds. However, the growth-history of each volcano of KVG still remains an unknown.

On the basis of detailed observations of crater walls of each volcano of KVG, Kobayashi (1979,1981) emphasized that alternations of densely and partially welded pyroclastic fall and/or flow deposits near the vents give a false impression that the lava flows are dominant, and proposed firstly the schematic cross section of a stratovolcano common in KVG. Base surge deposits derived from the Mi-ike maar (Fig.3) had first been reported by Kobayashi (1980). The sedimentary structures in the base surge deposits were described in detail by Kaneko et. al (1985,1986).

Recently, Nagaoka(1984),Okada(1985) and Nakamura(1987) have published the results of the tephrostratigraphical study of KVG, clarifying the ages of the second and third stages of volcanic activity of KVG from their stratigraphic positions settled with reference to time-marker beds such as Aso-4 pyroclastic flows and Ito pyroclastic flows, whose eruptive ages are already decided by another methods.

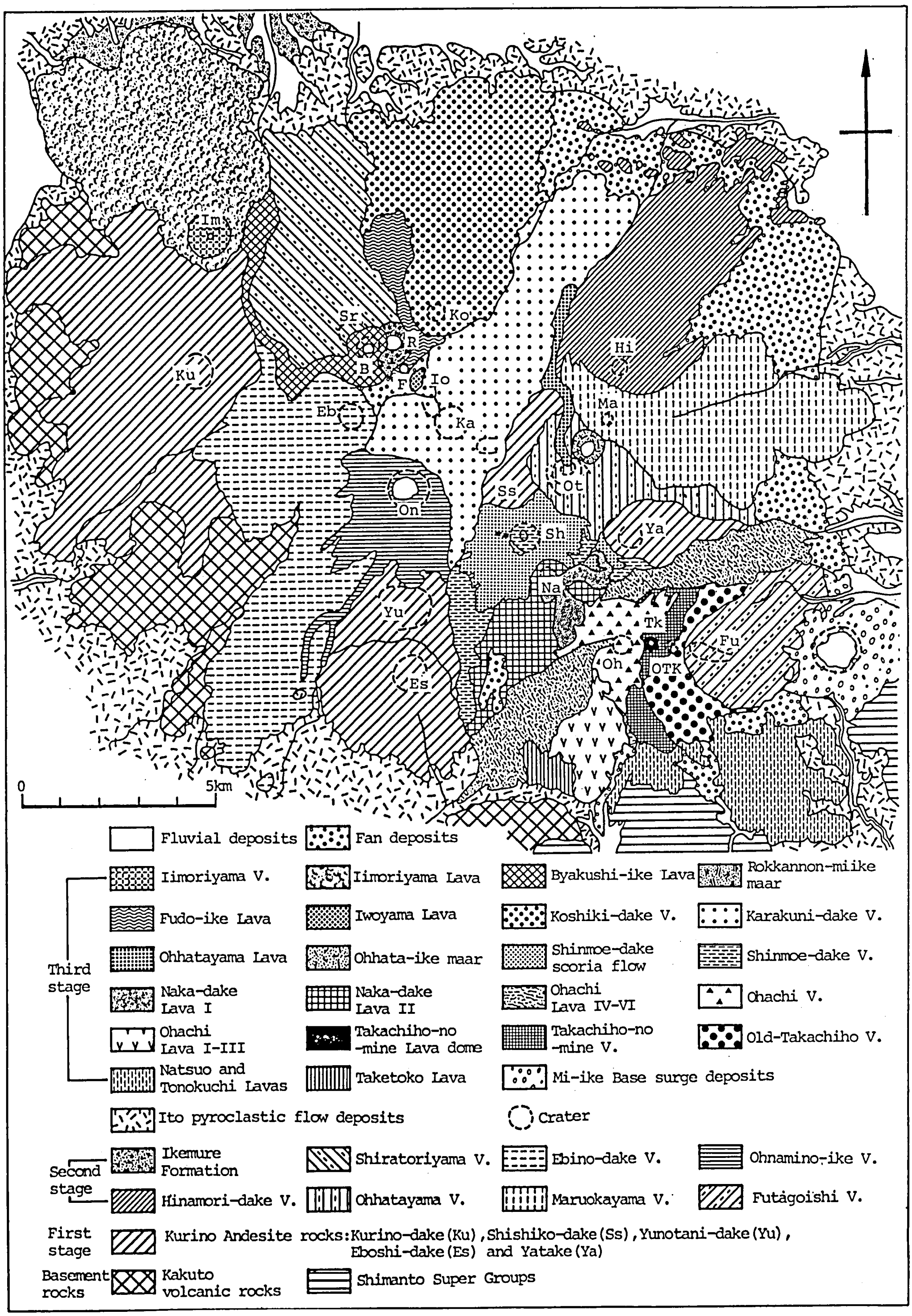

Fig. 3. Simplified geologic map of Kirishima Volcano Group.

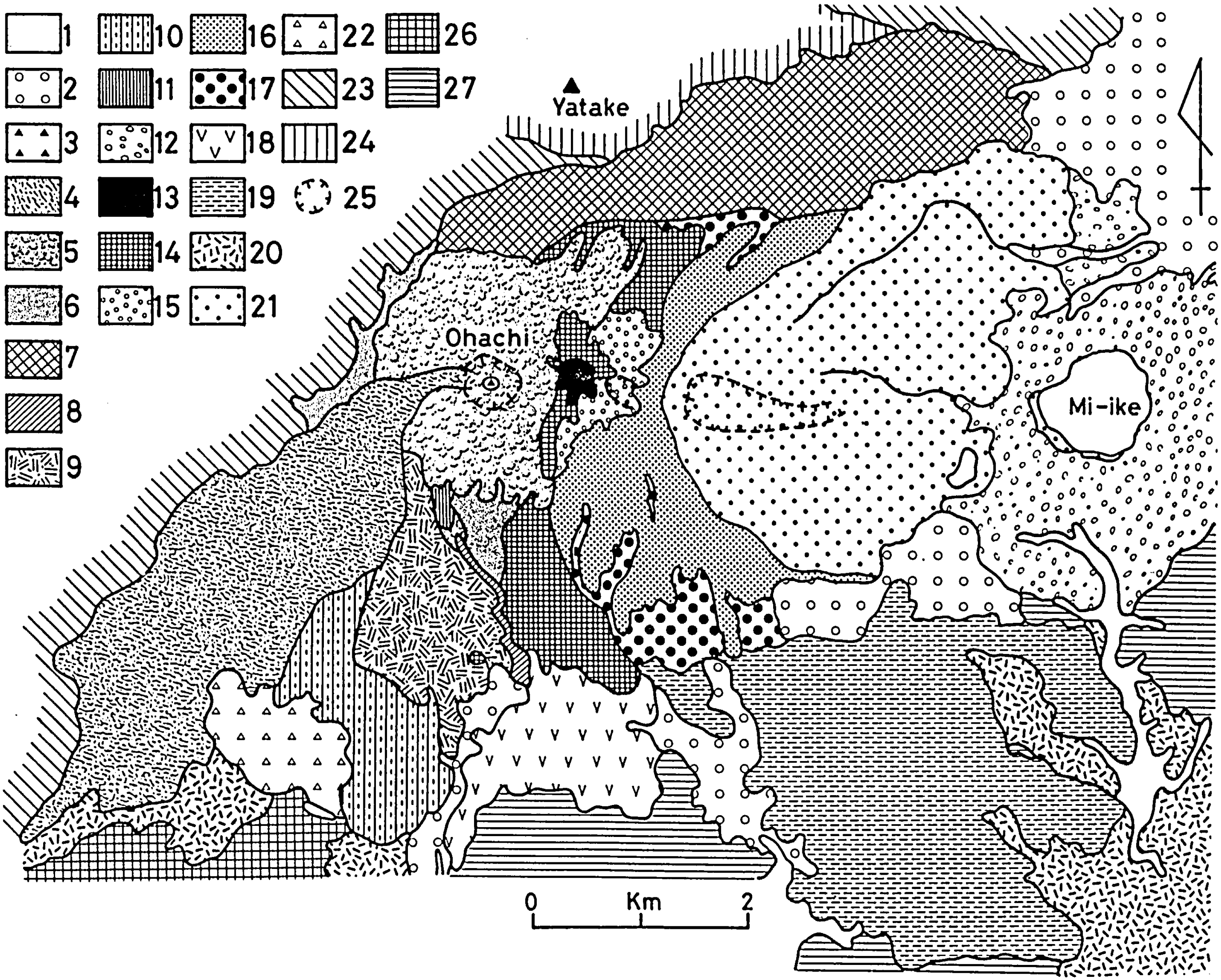

Fig. 4. Geological map of Takachiho Compound Volcano.

1, Alluvium; 2, Fan deposits; 3, Ohachi lava flow VIII; 4, Ohachi lava flow VII.VI; 5, Cone part of Ohachi Volcano; 6, Ohachi scoria flow deposit; 7, Ohachi lava flow V; 8, Ohachi lava flow IV; 9, Ohachi lava flow III; 10, Ohachi lava flow II; 11, Ohachi lava flow I; 12, Mi-ike base surge deposit; 13, Takachiho-no-mine lava flow II; 14, Takachiho-no-mine lava flow I; 15, Cone part of Takachiho-no-mine Volcano; 16, Old-Takachiho lava flow; 17, Cone part of Old-Takachiho Volcano; 18, Tonokuchi lava flow; 19, Natsuo lava flow; 20, Ito pyroclastic flow deposit; 21, Futagoishi Volcnao; 22, Taketoko lava flow; 23, Eruptive products of the third stage activity; 24, Eruptive products of the first stage activity; 25, crtater; 26, Kakuto volcanic rocks; 27, Shimanto Super Group:

3. Basement and first stage volcano group

The Basement rocks of KVG are the Shimanto Supergroup of Cretaceous to Paleogene age and the Kakuto Andesite group (Ota and Sawamura, 1971) of early to middle Pleistocene age. The former is composed of siltstone, sandstone, conglomerate, chert and minor basaltic rocks, and are exposed on the southeastern end of KVG. The latter crops out at the western and southern end of KVG.

The first stage volcano group which are older in age than the Kakuto pyroclastic flows (KPF) includes at least five volcanoes, Yunotani-dake, Shishiko-dake, Kurino-dake, Eboshi-dake and Yatake Volcanoes(Fig.2). Because each volcano rises separately, their stratigraphic relation has not been yet known. However, the former three volcanoes are so highly dissected in comparison with the latter two ones, that the former seems to be older in age than the latter.

Yunotani-dake Volcano lies in the southern part of KVG and Shishiko-dake Volcano in the central part. The former is composed of andesite lava flows and the latter consists of an alternation of andesite lava flows and pyroclastic materials. The bodies of these two volcanoes are highly dissected and have undergone intense hydrothermal alternation, showing that their primary forms as volcano are remarkably destroyed.

Kurino-dake Volcano, situated on the western end of KVG, is made up predominantly of andesite lava flows and overlies the Kakuto Andesite group. The volcano is of shield-like form with westward spreading slope. Its summit crater is enlarged by erosion and opens to the west. The rocks of the above mentioned volcanoes, except for Yunotani-dake Volcano consisting of hornblende andesite, are hypersthene-augite andesite with or without olivine phenocryst.

Eboshi-dake and Yatake Volcanoes are small stratovolcanoes and made up of an alternation of basalt lava flows and pyroclastic materials. Eboshi-dake Volcano with nearly conical shape rises near Yunotani-dake Volcano(Fig.3). Yatake Volcano is located on the eastern side of KVG and is surrounded with the second and third stage volcanoes, for instance, Ohachi and Sinmoe-dake, etc.(Fig.3). The topography of these two volcanoes are well-preserved in comparison with that of the other first stage volcanoes, although their summit craters are enlarged by erosion. The fact that, though the basalt lavas constituting these two volcanoes are so fluid, the volcanoes have steep outer slopes of angle ranging from 20° to 30°, indicates that pyroclastic materials are predominant in comparison with lava flows. The rocks of the volcanoes are augite-olivine basalt with or without hypersthene.

Although Yamasaki(1979) dated the volcanic rocks of the first stage by Fission track method to be 0.15 Ma, the starting age of volcanic activity of the first stage has not been known well.

4. Second stage volcano group

At least seven volcanoes were formed during this stage ; namely, Ebino-dake, Shiratori-yama, Ohhata-yama, Ohnamino-ike, Maruoka-yama, Hinamori-dake and Futagoishi Volcanoes(Fig.2 and 3). Judging from the degree of dissection of the volcanic body, the former three volcanoes seem to be older than the others. The activity of the second stage volcano group has began after the eruption of KPF(ca.0.1 Ma). But its starting age has not been still clarified. Recently Nagaoka (1984) has roughly estimated the eruptive age of the Aya pumice fall deposit(Nagaoka,1984), which is of the early time of the second stage, to be about 60,000 y.B.P. from its stratigraphic position settled with reference to the time-maker tephras such as Aso pyroclastic flow deposits(ca. 70,000 y.B.P.) and Ito pyroclastic flow deposits(22,000 y.B.P.). From this result it is concluded that the starting age of activity of the second stage volcano is older than 60,000 y.B.P.

Ebino-dake and Shiratori-yama Volcanoes lie on the eastern flank of Kurino-dake Volcano and are predominantly composed of andesite lava flows. Their shapes are characterized by a shield-like form with large summit crater, whose diameter is about 700 m in both volcanoes. The craters are subjected to erosion to some extent, but their circular outlines are well-preserved. These craters are greatly different in preservation degree from the summit craters of stratovolcanoes with conical form such as Hinamori-dake and Futagoishi Volcanoes. The latter is partially destroyed by erosion showing poorly preserved circular outlines. The difference of preservation degree of the craters may be related to that in materials between the volcanic edifices. As will be discussed in Chapter III, Hinamori-dake and Futagoishi Volcanoes are stratovolcanoes rich in loose pyroclastic materials, whose crater walls consist of accumulations of the coarse- to fine-grained pyroclastic materials with little resistance to erosion. While the crater walls of Ebino-dake and Shiratori-yama Volcanoes are composed of the piles of lava flows. The southeastern half of the summit crater of Shiratori-yama Volcano is buried by volcanic materials erupted from the Byakushi-ike pit crater which are younger in generation age than the Ito pyroclastic flow deposits(Fig. 3). The rocks of the above two volcanoes are hypersthene-augite andesite with or without olivine phenocryst.

Ohnamino-ike Volcano situated on the southeastern slope of Ebino-dake Volcano is made up essentially of an alternation of densely welded pyroclastic and non-welded pyroclastic materials. The distribution of lava flows and welded pyroclastic flow deposits is restricted to the southern foot of the volcano. The shape of the volcano is a short stubby cone with a large top crater, most part of which constructs a crater lake. The crater is 1,150m in diameter and is surrounded by steep walls of less than 170m in relative height. The rigid rocks exposed on the crater wall are welded pyroclastic rocks which have previously been thought to be lava flows. These welded pyroclastic rocks represent the deposits produced near the vent, where the ejected essential materials were so hot that they welded together to form massive aggregate before and during cooling. The rocks of the volcano are hypersthene-augite andesite with or without olivine phenocryst.

The stratigraphic relationships between Ohnamino-ike Volcano and IPF have not been so far confirmed, because the degree of dissection of the volcano is less than that of Karakuni-dake Volcano which is younger in generation age than IPF. However, recently Okada and Yokoyama (1982) discovered IPF within the crater of Ohnamino-ike Volcano. Therefore it became clear that Ohnamino-ike Volcano is older in generation age than IPF. The Iwaokoshi pumice fall (Okada,1985; Nakamura,1987), which is a product of plinian eruptions and widely dispersed to the northeast direction of KVG(Nagaoka,1984), is a air-fall tephra which is assumed to have been derived from Ohnamino-ike Volcano. Nagaoka(1984) has roughly estimated the eruption age of the Iwaokoshi pumice fall to be ca. 40,000 to 30,000y.B.P. by the use of the time-maker tephra such as Aso pyroclastic flow deposits(APF) and IPF.

Ohhata-yama, Maruoka-yama and Hinamori-dake Volcanoes situated in the northeastern side of KVG(Fig.3) are small stratovolcanoes, are partly overlapping and arranged from southwest to northeast.

Ohhata-yama Volcano is a double stratovolcano which is characterized by the presence of double summit craters, inner and outer crater, and is made up of scoriaceous pyroclastic materials and minor lava flows. The body of the volcano is so highly dissected and modified by the formation of Ohhata-ike explosion crater, that it is impossible to restore its primary form as a volcano. Indeed, the northern and southern parts of the outer crater are completely destroyed. The diameter of the outer crater, which is restored by extrapolating its remnant parts to form a circular shape, amounts to ca. 1,100m. Its size is as large as that of the craters of the other stratovolcanoes and is equivalent to that of the Ohnamino-ike and Karakuni-dake craters and of the Mi-ike maar. Large-scale eruptions(or plinian eruption) appear to have been responsible for the formation of a large crater such as the Ohnamino-ike and Karakuni-dake craters and Mi-ike maar. Judging from this fact, there is a large possibility that eruption of voluminous scoria or pumice falls took also place at the later stage of the activity of Ohhata-yama Volcano, although no scoria or pumice falls derived from the volcano has been found in the piles of air-fall ejecta covering the eastern foot of KVG. On the other hand, the inner crater, whose diameter is ca. 500m in average, is an ellipse in shape and the degree of dissection of it is less than that of the outer crater. There exist three small craters within the inner crater and one of them has effused lava flow to the northern flank of the volcano. The rocks of the volcano are two pyroxene andesite.

Hinamori-dake Volcano with nearly conical shape is made up predominantly of scoriaceous pyroclastic materials and a small amount lava flows. Most of the lava flows was extruded to form a lava plateau of small size at the northern foot of the volcano. The lava plateau is directly covered by the pumice fall deposit which immediately underlies IPF in many places(Sawamura and Matsui,1957). Therefore, the starting age of activity of the volcano is considered to be apparently older than the eruptive episode of IPF.

The summit crater of Hinamori-dake Volcano is enlarged by erosion and opens toward the east, and its body is also highly dissected, showing that considerable parts of its foot are occupied with volcanic fans composed of volcanic detritus. The rocks of the volcano are olivine basalt and two pyroxene andesite with olivine phenocryst.

Of many air-fall tephra layers overlain by IPF on the eastern foot of KVG, ten air-fall tephra sheets including the Aya pumice falls and Iwaokoshi pumice falls are thought to be of KVG origin (Nagaoka,1984; Nakamura,1987). The sources of those air-fall tephra layers, except for the Iwaokoshi pumice falls, have not been precisely confirmed still now. However, the Awaokoshi scoria falls, which are underlain by the Iwaokoshi pumice falls with some intervening weathered ash deposits, are guessed to have been derived from Hinamori-dake Volcano (Endo et al.,1969; Nakamura,1987). The scoria falls have roughly been estimated by Nagaoka(1984) to be 40,000-30,000y.B.P. and its total volume has been roughly estimated by Nakamura(1987) to be about 5.0 km^3. It is the largest one of all plinian deposits of KVG.

Maruoka-yama Volcano is also a double stratovolcano and its summit part is occupied by the lava dome consisting of glassy two pyroxene andesite. Sawamura and Matsui(1957) considered that the volcano is older in generation age than the Hinamori-dake volcano. However, the topographic relationship between these two volcanoes show that the eruptive products of Maruoka-yama Volcano covers the foot of Hinamori-dake Volcano. Therefore, it seems probable that the former is younger in generation than the latter, like Okada(1985)' opinion.

Futagoishi Volcano situated on the southeastern end of KVG(Fig.3) rises steeply from the flat ground. Although the western half of the volcano is buried beneath Old-Takachiho volcano which belongs to the third stage volcano group, its shape is apparently conical associating a summit crater. The summit crater is enlarged by erosion and opens toward the east. The rocks of the volcano are olivine-hypersthene andesite and augite-hypersthene andesite. The stratigraphic relationship between Futagoishi Volcano and IPF has been only poorly known up to the present. However, recently Inoue(1988) pointed out that the majority of eruptive activity of Futagoishi Volcano terminated before the eruption of IPF, based on the tephrochronological fact that the air-fall ejecta from Futagoishi Volcano is not found in the piles of air-fall ejecta overlying IPF on the eastern foot of KVG.

On the other hand, the Nojiri scoria falls(Nakamura,1987) which are found in the piles of air-fall tephra layers underlying IPF and are overlain by the Iwaokoshi pumice falls with some intervening soil layer, are probably derived from the Futagoishi volcano. Nakamura(1987) has said that the source of the Nojiri scoria falls is probably Takachiho-no-mine Volcano, because their grain size and thickness increase toward the volcano. However, as Takachiho-no-mime Volcano, which is situated to the west of Futagoishi Volcano, is younger in generation age than IPF(Inoue,1988), the source of the Nojiri scoria should be ascribed to Futagoishi Volcano. The scoria fall is roughly dated to be 38,000y.B.P. with reference to the relations between the thickness of soil above the tephra and the weathering speed of the tephra(Nakamura,1987).

5. Third stage volcano group

Seven small polygenetic volcanoes and eight monogenetic ones have been formed during this stage, which are aligned from southeast to northwest as follow : Mi-ike, Old-Takachiho, Takachiho-no-mine, Ohachi, Naka-dake, Shinmoe-dake, Karakuni-dake, Ohhata-yama, Ohhata-ike, Iwo-yama, Fudo-ike, Rokkannon-miike, Byakushi-ike, Koshiki-dake and Iimori-yama(Fig.3).

The third stage of activity began with the plinian eruption of the Karakuni-dake scoria fall about 18,000 years ago(Imura and Kobayashi, 1987 ; Nakamura, 1987), after a repose of more than 10,000 years, and continues since then. The topography of these youngest volcanoes is well-preserved, showing that many kinds of volcanic landforms are distinguished among them : for instance, lava dome, maar, pit crater, scoria cone and stratovolcano etc. These volcanic edifices and eruptive centers are concentrated in a linear zone having NW-SE direction and this arrangement governs the elongated direction of KVG.

The third stage volcanoes group are divided into two groups, NW group and SE group(Fig.2), according to the difference of a main period of activity. The NW group consists of the following volcanic centers : Karakuni-dake, Iwo-yama, Fudo-ike, Byakushi-ike, Rokkannon-ike, Koshiki-dake and Iimori-yama. The SE group includes the following volcanic centers: Mi-ike, Old-Takachiho, Takachiho-no-mine, Ohachi, Naka-dake, Shinmoe-dake, Ohhata-yama and Ohhata-ike. The main active period of the NW group is older than 9,000 y.B.P. but probably younger than 20,000 y.B.P. On the other hand, the activity of the SE group began ca.10,000 years ago, except for Shinmoe-dake Volcano. The starting age of activity of Shinmoe-dade Volcano is older than the age of 13,000-14,000 y.B.P. Shinmoe-dake and Ohachi Volcanoes belonging to the SE group have been active in historic times.

The NW group is characterized by monogenetic craters and cones, and polygenetic pyroclastic cones with considerably short life span. The Rokkannon-miike, Byakushi-ike and Fudo-ike craters, which are either or and pit crater, are occupied by crater lake. Karakuni-dake Volcano, which rises in the central part of KVG, is polygenetic pyroclastic cone and its shape is well similar to that of Ohnamino-ike Volcano. The Kobayashi pumice falls dated to be around 13,000-14,000 y.B.P. is derived from Karakuni-dake Volcano. The rocks of the above described volcanoes are hypersthene-augite andesite and augite-olivine basalt.

On the other hand, the SE group is characterized by small stratovolcanoes. Naka-dake and Shinmoe-dake Volcanoes, which lie between Karakuni-dake and Ohachi Volcanoes, are lava volcanoes composed of lavas which flowed out from their top craters. The rocks of the above two volcanoes are two pyroxene andesite with or without olivine phenocryst.

Ohachi, Takachiho-no-mine and Old-Takachiho Volcanoes situated in the southeastern end of KVG are small stratovolcanoes composed of an alternation of pyroclastic materials and lava flows. They show a steeply conical form, though Ohachi Volcano is truncated by a top crater. These three volcanoes and Futagoishi Volcano are partly overlapping and aligned in E-W direction (Fig.3). The arrangement of these four volcanoes are ascribed to the westward migration of vent position. They have been collectively called Takachiho Compound Volcano(TCV) by Inoue(1988). The ejecta of TCV is the youngest one among the various deposits on the eastern foot of KVG. Therefore it is most widely developed and usually identified without difficulty. The rocks of TCV are quartz-augite-hypersthene andesite with or without olivine phenocryst and augite-olivine basalt with hypersthene phenocryst.

The Miike is a maar filled with water and situated on the eastern foot of Futagoishi Volcano. It is about 1 km across and was formed by a Plinian pumice eruption about 3,000 years ago(Kuwano et al., 1959). Base surge deposits interbeded with air-fall pumice near the source indicate phreatomagmatic nature of eruption(Kobayashi et al., 1981; Kaneko et al., 1985).

Vast amount of air-fall tephras erupted from the craters of KVG have been mainly accumulated on its eastern foot throughout the successive stages of volcanic activity. The air-fall tephras are freshly preserved and exposed on many cliffs and road cuttings over the whole area of KVG. Recently, many tephrochronological studies of KVG have been performed clarifying the growth history of KVG : a) No large-scale eruptions(or Plinian eruptions) took place in the period from 30,000 to 20,000y.B.P.(Nakamura,1987). This quieter period divids the third stage volcano activity from the second stage one. b) Judging from number of Plinian eruptions, the volcanic activity is considered to have been much more violent in the second stage than in the other stages (Nagaoka,1984; Nakamura,1987). And c) the air-fall tephras derived from TCV show that the styles of explosive activity had been gradually changed with time from vulcanian type of Old-Takachiho Volcano to sub-plinian one of Ohachi Volcano(Inoue, 1988).

III. Geology and Growth History of the Third Stage Volcano Group

1. General statement

As mentioned in Chap.2, the explosive activity of the third stage began ca.18.000 years ago and continues until now. During this period, volcanic centers of various kinds were formed in a narrow zone having NW-SE direction(Fig.3). Some of them are monogenetic volcanoes and the others are polygenetic ones. These volcanoes also display a complete spectrum of activity ranging from an emission of relatively fluid lava to catastrophic Plinian eruptions. Therefore, it can be said that the third stage volcano group is the interesting object of study to research the mutual relationships among the volcanic landform, the internal structure of volcanic edifice and the mode of eruption.

The third stage volcano group is divided into two group, NW group and SE group as mentioned in the preceding chapter. However, looking at its constituent volcanoes on the viewpoint of volcanic landform, they are further divided into the following four groups : Takachiho Compound Volcano, Naka-dake and Shinmoe-dake Volcanoes, Karakuni-dake Volcano and crowded monogenetic volcanoes situated on the northwestern side of Karakuni-dake Volcano. The geology, tephrostratigraphy and growth-history of those four groups are in details described in this chapter.

2. Takachiho Compound Volcano(TCV) and the Mi-ike maar

a. General statement

Takachiho Compound Volcano is situated at the southeastern part of Kirishima Volcano Group(Fig.3). As shown in Fig.4 and 5, the compound volcano consists of four volcanic edifices which are partly overlapping and arranged from east to west in the following order, Futagoishi, Old-Takachiho, Takachiho-no-mine and Ohachi Volcanoes. Futagoishi Volcano is the oldest one of them and belongs to the second stage volcano group. They become younger in age toward the west. The Mi-ike maar is situated on the eastern foot of Futagoishi Volcano and its activity took place in the repose-time between the activity of Takachiho-no-mine Volcano and Ohachi Volcano.

Fig. 5. Takachiho Compound Volcano with aligned three volcanoes seen from the northwest. The highest point(Takachiho-no-mine) in the central part of the volcanoes is 1,574 meters above sea level. The right side of the Takachiho-no-mine is Ohachi Volcano with a large top crater, and the left side is Futagoishi Volcano.

b. Futagoishi Volcano

Futagoishi Volcano lies in the eastern edge of the compound volcano and rises 1.321 meters out of the sea. The eastern foot of the volcano is widely covered with the base surge deposits interbeded with the air-fall pumice derived from the Mi-ike maar. The eastern slope of the volcano is cut by a broad and deep valley, which runs from its destroyed top crater to its eastern foot. On the other hand, the western half of the volcano is buried beneath Old-Takachiho Volcano. Thus the volcano dose not maintain its original landform at present. However, it is not so difficult to restore its original shape from remnant topography. The original shape, which is restored by extrapolating the contours of the remnant topography to form a symmetrical shape around the top crater, is a typical conical form and its estimated volume amounts to 2.38 km^3.

Sawamura and Matsui(1957) mentioned that Futagoishi Volcano is composed only of lava flows of olivine-pyroxene andesite and pyroxene andesite. Indeed, the author's detailed observation of its crater wall supports the fact that lava flows are predominant in the wall as compared with pyroclastic materials. However, Futagoishi Volcano is of a typical conical form and the inclination of the slope around the summit attains to 33°. From the fact that the cone-forming lava flows are commonly low viscous and the thickness of one flow unit is less than 5 m, it can be said that there are still problems in the conclusion about the internal structure of Futagoishi Volcano presented by Sawamura and Matsui.

c. Old-Takachiho Volcano

c-1. General statement

Old-Takachiho Volcano is situated on the western flank of Futagoishi Volcano and covers its western slope. The volcano is a small stratovolcano, rising 1450 m above sea level. The main cone of the volcano is asymmetric and not freely developed because of the older topography. The northwestern half of the volcano is buried beneath Takachiho-no-mine Volcano, so that the appearance of the Old-Takachiho is far from a typical conical form.

Sawamura and Matsui(1957) failed to find out Old-Takachiho Volcano, considering that Old-Takachiho and Takachiho-no-mine Volcanoes form a double stratovolcano, the former is a main volcanic body of the double stratovolcano and the latter is a secondary small body which was formed by filling up of older crater by massive lava and scoria. From the topographical, geological and tephrochronological evidences, however, Takachiho-no-mine Volcano is a apparently isolated small stratovolcano(Inoue,1988).

c-2. Natsuo lava flow

Before the construction of the main cone of Old-Takachiho Volcano, the Natsuo lava flow was extruded to the southeastern area of the volcano and filled up the depression of the basement which is developed at the southern foot of Futagoishi Volcano. Judging from the topographic feature, the Natsuo lava flow is divided into three flow units and forms a lava plateau of small size. These lava flows retain their fresh surface such as frontal and lateral scarps of lava flow, attaining more than 80 m thick at the terminal. The estimated volume of the lava flow is 0.46 km^3 and accounts for 25 percent of the whole volume for Old-Takachiho Volcano. These constituent rocks are quartz bearing augite-hypersthene andesite.

c-3. Shape and internal structure of the cone

The original shape of Old-Takachiho Volcano, which is restored by extrapolating the contours of the remnant topography to form a symmetrical shape around the top crater, shows a conical form with summit crater, diameter of which is about 250 m, and its estimated volume amounts to 1.98 km^3. As the most part of the summit crater is filled up

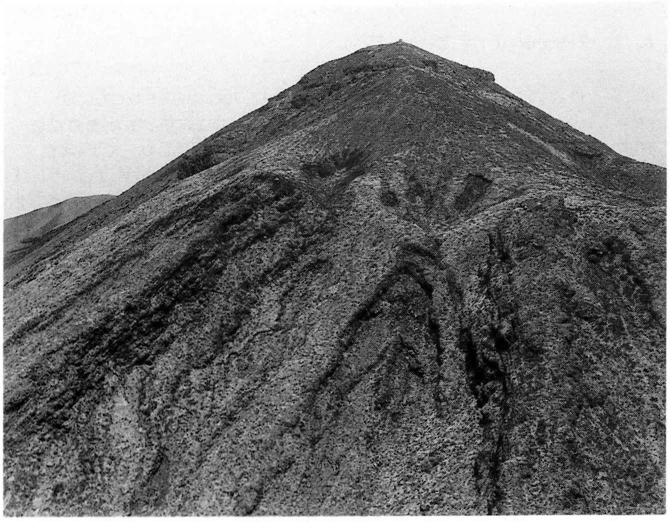

Fig. 6. Aerial view of Takachiho-no-mine Volcano and summit parts of Old-Takachiho Volcano. Looking from the southeast(Photo by T. Kobayashi, 1985). Note the accumulations of thin lavas (Old-Takachiho lava flows) which overflowed repeatedly from the top crater of Old-Takachiho Volcano.

with the black scoria and reddish brown agglutinate derived from Takachiho-no-mine Volcano, no crater wall exposes around there. However, as easily visualized from Fig.6, the effusion of thin lava flows repeatedly occurred from the top crater.

As no valley cuts enough deeply the slope of Old-Takachiho Volcano to let us see the inside of the volcanic edifice, the internal structure of the cone is a matter of conjecture. Detailed field-observations, however, are a still great means to assume the internal structure of the volcano. As shown in Fig.6, several thin lavas are superposed one on another forming a localized accumulation around the vent. On the lower slope are found a few lava flows alternated with layers of pyroclastic materials, suggesting that the main volcanic body has stratified structure. The pyroclastics materials are composed of sub-angular blocks and black volcanic ashes derived from densely solidified lavas. From these geological data, the internal structure of Old-Takachiho Volcano is illustrated in Fig.7(A) showing that Old-Takachiho Volcano is a stratovolcano composed of an alternation of lava flow layers and pyroclastics layers. It is also notable that all the pyroclastic materials are poor in vesicles and porous pyroclastics such as scoria are not found at all in them. On the other hands, the lava flow layers consist of a few flow units of dark andesite. As the distance from the vent decreases, the thickness of individual flow units decreases from 4 to 2 meters and, on the contrary, the number of flow units in each layer increases.

c-4. Tonokuchi lava flow

During the period of construction of the main cone, vast amount of andesite lavas flowed out of the top crater. No lava flows, however, descended to the foot of Old-Takachiho Volcano, except for Tonokuchi lava flow. Such lava flows may exist on the northwest foot of the volcano, but they are hidden under Takachiho-no-mine Volcano at present. The Tonokuchi lava flow descended to the southern foot of the volcano and was extended on the hill of the basement. The thickness of the lava flow at the terminal, as seen from the topography, may well exceed 30 meters. The lava flow is black with abundant visible phenocrysts of plagioclase and has the same property as the cone-forming pyroclastics. The rock of the lava is olivine bearing hypersthene-augite andesite.

c-5. Old-Takachiho lava flows

The Old-Takachiho lava flows are the youngest one of the effused materials and good example to let us see the mode of occurrence of cone-forming lava flows. Based on the field observation of these lava flows(Fig.6), the internal structure of the volcano around the vent is drawn(Fig.7(A)).

The Old-Takachiho lava flows are compact and show a black color appearance. The rocks are olivine bearing augite-hypersthene andesite and the thickness of one flow unit is less than 3 m.

As shown in Fig.4, the Old-Takachiho lava flows cover thinly the most part of the cone and are separated into several branches. Some of them are likely formed by erosion. The majority of the lava flows stopped descending at the middle part of the cone, but the lavas which flowed down along the boundary between Old-Takachiho and Futagoishi Volcanoes form far-reaching flows. Judging from the uniform distribution of the Old-Takachiho lava flows around the crater, they appear to have overflowed repeatedly to all directions from the top crater. Therefore the far-reaching lava flows developed along the boundary of two volcanoes suggest that lavas of relatively vast volume tended to have been gathered there.

The Old-Takachiho lava flows consist of one or two flow units at the lower part of the cone. While, around the top crater, they consist of flow units of more than 10 and the top crater is filled up with accumulated lava flows(Fig.6). Such the mode of occurrence of the lava flows suggests that, in one eruption cycle, the initialy extruded lavas tend to have been of far-reaching flow as compared with the finally extruded lavas(Fig.7(A)).

Pioneering work by Walker(1973a) questioned the common belief that the length or distance of a lava flow stream depends solely or principally on the viscosity of the lava. And then, based on the data for about 40 flows on 19 volcanoes, he concluded that the effusion rate is the most important factor which controls the length of a lava flow stream. However, Malin(1980) stressed that the trend of Walker's(1973a) opinion is principally for flows on Mount Etna. According to the data for 84 Hawaiian flows, Malin(1980) has pointed out that cross-sectional area, effusion rate and volume all play important role in the emplacement of lava flows in Hawaii.

In the case of the Old-Takachiho lava flows, probably their cross-sectional area seldom varied through the duration of an eruption, because they always overflowed from the top crater without any preference for the direction of outflow. Thus the controlled factors for the length of the Old-Takachiho lava flows may be attributed to the effusion rate and volume of extruded lava. The

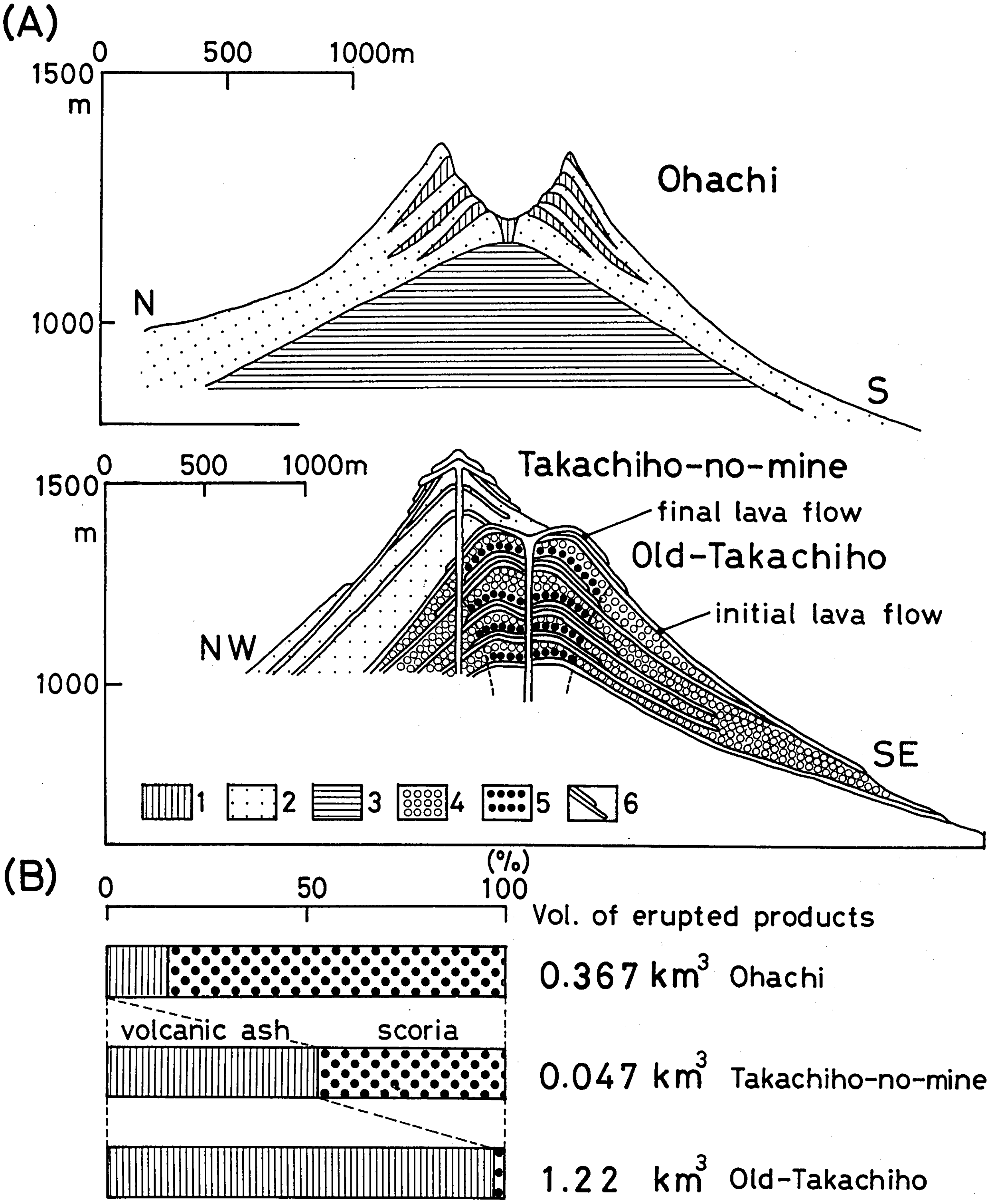

Fig. 7. Diagrams showing schematic cross sections of Ohachi, Takachiho-no-mine and Old-Takachiho Volcanoes(A) and volume percentage of the fall deposits of two kinds derived from those volcanoes(B). Numbers of (B) show total volume(km^3) of fall out products: (1) welded air fall deposits(agglutinates). (2) scoria deposits. (3) western part of Takachiho-no-mine Volcano. (4) weakly vesiculated pyroclastic materials. (5) agglutinates. (6) lava flows.

mode of occurrence of the Old-Takachiho lava flows lead to the following conclusion: in one eruption cycle, the volcanic activity began with a vigorous and voluminous eruption, which is indicated by the existence of the far-reaching lava flows. Subsequently the activity diminished toward the end of eruption, so that the lava flows were piled up layer upon layer to form a local accumulation of limited lateral extent near the vent.

d. Takachiho-no-mine Volcano

d-1. General statement

Takachiho-no-mine Volcano is the highest in Takachiho Compound Volcano, rising 1.574 m above sea level. The volcano rides on the northwestern flank of Old-Takachiho Volcano and covers the western half of it. On the other hands, the western part of Takachiho-no-mine Volcano is buried beneath Ohachi Volcano, but the Takachiho-no-mine show a beautiful conical form. The estimated volume of the volcano is 0.32 km^3.

From the fall out tephra derived from Takachiho-no-mine Volcano, the volcano is not a monogenetic volcano but a polygenetic one. However, its active period is the shortest as compared with the active periods of the other volcanoes forming the compound volcano.

d-2. Shape and internal structure of the cone

As shown in Fig.6, the summit crater of Takachiho-no-mine Volcano is filled up with a exogenous lava dome, which is called here Takachiho-no-mine lava flow II. Therefore, the volcano shows a typical conical form without a crater at the top(Fig.7(A)).

The slope developed to the north smoothly extends to the southern margin of the Ohachi lava flow V, below which it is completely buried. Although the half of the northern slope is thickly covered by the very recent ejecta of Ohachi Volcano, the original shape is maintained at the northern slope, whose inclination attains 39^{o}.

The internal structure of the cone may be conjectured mainly from the gorges developed along the boundary between Takachiho-no-mine and Ohachi Volcanoes. On the basis of the observations of the gorges and cone- forming lava flows exposed around the top crater, the internal structure of Takachiho-no-mine Volcano is drawn in Fig.7(A), showing that it is a small stratovolcano composed of an alternation of thin lava flows and pyroclastic materials erupted from a top crater. The layers of pyroclastic materials are composed predominantly of compact scoriaceous blocks, lapilli and ashes associating small amount of spindle bombs. The scoriaceous blocks vary from subangular forms to sub-round ones. All or upper part of the pyroclastic layers alters frequently to reddish brown from black owing to the high temperature oxidation.

On the other hand, the layers of lavas consist of several flow units and the thickness of individual flow units is less than 4 m. Also, the number of flow units in each lava layer increases, as the distance from the vent decreases. At the northern slope of the main cone the number of the accumulated flow units amounts to more than 10 as shown in Fig.8. The lava on the southern slope flowed down to the foot along the boundary between Old-Takachiho and Takachiho-no-mine Volcano(Fig.4). These cone-forming lava flows are collectively called here Takachiho-no-mine lava flow I. Its constituent rock is augite-hypersthene andesite with or without olivine crystal.

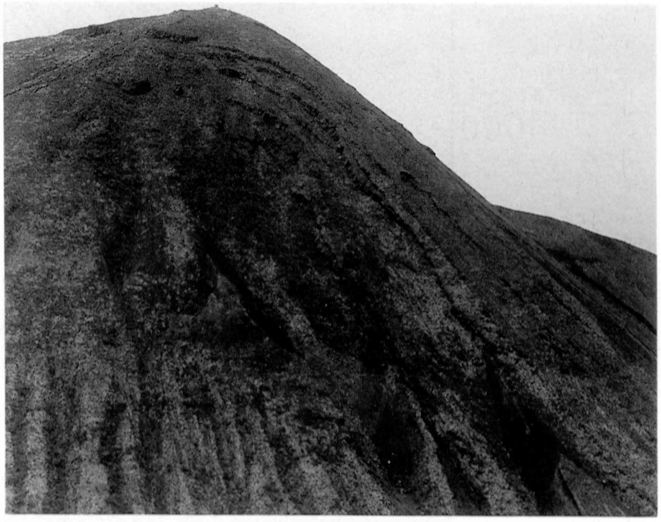

Fig. 8. Aerial view of Takachiho-no-mine Volcano seen from the northeast(Photo by T. Kobayashi, 1985). Note the accumulation of thin lava flows(Takachiho-no-mine lava flow I) effused repeatedly from the top crater.

d-3. Takachiho-no-mine lava flow II

Takachiho-no-mine lava flow II is the youngest of all the effused materials of Takachiho-no-mine Volcano. As seen in Figs.6 and 9, the lava flow stopped descending near the vent and was piled up around the top crater, resulting in an exogenous lava dome on the summit[Fig.7(A)]. The maximum thickness of the flow unit at the terminal amounts to 15 m. The constituent rock is augite-hypersthene andesite with olivine crystal.

Takachiho-no-mine lava flow II may be assumed to have been highly viscous, because of great thickness of individual lava flows, which is four times as large as that of Takachiho-no-mine lava flow I. However, it really dose not appear to be so viscous as compared with the lava flow I. This inference has the following basis : 1) The SiO_2 content of the Takachiho-no-mine lava flow II is 53.6 per cent in weight, while that of the Takachiho-no-mine lava flow I varies from 53.4 to 56.2 per cent in weight. And 2) the total phenocryst content of the former is 45 per cent in volume, while that of the latter varies from 43 to 46 per cent in volume, showing that there is no significant difference between them.Therefore, the causes that the Takachiho-no-mine lava flow II was piled up around the top crater may be to its low effusion rate and /or small volume, but not to its viscosity.

Fig. 9. Aerial view of the summit of Takachiho-no-mine Volcano seen from the southeast(Photo by T. Kobayashi, 1985). The summit crater is filled up with the Takachiho-no-mine lava flow II, some branches of which spilled over the crater crest and advanced southward.

e. Ohachi Volcano

e-1. General statement

After the top crater of Takachiho-no-mine Volcano had been completely filled up with exogenous lava dome, Takachiho Compound Volcano is considered to have returned to the state of dormancy, which corresponds to the second major period of silence since the birth of the compound volcano. After the dormancy probably lasted for a few hundred years or more, suddenly a catastrophic eruption took place at the eastern foot of Futagoishi Volcano. This plinian pumice eruption was responsible for the formation of the Mi-ike maar. A few hundred years or more of quiet followed the catastrophic eruption of the Mi-ike maar.

The present stage activity of TCV began about 2,500 years ago. It is characterized by sub-plinian eruptions which occurred intermittently and produced thick scoria and ash beds on the eastern foot of TCV. Consequently, a new volcano, Ohachi, was born on the western flank of Takachiho-no-mine Volcano and has been active since then.

As shown in Fig.4, there is a marked difference between constituent materials of Ohachi Volcano above and below the altitude of 950 m. They above the altitude of 950 m are composed of an alternation of pyroclastic materials and agglutinates, while they below that are made up mainly of lava flows and small amount of scoria flow. In these lava flows are distinguished eight discrete flows units, which are called here Ohachi lava flow I to VIII in order of young-becoming.

e-2. Shape and internal structure of the main cone

The topography of Ohachi Volcano is an asymmetrical truncated-cone with a large crater-pit at the top. The surface of the slop of the cone is thickly covered by loose ejecta and agglutinate projected in recent eruptions. It is therefore naked only all over the slope above the altitude of 1100 m.

The net height of the cone from the underlying western slope of Takachiho-no-mine Volcano is 260 m(Fig.7(A)). The estimated volume of it is 0.74 km^3.

The pit crater is roughly circular in horizontal section and about 500 m or more in diameter, being surrounded by steep walls of less than 200 m in relative height. On the floor of crater, its central part is filled up with talus, but at the southeastern part there exists a small fumarole, diameter of which is 60 m. The western rim of the crater is lower to some extent in height than the other part, and so was a way for lava flows and scoria flow to the western flank.

A topographic cross section of Ohachi Volcano shows that the western slope of Takachiho-no-mine Volcano exists under the floor of crater-pit of Ohachi Volcano and the distance between them is less than 70 m. From this fact it follows that three quarters part of the internal structure of Ohachi Volcano is exposed on the crater wall. Based on the observations of the crater wall, a schematic cross section of the volcano is shown in Fig.7(A). On the crater wall about 7 to 8 agglutinate(or welded air-fall tuffs) layers ranging in thickness from 1 to 40 m or more are observed to alternate with layers of pyroclastic materials(Fig.10). In these rigid layers no lava flows are founded at all. Thus the cone consists of an alternation of agglutinates and loose pyroclastic materials.

However, the difference in the degree of consolidation of agglutinates and the ratio of the agglutinate to the loose pyroclastic materials make the appearance of the crater wall strikingly different from part to part. For instance, in the northeastern and southwestern part of the crater, where the ejected fragments retained the heat large enough to weld firmly the fragments, very thick layers of massive agglutinate were formed, thickness of which attains to 40 m or more. On the other hand, the pyroclastic materials in the eastern part of the crater are incoherent, so that vast amount of thin layer in colors of black and reddish brown are observed to overlie horizontally one another.

As pointed out by Kobayashi(1979), the agglutinates are so rigid and so similar to lavas in macroscopical and microscopical appearance, that they have previously been mistaken for lavas. The following field evidence, however, support the conclusion that such the rigid rocks exposed on the crater wall are of air-fall origin : 1) As shown in Fig.10, some layers of rigid rock sometimes separates into two branches at the terminal and grades laterally into lose pyroclastic materials. 2) As the distance from the vent increases, the thickness of the layers of rigid rocks diminishes gradually. If the rigid rocks were of lava flows origin, the thickness of the layers should become rather thick at the terminal. 3) The loose pyroclastic materials tend to grade vertically into the rigid rocks through transitional zone where the pyroclastic materials have weakly welded.

On the other hand, the layers of the loose pyroclastic materials are mainly composed of porous scoriaceous blocks, lapilli and ashes, associating small amount of spindle bombs and driblet. The driblets, length of which attains to about 2 m, are not uncommon in the lower part of the crater wall. In most cases, the constituent fragments, as well as fine matrices are oxidized to brownish and reddish color showing variation in tenor of colors from part to part.

As the volcano grows, consolidated pyroclastics are confined only near the crater, promoting the volcanic edifice

Fig. 10.Inside view of the top crater of the cone of Ohachi Volcano showing the structure of the northern part of its cwalls. Welded air fall deposits(rigid parts) are interspersed with the fragmentary deposits that make up the stratified layers of ash, lapilli and bombs.

to grow higher by forming a rigid mass around the vent. It is notable that in this process no lava flows made a essential contribution to the upward growth of the volcano. This mechanism is greatly different from that of the growth of Old-Takachiho and Takachiho-no-mine Volcanoes, where lava flows of vast amount play important roles in promoting the volcanic edifices to grow upward.

The rocks constituting the cone of Ohachi Volcano are augite-olivine basalt with or without hypersthene phenocrysts and olivine-bearing augite-hypersthene andesite.

e-3. Ohachi lava flow I, II and III

Before the construction of the main cone, Ohachi lava flow I,II and III were extruded to the southern slope of Ohachi Volcano(Fig.4). They were so viscous that their thickness amount to 80 m or less at the terminal of each lava flow.

The Ohachi lava flow I is a small volcanic body extruded near the vent and shaped like a tongue. The lava is rugged and of black color with abundant visible phenocrysts of plagioclase, size of which is from 1 to 2 mm. Glomeroporphyritic aggregates of plagioclase, pyroxene and opaque minerals are found. They size ranges from 3 mm to 5 mm.

On the southern foot of Ohachi Volcano is found the Ohachi lava flow II being overlain immediately by the lava flows of younger ages. Therefore the position of the vent is hidden beneath the younger lava flows at present. The lava flow II is similar to the Ohachi lava flow I in macroscopical appearance and contains many angular accidental inclusions, which are of sedimentary rocks origin and range from 10 to 25 cm in size.

The Ohachi lava flow III flowed out from the vent opened at the altitude of 950 m to the southern slope of the volcano. This lava flow stands out from the adjoining lava flows by its fresh surface features such as lava wrinkles and lava levees. The lava is bluish gray in color and similar to the above described two lava flows in macroscopical appearance, but can be discriminated from the lava flow I and II by the presence of olivine crystals which range from 0.3 mm to 0.6 mm in size.

The total area covered by the lava amounts to 2.13 km^2 while the total volume to $1.07X10^8$ m^3, assuming the mean thickness of the lava to be 50 m.

The rocks of the Ohachi lava flow I, II and III are augite-hypersthene andesite with or without olivine crystal.

e-4. Ohachi lava flow IV

The Ohachi lava flow IV flowed out from the vent opened at the southern flank of the volcano and flowed down along the eastern margin of the Ohachi lava flow III. It has a distribution like a snake. The lava is about 3 m in apparent thickness and traveled about 1.45 km in horizontal distance from the vent.

The lava is scoriaceous hypersthene-olivine-augite basalt with black color appearance. Abundant pyroxene and plagioclase in small lath-shaped crystals are visible in hand specimen.

The strata of the fall out tephra overlying the lava flow IV are identical with those covering the Ohachi lava flow III, though full particulars will be mentioned later, Therefore it is considered that no long period of quiescence exists between the activities of the two lava flows.

e-5. Ohachi lava flow V

The Ohachi lava flow V has an extensive distribution on the northern foot of TCV. As shown in Fig.4, the lava is confined to a narrow valley between Yatake Volcano and Takachiho Compound Volcano, and traveled about 6.5 km in horizontal distance from the top cater. The mean thickness of the lava is less than 4 m, but as seen from the topography the thickness of it at the terminal attains 10 m or more.

The lava is fresh, compact and black in color with abundant visible phenocrysts of plagioclase, which ranges from 1 to 1.5 mm in size. The constituent rocks are augite-hypersthene andesite.

The total area covered by the lava flow V amounts to 5.37 km^2, while the total volume to $2.15X10^7$ m^3, assuming the mean thickness of the lava to be 4 m.

e-6. Ohachi lava flow VI and VII

The Ohachi lava flow VI and VII are traced over 6.1 km from the top crater down to its southwestern foot. The mean thickness of the lava is 5 m or a little more, but the thickness diminishes near the crater attaining 1 m or less.

The Ohachi lava flow VI is overlain by the Takaharu scoria fall deposits which are the ejecta of the A.D.788 activity of Ohachi Volcano, while the Ohachi lava flow VII covers the Takaharu scoria fall deposits with some intervening soil layers. Thus the eruptive epoch of the lava flow VI is clearly different from that of the lava flow VII. Because of the absence of the unique feature available for the distinction of the two lava flows, however, it is not always easy, and in many cases impossible, to discriminate between them out on the fields. Moreover, on the southwestern slope of the volcano, the Takaharu scoria is not found beneath or above those lava flows, because most of the fall out tephra of Ohachi Volcano was transported toward the east from the crater. Therefore, these two lava flows are lumped together in a single symbol on the geologic map of Fig.4.

The two lavas are compact and dark gray in color with abundant visible phenocryst of plagioclase and pyroxene. The lava flow VI is olivine-hypersthene-augite andesite, and the lava flow VII is hypersthene-olivine-augite basalt and hypersthene bearing augite-olivine basalt.

e-7. Ohachi scoria flow deposit

The Ohachi scoria flow deposit is unstratified and consists of large lumps of scoria up to 80 cm in diameter and of interstitial ash which are closely packed together. All lumps of scoria are well to moderately rounded owing to strong abrasion during the advance of flowing. The scoria and interstitial ash consist of the same material. The porosity is variable between different fragments and between different parts of the same fragment. The color of the scoria is iron black, being in good contrast to the pale gray color of the pumice which is sometimes observed in a base zone of the scoria flow.

The scoria flow deposit does not fail to yield ample evidence for the high-temperature of emplacement by containing carbonized woods(tree branches and trunks) in its various parts. The fragments of carbonized woods range from a log of a few tens centimeters long to fine particles barely detectable with a hand lens, but most of them are less than ten centimeters in size.

The scoria flow deposit is divided into two parts, one flowing down to the south and the other flowing down to the west(Fig.4). The southern part of the scoria flow is always associated with a layer of scoria fall deposits. On the other hand, the western part of it occurs without any fall out tephra, but the lower part of the flow unit is strongly consolidated.

The scoria flow is dammed up to the south by the Ohachi lava flow III and Takachiho-no-mine lava flow I, and is preserved on the southern flank of Ohachi Volcano at the altitude between 750 m and 1,000 m, where the slope dips about 10^{o}. The thickness of the deposit is more than 10 m in the terminal.

The scoria flow deposit is confined to the same horizon in every section. For example, it is always underlain by a well-sorted scoria layer without any intervening soil layer(TCV109 in Fig.12) and, on the contrary, is overlain by a layer of scoria which is characterized by the pumice with yellowish white appearance and with a banded appearance(TCV110 in Fig.12). As seen in TCV108 or TCV111 of Fig.12, these scoria fall layers both are correlative with a single layer of scoria which is called here Takaharu scoria falls. From this fact, it is concluded that the scoria flow is intercalated into the Takaharu scoria fall deposits.

The main stream of the scoria flow rushed down toward the western foot of the volcano, but was prevented by a hill composed of lava flows of Naka-dake Volcano. Consequently, the main stream was subdivided into two branches, one descending to the northeast and the other descending to the south. Takachiho-gawara(Fig.13) situated at the western foot of Ohachi Volcano is the place where the scoria flow branches off into two directions. Welded parts of the scoria flow are not uncommon around the Takachiho-gawara. The welded parts sometimes contain many big driblets, which range from 1 to 2 m in length, and are overlain by the non-welded parts of the scoria flow of five meters or more in thickness. Most parts of the southern branch are overlain by the Ohachi lava flow VII. The another branch flow streamed down through a valley cut between Ohachi and Naka-dake Volcanoes toward the northeast. The thickness of the scoria flow at the Takachiho-gawara is 270 cm and diminishes rapidly to 60 cm .

The maximum thickness of the Ohachi scoria flow deposit attains more than 10 m and the area covered by the deposit is about 0.7 km^2. Assuming the mean thickness to be 5 m, the total volume of the deposit is estimated as $3.5X10^6 m^3$, which is only a seventieth of that of the Takaharu scoria fall deposits.

e-8. Ohachi lava flow VIII

The Ohachi lava flow VIII is observed in the top crater where it is hanging on the lower part of the crater wall, but dose not exist on the outer slope of the volcano at all. This mode of occurrence of the lava suggests that the Ohachi lava VIII filled up the lower part of the crater in the latest time. Therefore, the lava is considered to be the youngest one among the lavas of Ohachi Volcano origin.

The lava is fresh, ragged and black in color with abundant visible phenocrysts of plagioclase, which ranges from 0.2 to 3 mm in size, and of pyroxene. The constituent rock is olivine bearing hypersthene-augite andesite.

f. Age relations

f-1. General statement

As mentioned above, Takachiho

Compound Volcano is composed mostly of subaerial volcanic products of basaltic and andesitic nature, i.e., lavas, scoria flow deposits and fall out tephra deposits(scoria, pumice and ash), and secondary deposits at the foot of the compound volcano. The lava and scoria flows are restricted in distribution on the flank of the compound volcano, whereas the fall out tephra tend to be distributed more uniformly and widely, being controlled by the direction of prevailing winds and distance from the crater.

From the stratigraphic sequence of the fall out tephra layers overlying individual lava flows and scoria flows, the eruptive order of them will be revealed. And then the horizons of lava flows and scoria flows will be compiled into a single stratigraphic column.

The correlation of the fall out tephra deposits developed in various localities is shown by the columnar sections in Figs.11 and 12, in which idealized "standard sections" of the scoria and ash fall deposits are also shown. The standard sections illustrate an imaginary columnar section in which all the stratigraphic units are indicated successively without any missing part.

As seen in the standard sections, the minimum geologic unit is a fall unit defined by Nakamura(1964) in Oshima Volcano, which is regarded as a single bed with reference to distinctive features such as color, grain size and lithofacies. Because a single fall unit is difficult to trace laterally, Nakamura defined larger unit, called members, as a minimum stratigraphic unit for wide mapping and correlation. The eruptive history of a volcano can be best described by the concept of the stratigraphic unit or member, which is a succession of eruptions separated by apparently dormant intervals inferred from intercalated soils and weathering breaks.

f-2. Sequence of volcanic products

Old-Takachiho Volcano :

Layers of dark blue ash found throughout the Kirishima districts(TCV100, TCV102, etc. in Fig.11) are correlated to the stage of the activity of Old-Takachiho Volcano. These layers(Ushinosune ash deposits; Inoue, 1988) are easily distinguished from other layers by their characteristic coloring. These fall out deposits are very useful as a key bed.

As the columnar section of TCV102 in Fig.11 shows, the Natsuo lava flow is overlain by the Ushinosune ash deposits with an intervening weathered ash layer. On the contrary, the lava flow is underlain by a reddish brown scoria bed, called Uramuta scoria deposit by Inoue(1988)(TCV100 in Fig.11).

The Tonokuchi lava flow is overlain by the Ushinosune ash deposits without any intervening soil layer(TCV103), and, as seen in the columnar section, the eruptive age of the lava flow is evidently older than that of Kikai-Akahoya ash(6,300 y.B.P)

At the locality TCV104 on the southern slope of Old-Takachiho Volcano(Fig.13), where the thickness of the Ushinosune ash deposits is expected to be 200 cm or more, no layer of the ash deposits is found at all on the Old-Takachiho lava flows. This field observation is harmonious with the fact that the Old-Takachiho lava flow is the latest effused lava flow among the volcanic products derived from Old-Takachiho Volcano. Moreover, the lava flows are overlain by the Mochiharu ash deposit(Inoue, 1988) with intervening weathered ash layers.

Takachiho-no-mine Volcano :

Two layers of fall out tephra are found to lie above the Old-Takachiho lava flows in many places on the southern slope of Old-Takachiho Volcano(TCV104 in Fig.11). The older tephra between them is the Mochiharu ash deposit, and the younger one is the Ohji scoria deposit(Inoue, 1988). There are no exposures that indicate the stratigraphic relations among the above-mentioned tephra layers and the lava flows of Takachiho-no-mine Volcano origin. The Mochiharu ash deposit developed on the Takachiho-no-mine lava flow I is not found anywhere. Because the Mochiharu ash deposit is expected to attain a thickness of 10 cm on the Takachiho-no-mine lava flow I according to its isopach map(Fig.30,E), however, the former ash deposit is evidently overlain by the latter lava flow. As the distribution of the Ohji scoria deposit is circumscribed within a narrow area, its stratigraphic horizon among the sequence of volcanic products of Takachiho-no-mine Volcano still remains as an unknown. As the columnar sections of TCV105 and TCV106(Fig.11) show, the Takachiho-no-mine lava I is evidently overlain by the Mi-ike pumice falls.

Ohachi Volcano :

Ten members or stratigraphic units have been identified in the columnar section for Ohachi Volcano proper, being named Oh1 to Oh10 in ascending order. An alphabetical code is assigned to each fall unit of individual members. Full particulars in each member will be mentioned latter.

As shown in Fig.12, the fine ash deposits of Oh3 member, which contains thinly reddish brown scoria and are

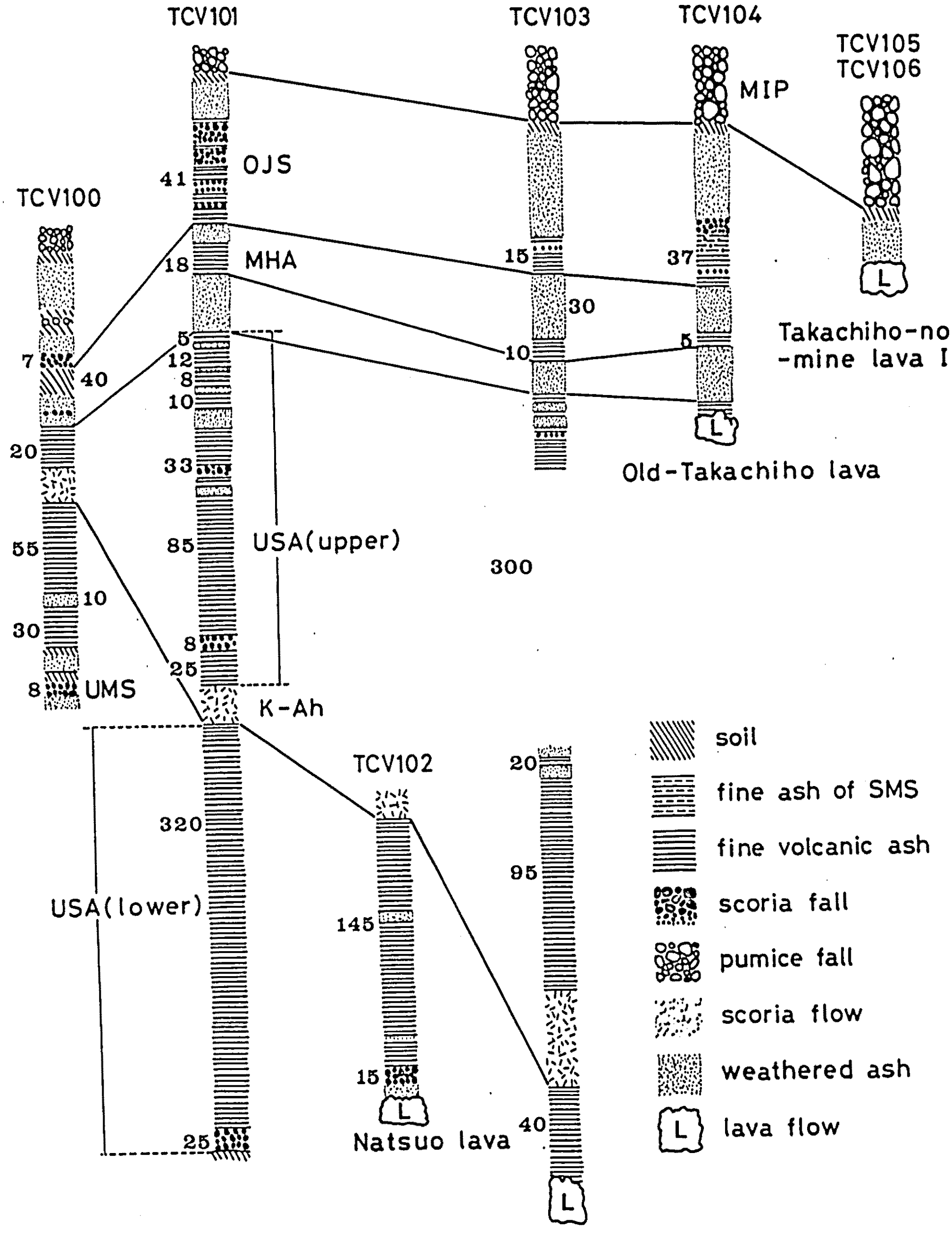

Fig. 11. Diagram showing representative stratigraphic sections and an idealized standard section of the fall out deposits from Old-Takachiho and Takachiho-no-mine Volcano. See Fig.13 for localities of those sections. Dashed lines show correlation of fall out deposits. Numerals in cross sections show layer thickness in cms.

easily distinguished from other layer by the characteristic coloring of the dispersed scoria fragments, can be traced laterally throughout TCV. Thus, the fine ash layer of Oh3 is a useful key bed, but strictly speaking, the Oh3 member is not a time-marker unit which shows only a short period in stratigraphy. Nakamura(1964) defined that a member is composed of materials erupted within a short period of probably less than ten years. Consequently, a member has no weathered zone within itself and scarcely includes even erosional breaks of smallest scale. However, the deposits of the Oh3 member are not so fresh and weathered to some extent as compared with scoria and ash layers of Oh4, Oh5, Oh6, Oh7 and Oh8 members. The lapsed time between the activities of Oh3 and Oh4 members is recorded as a brown, loamy ash layer developed at the top of

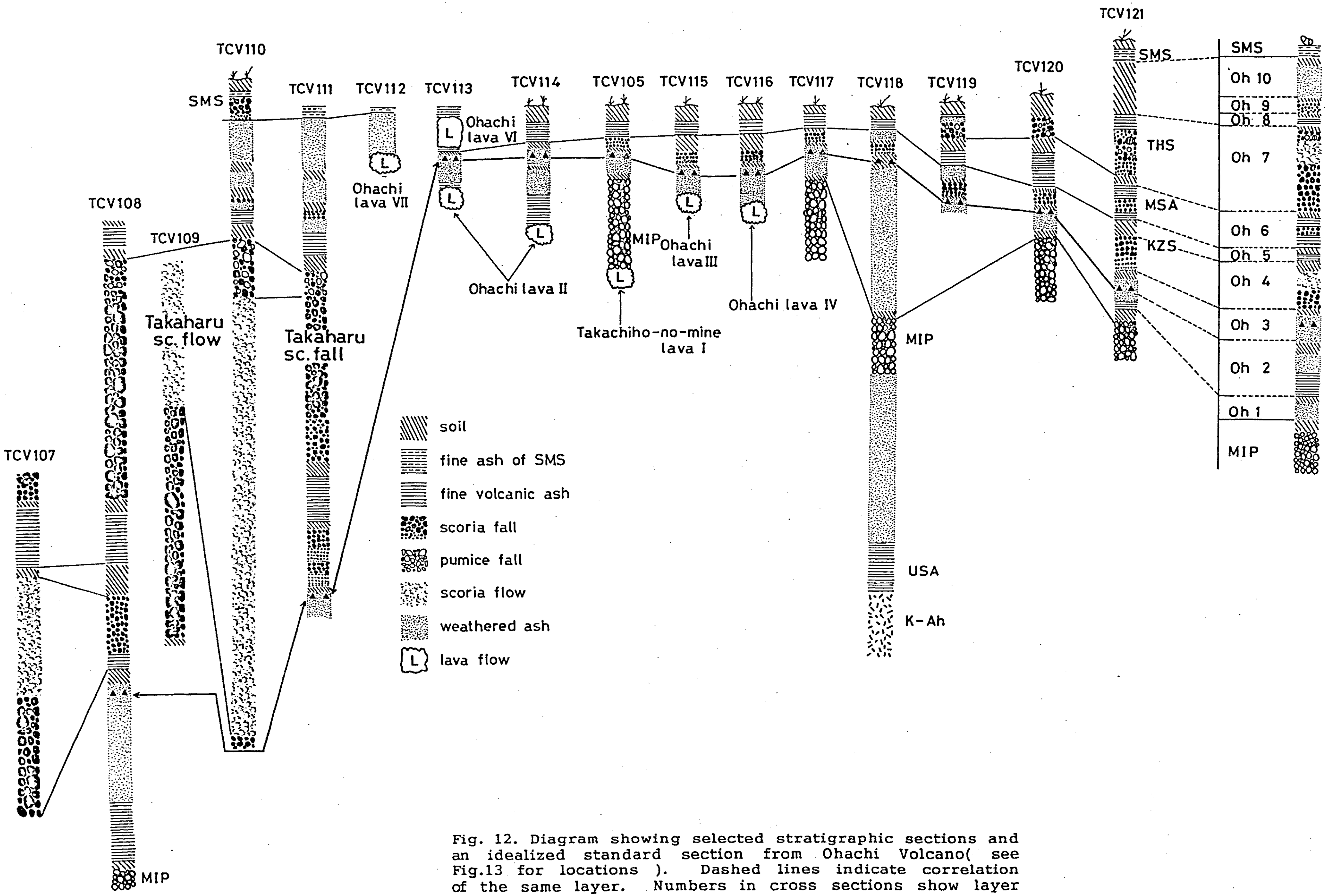

Fig. 12. Diagram showing selected stratigraphic sections and an idealized standard section from Ohachi Volcano(see Fig.13 for locations). Dashed lines indicate correlation of the same layer. Numbers in cross sections show layer thickness in cms.

Oh3 member. These facts indicate that the deposits of the Oh3 member were formed within a relatively long period in comparison with other members, during which small-scale eruptions continued intermittently.

No air-fall tephra deposits are found on the surface of the Ohachi lava flow I, so that its eruptive order is still a matter of conjecture. As mentioned before, however, judged from the fresh surface features such as lava wrinkles and lava levees, the lava flow I is probably older in generation age than the Ohachi lava flow III.

The Ohachi lava flow II is overlain by the black ash layer of Oh2 which underlies the fine ash layer of Oh3 with intervening brown loamy ash layer, whereas the Ohachi lava flow III and IV are directly overlain by the fine ash layer of Oh3 member(TCV113 and TCV114 in Fig.12). From these facts, the lava flow II is apparently older in generation age than the lava flow III. However, there is no positive evidence to decide the eruptive order between the lava flow I and II at present.

Because the fine ash deposits of Oh3 overlying the Ohachi lava III and IV (TCV115 and TCV116 in Fig.12) are not erupted materials deposited within a short period, it is doubtful that the two lavas belong to the same eruptive cycle as the ash layer of Oh3.

At the well-exposed section of TCV107 (Fig.12), another scoria flow consolidated weakly are intercalated into the scoria fall deposits of the Oh4 member. Its distribution is too narrow to represent on the geologic map of Fig.4.

The Ohachi lava flow V and VI (TCV113 in Fig.12) are immediately overlain by the black and fresh ash deposits of the Oh5 member. The Ohachi lava flow VII is immediately overlain by the fine ash with brown color of Oh10 at TCV112 in Fig.12.

g. Mi-ike maar

g-1. General statement

Mi-ike is situated at the southeastern edge of KVG and lies on the eastern flank of Futagoishi Volcano(Fig.3). About 3,000 years ago, large amounts of pumice and ash of dacite composition, together with debris of the underlying country rocks, were ejected, forming Mi-ike maar. Most of the materials were deposited on the southeast of Mi-ike, where air-fall layers form a blanket of generally less than 5 m thick. In the later stage of development of the Mi-ike maar, water apparently gained access to the active volcanic vents, and phreatomagmatic outbursts, including the kind of base surges described by Moor et al.(1966) for the 1965 eruptions of Taal Volcano, Philippines, became dominant. The maar is filled with water and thickly covered with vegetation at present. It is about 1 km in diameter and 101 m deep, having a rim height of 25 m to 130 m above the lake. As the topography map shows(Fig.14), the northern and northeastern parts of the rim, where no basement rocks are observed at all, show the original land form resulted from hydroclastic eruptions. The basement rocks composed of lava flows of Futagoishi Volcano are exposed at the southern and southwestern parts of the rim, whose top is thinly covered by the deposits of hydroclastic and fall out origin.

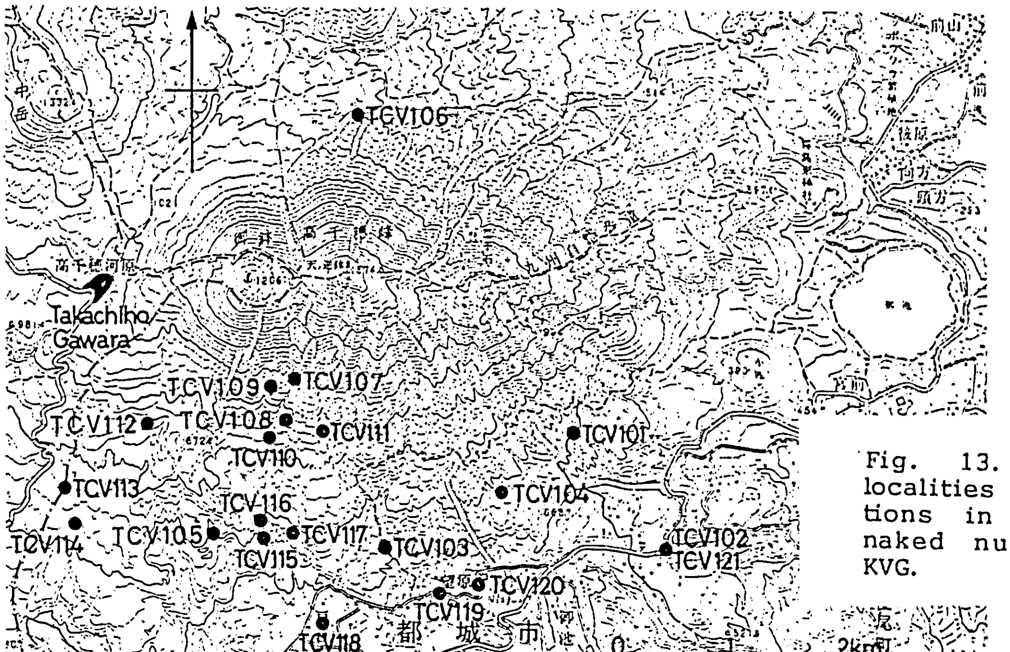

Fig. 13. Map showing the localities of columnar sections in Fig.11 and 12 by naked numerals with TCV or KVG.

g-2. Mi-ike pumice fall deposit

Distribution and thickness : The Mi-ike pumice fall deposit (Kuwano et al.,1959) may be a product of typical plinian eruption and is, with reference to volume, the largest of the fall out deposits developed in the third stage activity. The deposit has a broader fan-shaped distribution with its apex at the source and the dispersal axis extends in a direction of N 120 ° E(Fig.15). The outermost 50 cm isopach encloses an area of 502 km^2 and it is obvious that the overall dispersal area is far larger than 1000 km^2. The total volume of the deposit is 3.6 km^3 as calculated using the following empirical formula proposed by Hayakawa(1985): $V=12.2TS$, where T is thickness of an isopach and S is area enclosed by the isopach. The used isopach for calculating the volume is 100 cm, because the isopach is best constrained by the data points.

Profile of the deposit : The cross sections of the pumice fall deposit were examined throughout its whole width in order to clarify the progress of the eruption. These sections are shown in Fig.16(MI100, MI101, MI102 and MI103).

Before examining the vertical variation of grain size and contents of pumice and lithic fragments, representative sections of the deposits will be described in detail. Sketching has been made on the exposures of MI104 and MI101 : the former is located at about 1.5 km north-northeast of the Mi-ike maar and the latter at about 2.1 km northeast. The sketches of the sections are shown in Fig.17. Owing to the difference of grain size of pumice fragments and constituent materials, the Mi-ike pumice fall deposits are subdivided into the following four units : in a upward sequence, Mi-a, Mi-b, Mi-c and Mi-d. These units are well traced laterally around the northeastern area of the Mi-ike maar, but it is difficult to trace the units to the southern and southeastern areas, where the pumice fall deposits are accumulated as one fall unit layer.

The particles of volcanic block size(>64 mm) and lapilli size(64 to 2 mm in diameter after the classification of Fisher, 1961) which constitute each fall unit are composed of materials of the following three types :

(1)Fragments of pumice: Fragments of pumice are make up the bulk of the deposits. Most of them are very angular in shape with a rough surface, indicating that they are fragments produced by breaking down of larger pumice lumps which are already in a fairly rigid state. The pumice is very poor in phenocrysts and its vesicularity is lower than that of pumice included in other tephra. This is useful for the identification of the pumice fall deposit at the outcrop. Two kinds of pumice fragments are distinguished based on the difference of the color. Most of them have a yellowish white color when they are dry, and yellowish brown when moistened. The other is dark (or light)

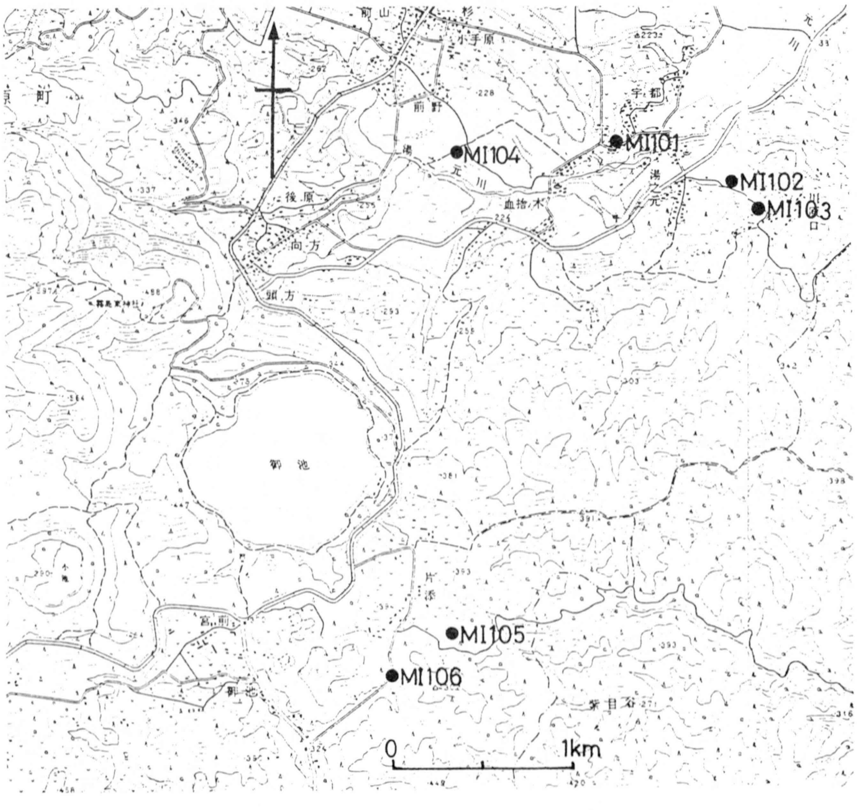

Fig. 14. Topographic and locality map. Naked numerals with MI indicate the localities of columnar sections in Fig.16 and 17.

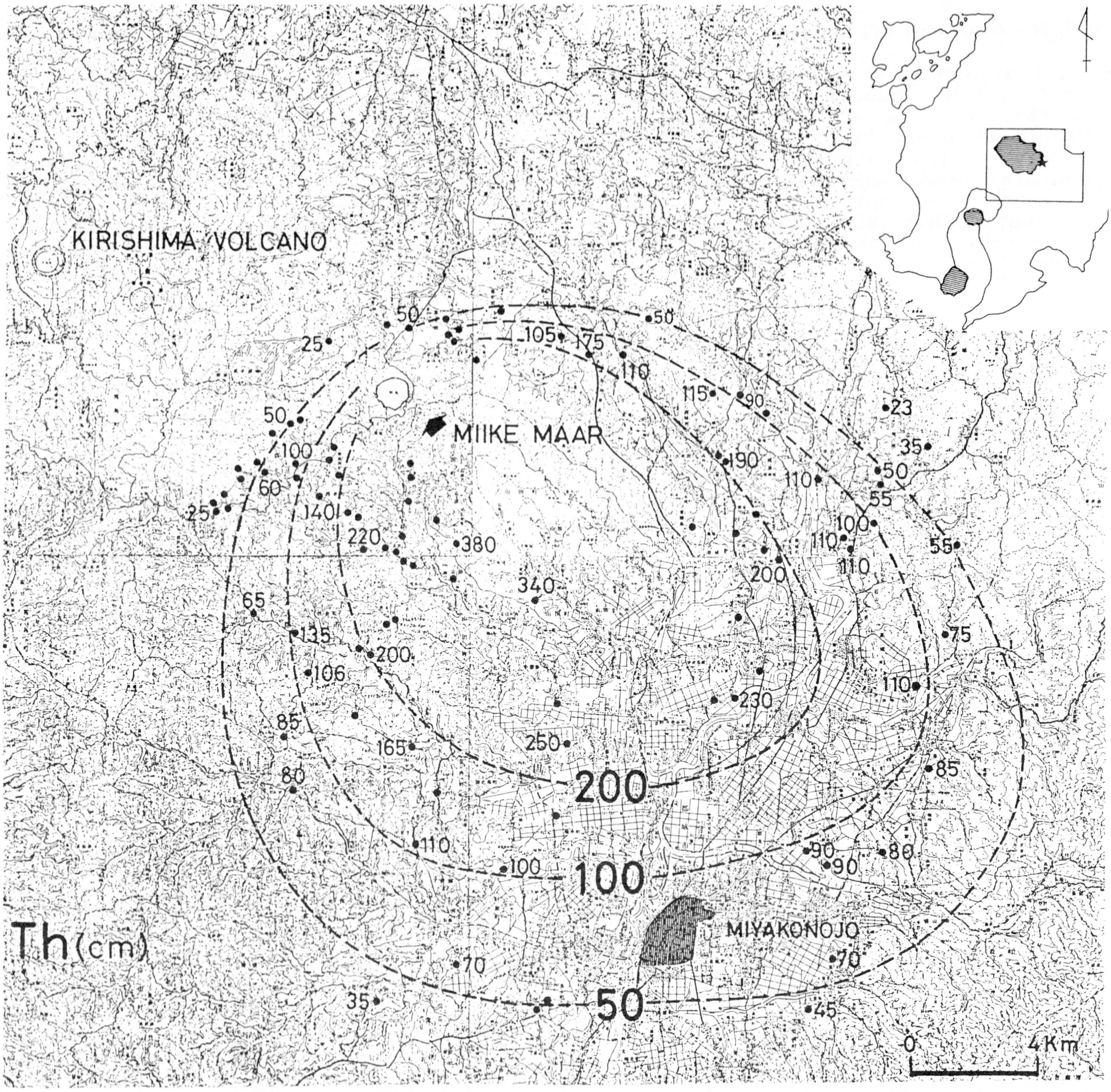

Fig. 15. Isopach map of the Mi-ike pumice fall deposits. Contour values in centimeters.

gray color in appearance. Many of the yellowish white pumice clasts contain irregularly shaped fragments of the gray pumice, and the both pumice fragments are frequently intimately mixed as streaks. The rocks of the pumice fragments are augite-hypersthene dacite, but some of the dark(or light) gray pumice clasts are quartz-olivine-hornblende-bearing augite-hypersthene andesite.

(2) Accidental fragments captured by the magma: Accidental fragments are easily distinguished from other fragments by their dark brown color induced by the oxidation of iron. They are mostly derived from inclusions contained in magma and so more or less subjected to thermal metamorphism. Most of them are sedimentary rocks in origin, which were derived from the Shimanto Super group, and the rest is derived from the lavas of Futagoishi Volcano.

(3) Fragments of the unaltered basement rocks: There are angular fragments of lavas and sedimentary rocks which commonly show little or no signs of thermal metamorphism. They are discharged materials during the opening and widening of the vent.

The particles of ash-size (less

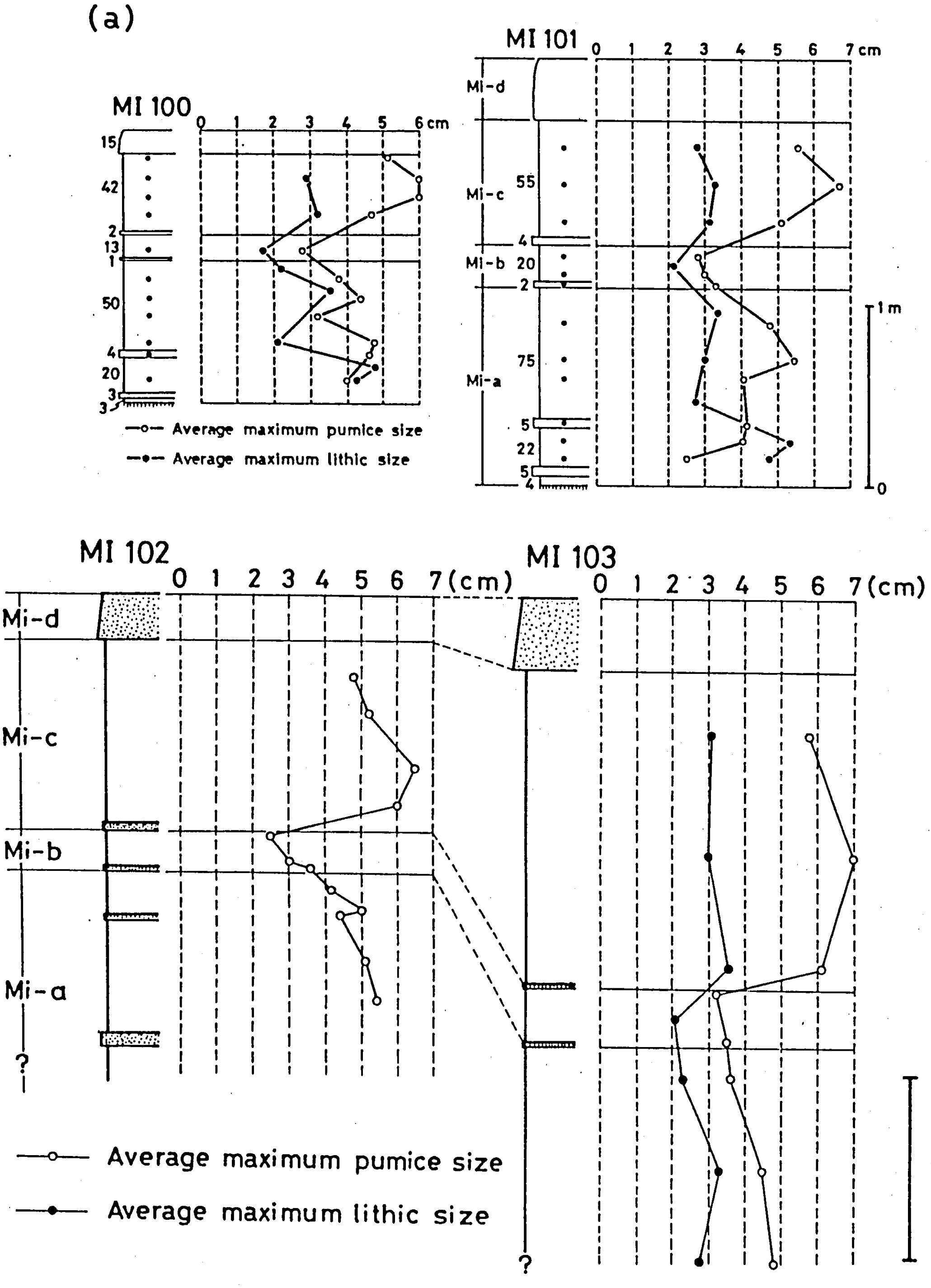

Fig. 16. Diagram for the data of the Mi-ike pumice fall deposits. (a) vertical variation of the average diameter of ten largest pumice and twenty(or thirty) largest lithic fragments.

than 2 mm in diameter) are composed mainly of glass shards associating a small amount of isolated crystals.

Vertical variation of grain size and contents of pumice and lithic fragments : The measurement of the grain size of pumice and lithic fragments and the mechanical analyses, by means of sieving methods, of samples of the deposit were made at the representative sections, with a view to obtaining information on the characteristics of the pumice fall deposit. The results are shown in Fig.16. The grain size of pumice shown in the figure is an average diameter of the 10 largest fragments, which are obtained from the particles of pumice

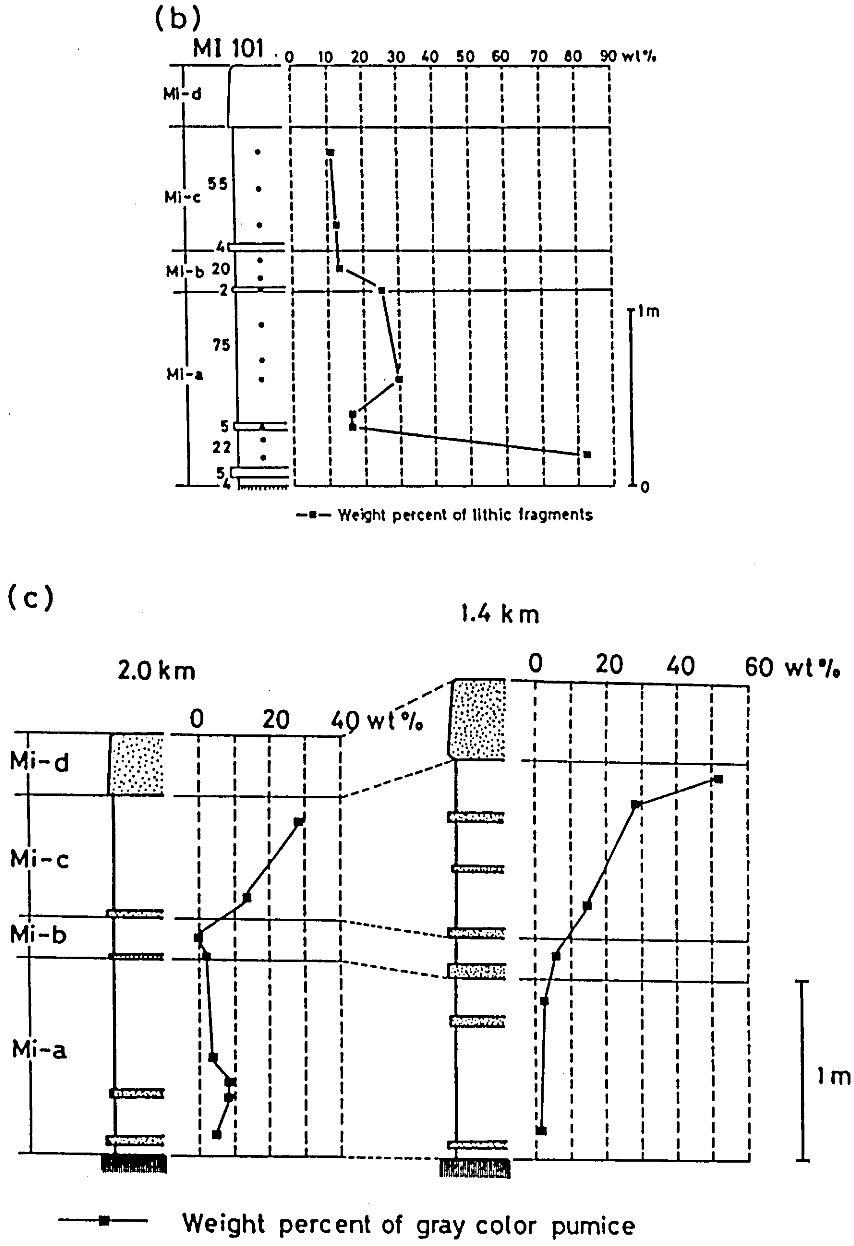

Fig. 16. (b) vertical variation of the weight percentage of lithic fragments. (c) variation of the weight ratio of gray color pumice to total pumice through the deposit.

lying along the horizontal straight line of one meter in length. The grain size of lithic fragments is an average diameter of the 20 (or 30) largest fragments contained within a layer which is 0.2 m wide and 2 (or 3) m long.

As shown in Fig.16(a), the vertical variation of the grain size of pumice fragments is characterized by the presence of the two maximum values, one of which is measured at the middle part of the Mi-a unit and the other of which exists within the Mi-c unit. The maximum size of them in the latter unit is always larger than that in the former unit. The Mi-b unit has a minimum value of the grain size of pumice and lithic fragments and is easily discriminated by its well-sorted nature, showing that the unit is a product of less intense eruption.

On the other hand, the largest particle of the lithic fragments occurs in the lowest part of the Mi-a unit and its diameter attains to 1.5 times the size of the lithic fragments contained within the other horizon of the deposit. Furthermore, the lowest part [(b) in Fig.16] shows high weight percentages of the accidental fragments and wall-rock pieces in comparison with the other part of the deposits. Most of the lithic fragments are unaltered rocks, which show light gray color and angular shape, and which were probably emplaced ballistically into the pumice deposit. These facts imply that the magma, which came up immediately after the opening eruptions, was charged with abundant xenoliths and it had to break wall-rocks in order to make its way out of the vent. The diameter of the lithic frag-

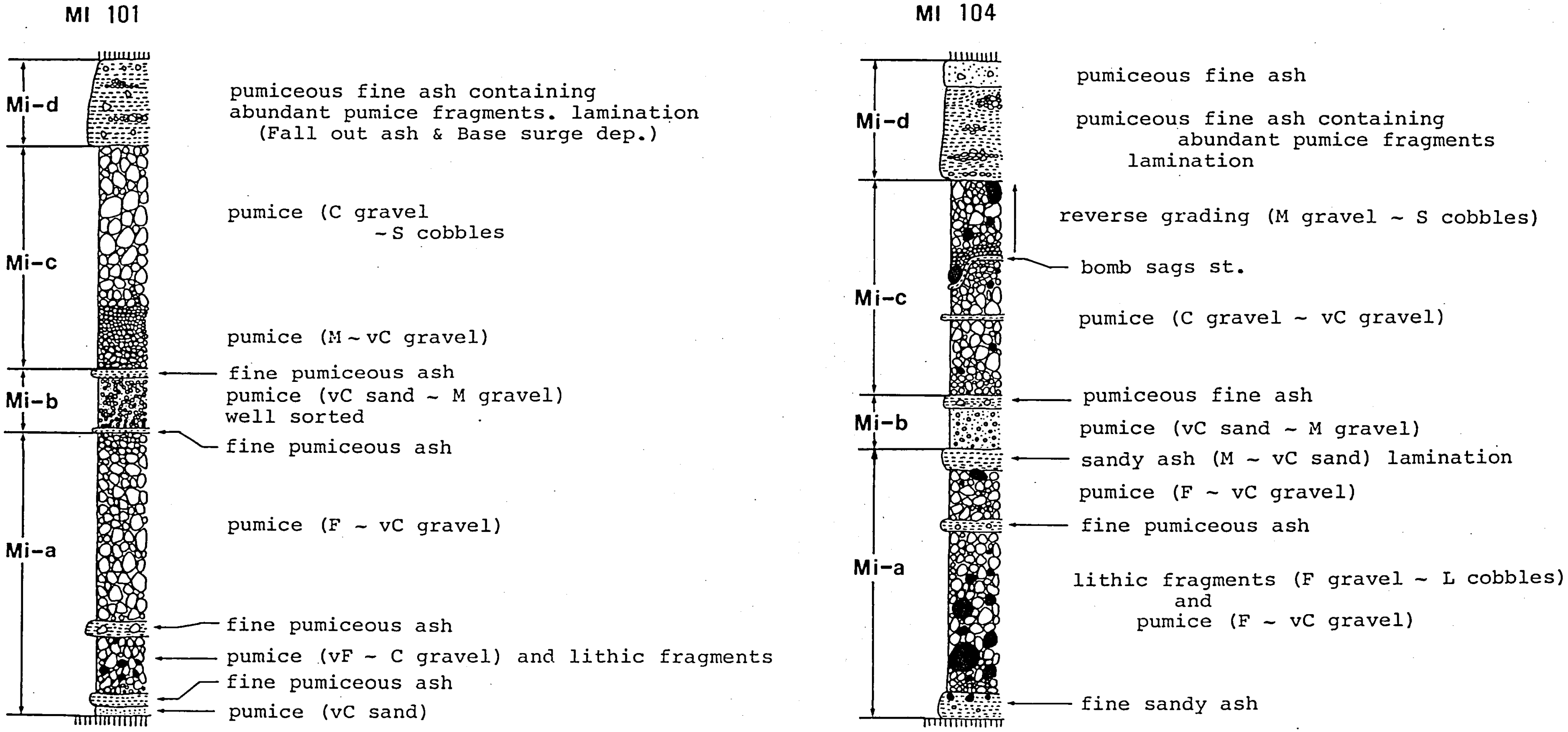

Fig. 17. Diagram showing cross sections of the Mi-ike pumice fall deposit. See Fig.14 for localities of sketched sections.

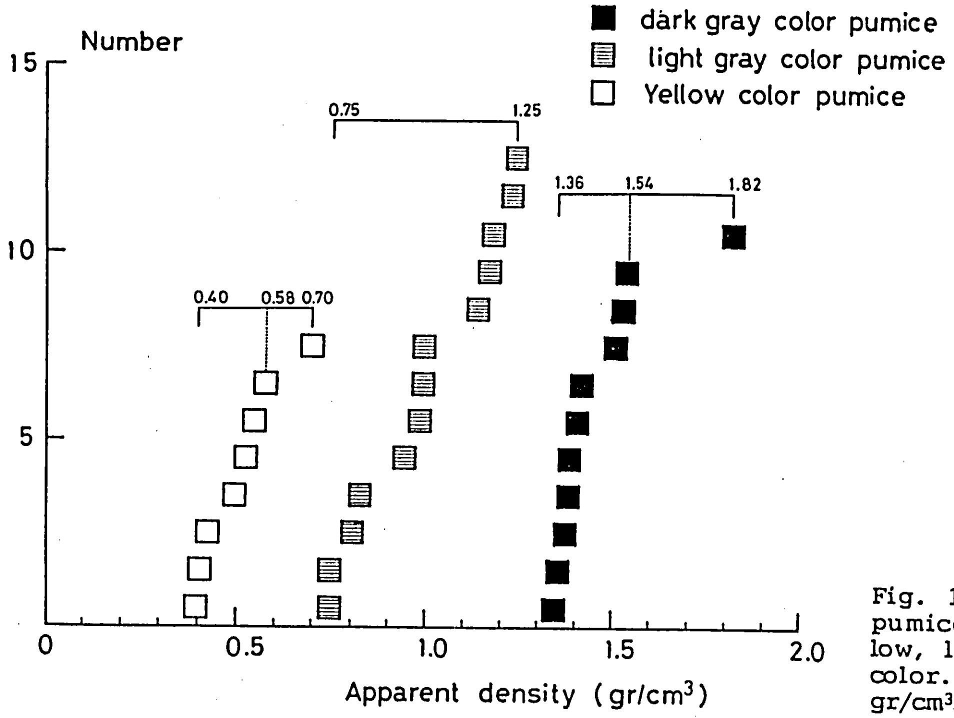

Fig. 18. Apparent density for pumice fragments showing yellow, light gray and dark gray color. Density values in gr/cm^3.

ments decreases toward the top of the Mi-b unit as the eruption proceeds, and at the Mi-c unit, their diameter increases again. These facts, coupled with the nature of the vertical variation of the grain size of pumice fragments, suggest that the eruption energy has fluctuated during the eruptions of Mi-a to Mi-c and attained to the maximum state at the respective unit of Mi-a and Mi-c.

Another most important feature of the deposit is coexistence of yellowish white pumice and dark(or light) gray pumice. The ratio of gray pumice to all pumice fragments varies systematically through the deposits. As shown in Fig.16(c), the ratio is nearly constant through the fall unit of Mi-a and Mi-b, but the ratio increased rapidly within the Mi-c unit as the eruption proceeds. The ratio through the Mi-a and Mi-b units is less than 10 weight percent, whereas, at the top of the Mi-c unit, the ratio attained to 30 or more weight percent. Similar fact was also observed in the 1977 tephra from Usu Volcano(Suzuki, et al., 1982).

The measurement of a apparent density of pumice fragments was made in order to see the change of vesiculation degree within the pumice fall deposit. The data of apparent density were obtained by a paraffin coating method and the results are shown in Fig.18. The apparent density of yellowish white pumice ranges from 0.40 to 0.70 g/cm^3, while the apparent density of gray pumice ranges from 0.75 to 1.82 g/cm^3. There is no large difference in true density between the yellowish white pumice and the gray pumice. The large difference emerged in the apparent density may be due to the difference of the vesiculation degree between them. This conclusion indicates that the vesiculation degree of yellowish white pumice is higher than that of gray pumice. A progressive increase in the contents of gray pumice fragments, as shown in the Fig.16(c), implies that the vesiculation degree of magma gradually decreases with time toward the end. Such a phenomenon may be interpreted in terms of a higher concentration of water in the upper part of magma column.

g-3. Pyroclastic surge deposits

General statements:

Much finer, ill-sorted and well-stratified deposits are intercalated within and overlie the fall out pumice deposit around the Mi-ike maar(Fig.4). These are extremely heterogeneous and the grain size of individual strata varies considerably. Cross-stratification and duned structures are very common(Fig.19(B)). These cross-stratified deposits are thought to have been formed by base surge rather than by more normal sedimentary processes because :
(i) They are composed largely of low density pumice and ash which would float in an aqueous environment. (ii) The deposits mantle the topography, and even occur on top of the hill of more than 150 m above the water-level of the Mi-ike lake. This indicates that they were

an expanded gas-particle mixture similar to that observed in recent base surge eruptions. (iii) Bomb sags occur between the cross-stratified beds, showing that volcanic explosions accompanied their formation.

These surge deposits surrounding the crater are approximately more than 30 m thick at the crater rim and extend out for slightly more than 7,500 m.

The base surge deposits derived from the Mi-ike maar has first been pointed out by Kobayashi(1980) and the bedding structures and other directional features of the surge deposits have been in details described by Kaneko et al.(1985,1986).

Bed forms

According to Kaneko et al.(1986), bed forms from base surges around the Mi-ike maar occur as five kinds; plane-parallel beds, wave beds, massive beds I, massive beds II and thin beds. These are briefly described as follows.

(1) Plane-parallel beds. Plane-parallel beds have their top and bottom surfaces which are generally planar and parallel to one another. Such beds are concordant with contiguous layers and sometimes normally or reversely graded, but unlike fall out layers, may erode underlying beds. As shown in Fig.19(A), layers of pumiceous fine ash alternate with layers of lapilli fragments composed mainly of pumice and accidental lithics. The thickness of one layer ranges from 5 cm to 15 cm, and their total thickness amounts to more than 1 m. The plane-parallel beds grade laterally into zones of cross bedding.

(2) Wave beds. The term wave beds is applied to beds with undulating surfaces or surfaces inclined to the depositional substrate and includes a variety of bed forms such as dunes, antidunes and internal laminae which are commonly very subtly cross-bedded or lenticular over short distance. These beds are composed of medium to coarse-sand size materials with relatively better sorting.

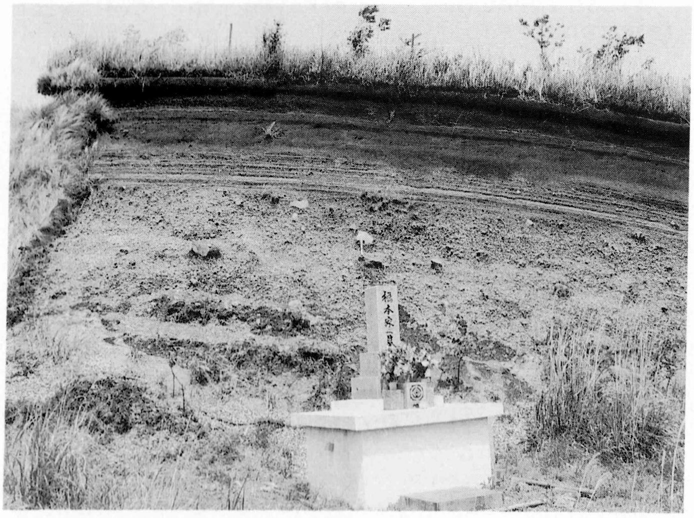

Fig. 19. Two bed forms of base surges formed in the Mi-ike eruption. (A) Upper part showing plane-parallel beds and generally finer-grained aspect than lower part made up of pumice fall deposit. Flow direction from left to right. Spade is 60 cm long.

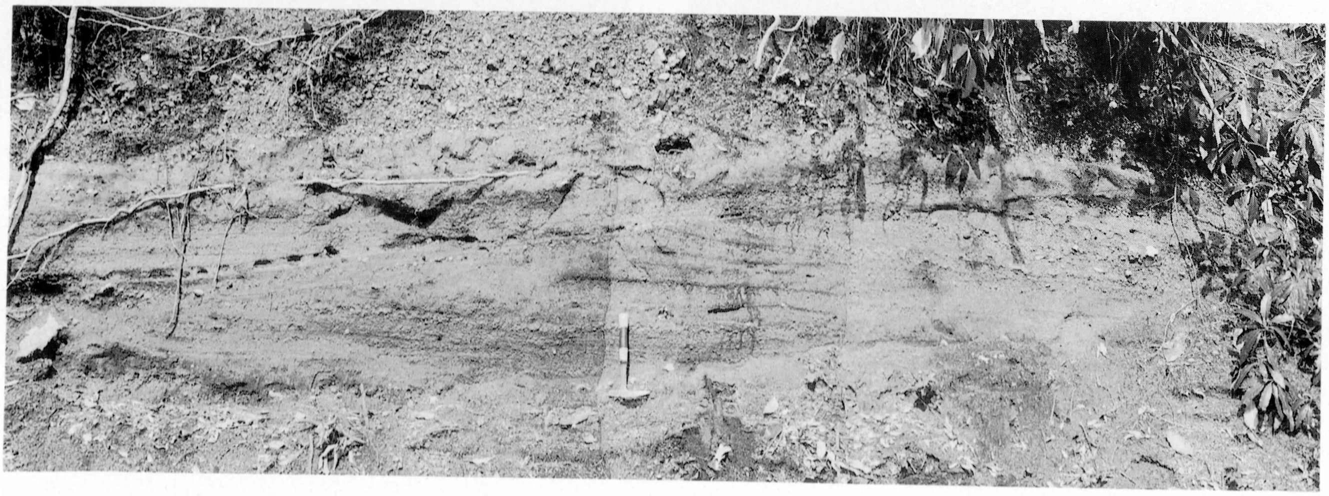

Fig.19 (continued). (B) Wave beds showing dune-like structure. Flow direction from left to right.

In exposures cut parallel to flow direction[e.g. Fig.19(B), current direction from left to right] many of wave beds occurs as parts of duned structures. These beds commonly erode underlying beds rather than evenly mantling underlying wave beds. Crests are broad, and downstream migration of the crests is more common. Furthermore, the beds with such characteristics show inverse grading and contain platy fragments which are aligned roughly parallel to bedding surfaces or are imbricated.

(3) Massive beds I. Massive beds I are mostly unstratified, ungraded and rarely show internal structures. They commonly randomly scattered cobble to boulder size accidental clasts and cobble size pumice lumps. The beds which are characterized by a dominance of fine ash materials closely resemble small ash flow deposits in appearance. The thickness of the beds is usually 1 m or less, but at the crater rim it attains to more than 10 m. They usually are thicker, and more poorly sorted than plane-parallel beds or wave beds.

(4) Massive beds II. Massive beds II are distinctive massive ash beds containing lapilli size fragments which are frequently arranged in ill-defined zones parallel to the bedding surfaces. These beds show sometimes internal structures such as parallel laminations and undulating laminae, though poorly developed.

(5) Thin beds. They are massive thin layers composed mainly of pumiceous fine ash and lapilli of pumice and lithics. As shown in Figs.17 and 20, the beds are commonly intercalated within the fall out pumice deposits. Their thickness ranges from a few tens to 1.5 cm. According to Kaneko et al.(1986), the term thin beds is for such beds that their thickness is less than 5 cm. However, the thin beds composed mainly of pumiceous fine ash with a few cm thick commonly change laterally into the sequences of bedded volcanic silt, ash and lapilli with several tens cm in thickness.

Lateral facies change of thin beds

Well then, is it really correct to recognize the thin beds as a member of base surge deposits ? For example, the mode of occurrence of the thin beds[Fig.20(a)] leads us to the idea that they are of fallout origin and represent the quieter periods of explosive activity. In deed, Kaneko et al.(1986) dose not deny the above idea and demonstrated a lateral variation of bed forms of surge deposits away from the vent, including thin beds as a member of the surge deposits.

Fig.21 shows a lateral facies change of the thin beds, in which eleven cross sections were examined and an alphabetical code is assigned to each cross section from A to K as away from the crater. Comparison of the eleven cross sections illustrates the following features:

(1) The thin bed recognized at the cross section of J peters out at the cross section K, although the distance between J and K is not so far cry , showing a abrupt decrease in thickness away from the source.

(2) At the cross section J, the thin bed with 4 cm thick shows an undulating appearance[Fig.20(b)].

(3) Observing an exposure of a thin bed, it is easily noticed that there is no distinct difference in grain size of pumice fragments between the upper and the lower sides of the thin bed. As seen from the Fig.16(a), the thin beds are also intercalated with the fallout pumice deposits regardless of vertical variations of the grain size of pumice fragments.

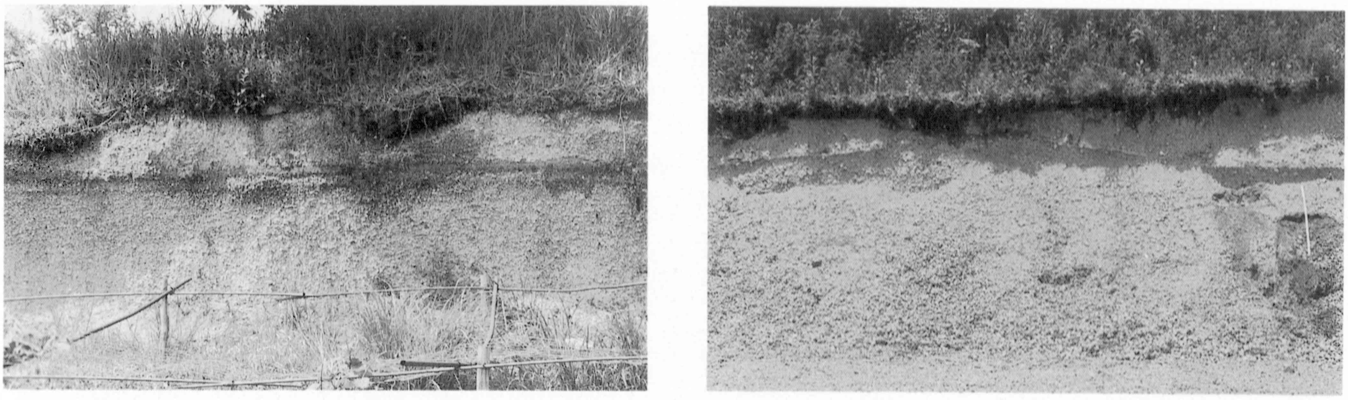

Fig. 20. Thin beds intercalated in pumice fall deposit.

(A) two layers of thin bed. The thickness of the upperbed is 8 cm and the lower is 3 cm thick.

(B) thin bed(4 cm in thickness) showing wavy appearance. Flow direction from right to left. Bar is 1 m long.

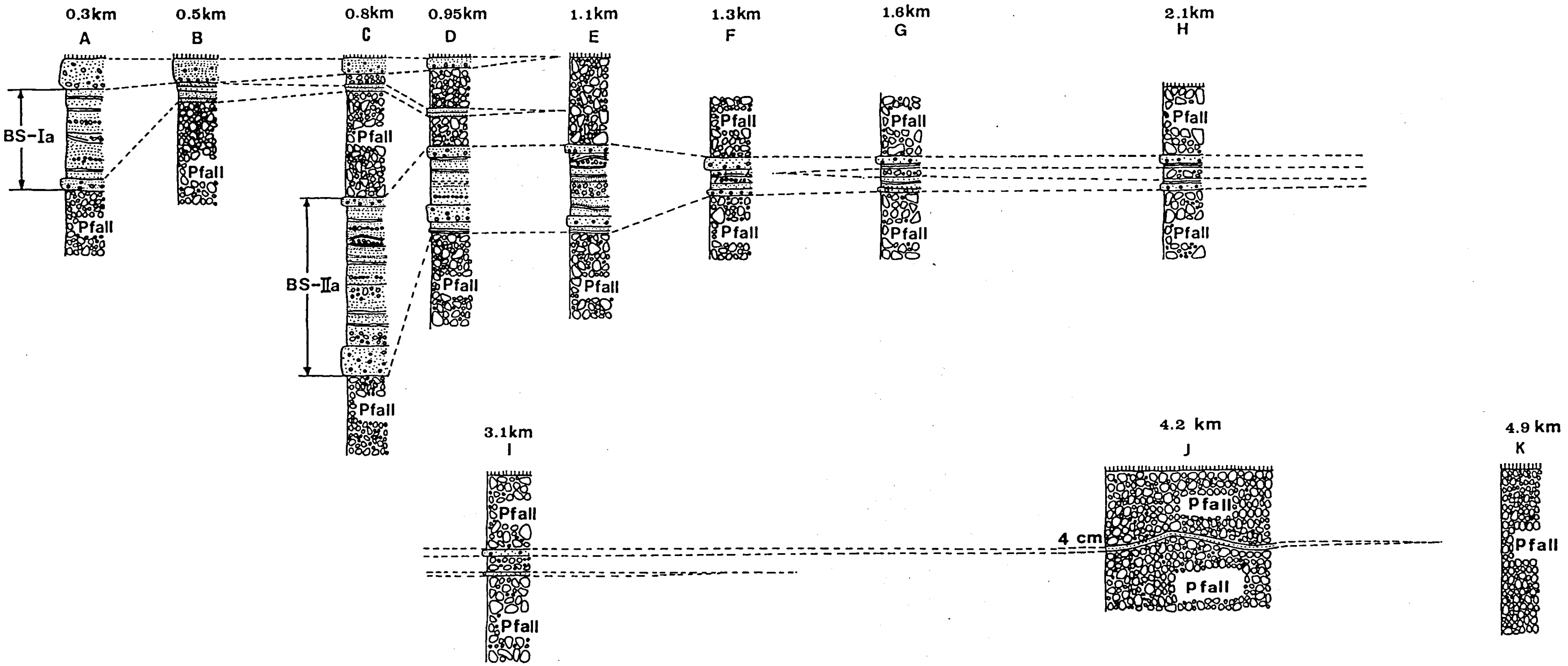

Fig. 21. Diagram showing the lateral facies change of thin beds. Dashed lines indicate correlation of the same bed. Flow direction from left to right. Numerals above columns are the distance from the source in kms.

(4) As the distance from the source decreases, two thin beds(G, H and I) merge into a single thin bed(F). As shown in Fig.22, the grown-up thin bed has a inner structure showing a flowage differentiation which is characterized by the concentration of lapilli-grained fragments in the central part of the bed. These features can not be explained by fallout mechanism.

The above described features indicate that the thin beds are of flow mechanism origin and correspond to apparently terminal facies of base surge deposits.

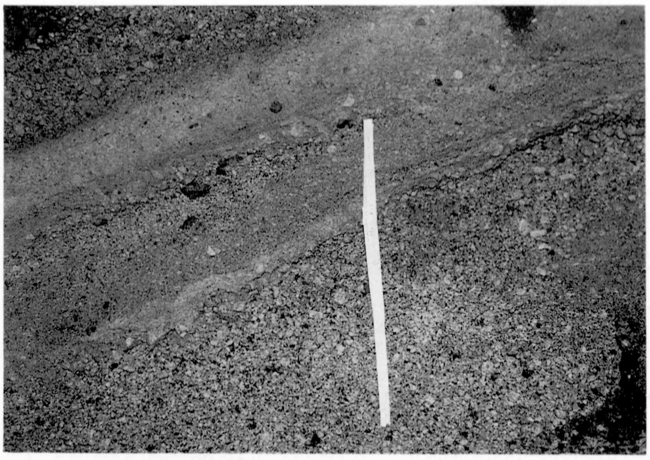

Fig. 22. Closer view of thin bed at the location of F in Fig. 21. Looking from a direction perpendicular to flow direction. Note the inner structure which flowage differentiation. Bar is 50 cm long.

g-4. Age relation

Date of the Mi-ike pumice fall deposit has been inferred from the excavated fragmental pottery remains as 3,000 y.B.P. (Kuwano et al.,1959), but this estimated age has not been yet confirmed by radiometric age determinations.

h. Fallout tephra deposits

During the third stage activity of KVG, vast amount of fallout tephras erupted from the many centers and was accumulated mainly on its eastern foot. Many of them are traceable to Takachiho Compound Volcano(TCV), and some of them are interbedded with the eruptive units such as lava flows and pyroclastic deposits which constitute the cones of TCV. Therefore, the study of stratigraphic sequence of such fallout deposits would give an important clue to dating the events of TCV.

Columnar sections of the representative outcrops of such fallout deposits are given in Fig.23, in which an idealized "standard section" of the tephra deposits is also shown. The standard section illustrates an imaginary columnar section without any missing part, on which the stratigraphic positions of the lava flows of TCV are superimposed.

The lithology of each fallout deposit is described here in ascending order referring to the representative columnar sections(Fig.23). Distribution of each deposit is shown by isopach lines in cms(Figs.25, and 28). Its total volume is calculated using the empirical formula proposed by Hayakawa (1985).

Karakuni-dake scoria deposit(KDS)

KDS, which is named by Imura and Kobayashi(1987), is the oldest eruptive products of the third stage activity of KVG. It is composed of an alternation of coarse scoria beds and fine ash beds. A good section of the deposit, 246 cm thick, is exposed on a roadcut north of the Daiichi Shiratori Onsen (Fig.24, KVG100):

60 cm	reddish brown scoria, MS(maximum scoria size) 8 cm
15 cm	black ash with normal grading
8 cm	brown fine ash
1-cm	reddish brown scoria with less than 1 cm in size
7 cm	black fine ash
110 cm	reddish brown scoria, MS 2.5 cm
10 cm	brown fine ash
10 cm	black fine ash
25 cm	reddish brown scoria, MS 2.5 cm

This scoria deposit have previously been thought to have come from Iimori-yama, but recently clarified to have been derived from Old-Karakuni-dake Volcano (Imura and Kobayashi,1987) which is completely overlain by Karakuni-dake Volcano. Nakamura(1987) roughly dated the eruption age of the scoria deposit to be about 18,000 y.B.P. with reference to its stratigraphic positions between the fundamental time-maker tephras.

Kobayashi pumice deposit (KYP)

The Kobayashi pumice deposit named by Naruse(1966) is the only fallout tephra of Karakuni-dake Volcano origin(Inoue, 1988). It is easily distinguished from other fallout pumice deposits by the presence of intercalated ash layers with bluish gray color. A typical whole succession of the Kobayashi pumice deposit is exposed at 750 m north of the Sano Shrine(Fig.24, KVG101) :

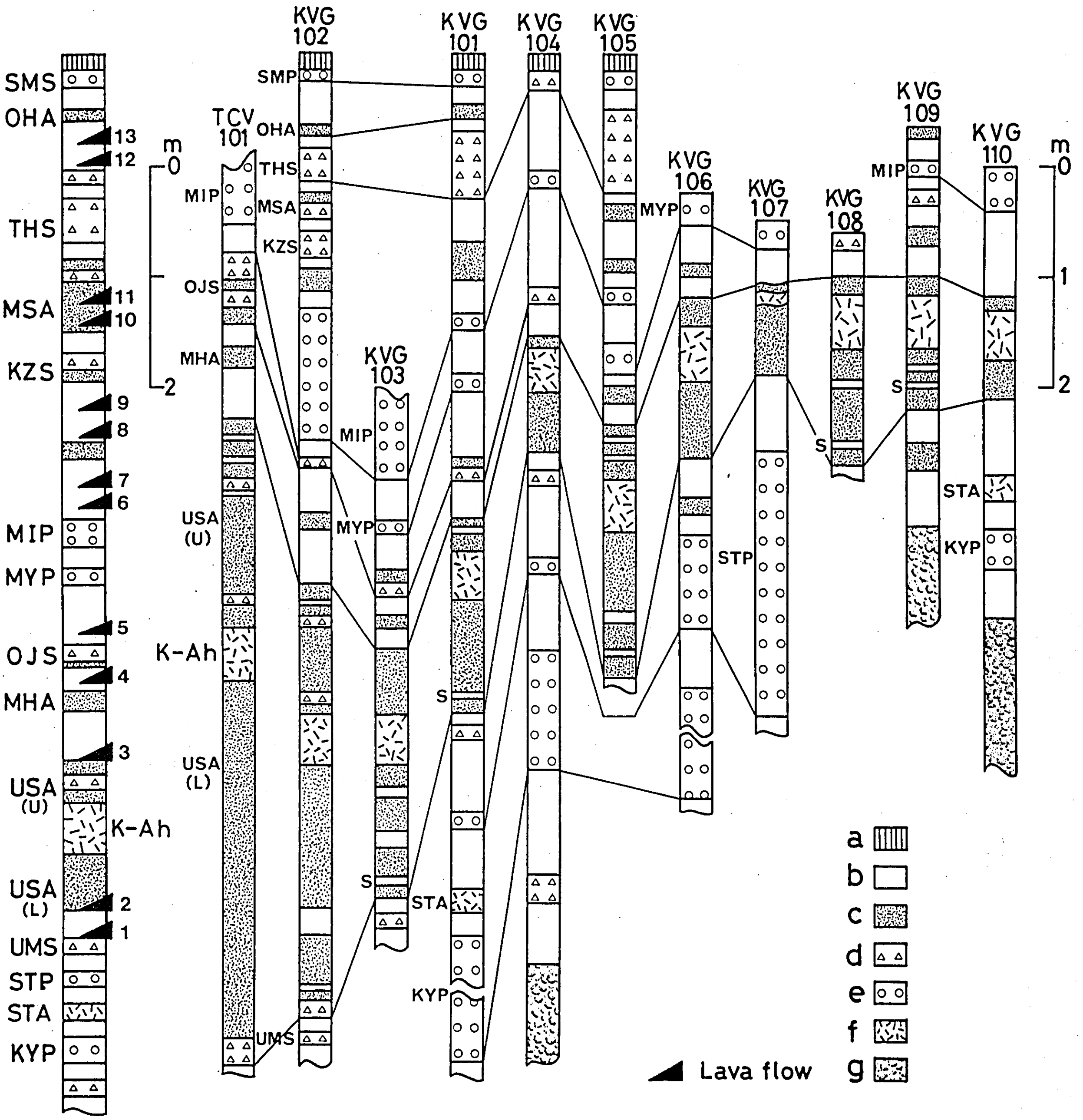

Fig. 23. Diagram shwing correlation of representative stratigraphic sections and an idealized standard section of the fallout deposits of the eastern foot of Kirishima Volcano Group. See Fig.26 for the localities of those sections. (a) soil, (b) weathered ash, (c) volcanic ash, (d) scoria, (e) pumice, (f) pumiceous fine ash, (g) Ito pyroclastic flow deposit. (1) Natsuo lava, (2) Tonokuchi lava, (3) Old-Takachiho lava, (4) Takachiho-no-mine lava I, (5) Takachiho-no-mine lava II, (6-13) Ohachi lava I-VIII. KDS: Karakuni-dake scoria, YPS: Kobayashi pumice, STA: Satsuma ash, STP: Setao pumice, UMS: Uramuta scoria, USA: Ushinosune ash, K-Ah: Kikai-akahoya ash, MHA: Mochiharu ash, OJS: Ohji scoria, MYP: Maeyama pumice, MIP: Mi-ike pumice, KZS: Katazoe scoria, MSA: Miyasugi ash, THS: Takaharu scoria, OHA: Ohachi volcanic ash, SMS: Shinmoe-dake scoria. (U) upper part, (L) lower part.

15 cm	brown fine ash with scattered pumice lapilli
8 cm	yellow pumice lapilli with abundant vesicles and crystals, MP(maximum pumice size) 3 cm
2 cm	reddish brown scoria, MS 2 cm
10 cm	bluish gray fine ash containing abundant scoria lapilli
50 cm	coarser yellow pumice lapilli accompanied by small amount of reddish brown scoria, MP 8 cm
10 cm	bluish gray very coarse ash
4 cm	brown fine ash wiht scattered pumice and scoria
12 cm	light gray very coarse ash with pumice lapilli
32 cm	yellow pumice lapilli, MP 5.8 cm
5 cm	bluish fine ash
7 cm	yellow pumice lapilli, MP 4 cm
3 cm	reddish brown scoria lapilli, MS 3 cm

As seen in the representative section, the Kobayashi pumice deposit is composed of many kinds of fallout units, but no distinct soil layer exists among them. However, thin layer of brown ash(4cm thick) intercalated at about two fifth from the base suggests the event in which the high plinian column was once lowered or interrupted during the eruption.

The radiocarbon date of 15,750 + 270 y.B.P.(Machida, et al., 1984) was obtained from the underlying humus soil. On the other hand, the pumice deposit is overlain by the vitric ash deposit called Satsuma (11,2200 + 200 y.B.P., Ishikawa et al.,1972) with intervening weathered zone. Their stratigraphic relationships suggest that the eruptive age of the pumice deposit may be around 13,000-14,000 y.B.P.

Satsuma tephra(STA)

At the two cross sections of KVG105 and KVG112 in Fig.24, the Satsuma tephras(Arai and Machida, 1980) layer is intercalated in the weathered ash or soil, where its pale orange color exhibits a striking contrast to the dark brown color of the surrounding weathered tephras. It is composed mainly of mircopumice of fine ash size, and at its base is scattered yellow pumice with less than 1 cm in size.

The thickness of the deposit is almost constant within KVG, but it increases gradually as away from KVG, suggesting that the tephra is not of KVG origin. As shown in its isopach map , the dispersal axis extends to N140^{o}W direction and its thickness increases toward Kagoshima City, where it has been identified as the Satsuma tephra derived from Sakurajima Volcano. The radiocarbon date of 11,220 + 200 y.B.P. was determined on carbonized wood from this horizon(Ishikawa et al., 1972).

Setao pumice deposit (STP)

One of the best exposures of the Setao pumice deposit is a roadcut at the northern foot of Yatake Volcano(Fig,24, KVG106), where the deposit consists of tree fall units:

15 cm	pumiceous fine ash with scattered pumice lapilli
43 cm	yellow pumice; MP 7 cm
25 cm	reddish brown pumice with a large amount of lithic fragments; MP 7 cm

As shown in the isopach map (Fig.25), the pumice deposit extends to N70^{o}E in a narrow dispersal fan from Shinmoe-dake Volcano and is represented as one-layer deposit at localities more than about 7 km distant from the source. At the eastern foot of Shinmoe-dake Volcano, a few bread-crust pumice lumps with a banded appearance (up to 80 cm in diameter) are emplaced ballistically into the pumice deposit.

Uramuta scoria deposit (UMS)

The Uramuta scoria deposit(Inoue, 1988) is the products first expelled during the period of the reopening eruptive activity of TCV which occurred after the state of dormancy for a long period. Its type section is observed in a roadcut on the 750 m north of the Sano Shrine(Fig.24, KVG101), where the 10 cm thick Uramuta scoria is intercalated in the black paleosol: 10 cm reddish brown scoria with brown fine ash, MS 3 cm

Although the isopach of the Uramuta scoria is less constrained(Fig.28 B), the dispersal axis is apparently traceable to Futagoishi or Old-Takachiho Volcano. But as seen from Fig.4, the vent positions of the two volcanoes are so close in distance that it is difficult to decide them using the isopach map only. At the southern limit of the isopach map, the scoria deposit is overlain by the Natsuo lava flow with the intervening thin layer of paleosol. But no distinct fallout tephra of Futagoishi Volcano origin lies below the Uramuta scoria deposit. These facts indicate that the eruptive activity of the scoria was closely related to the activity of the Natsuo lava flow which was extruded at the initial stage of activity of Old-Takachiho Volcano. Therefore, the eruptive source of the Uramuta scoria may be ascribed to Old-Takachiho Volcano rather than to Futagoishi Volcano. Its total volume is 0.012 km^3, as the isopach for calculating the volume is 8 cm.

Ushinosune ash deposit(USA)

The Ushinosune ash deposit, which

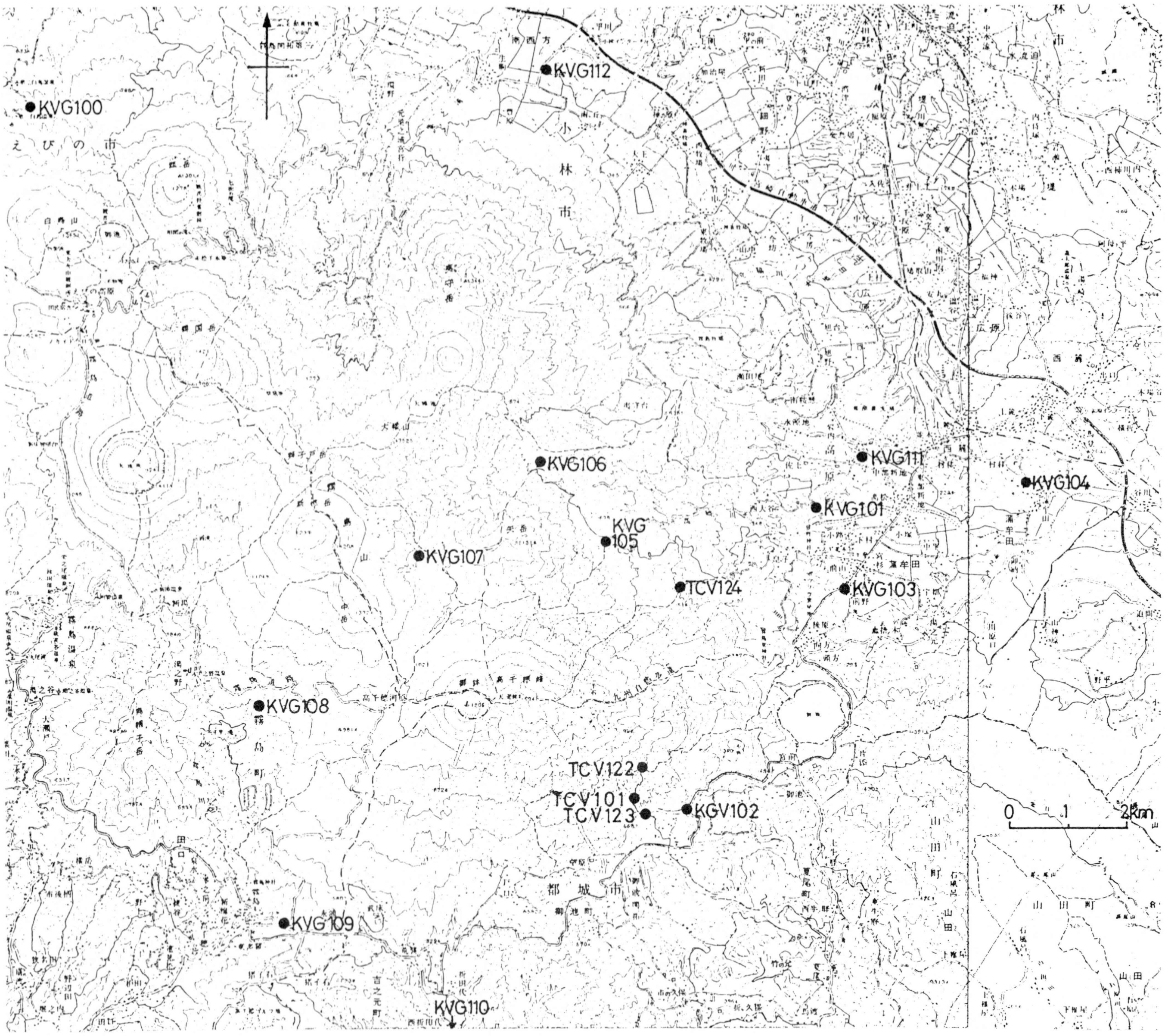

Fig. 24. Locality map. Naked number with TCV or KVG indicates the localities of columnar sections in Fig.23.

was redefined by Inoue(1988), is a representative fallout tephra of Old-Takachiho Volcano. The deposit is underlain by the Natsuo lava with some intervening weathered ash layers and is directly covered by the Old-Takachiho lava. It is well exposed on the 750 m north of Mi-ike elementary school(KVG102 in Fig,24), where Kikai Akahoya ash (K-Ah, Machida and Arai, 1978) is intercalated in the Ushinosune ash deposit. The ash deposit is :

20 cm	bluish gray ash with some intervening brown fine ash
3 cm	reddish brown scoria lapilli
60 cm	dark blue ash with lamination
8 cm	reddish brown scoria containig scattered lithic fragments
10 cm	dark blue ash with lamination
40 cm	orange color pumiceous fine ash containing accretionary lapilli at the bottom (K-Ah ash)
130 cm	laminated dark blue ash
25 cm	brown tight ash bed with a few intervening bluish gray ash
45 cm	laminated dark blue ash
12 cm	greenish gray fine ash
20 cm	reddish brown scoria with normal grading; MS 2.5 cm

As seen in the type section, the Ushinosune ash deposit consists of many fallout units and no distinct humus layer is present within the deposit. The ash parts with bluish color are characterized by the accumulation of ill-defined thin layers ranging in thickness from a few millimeters to several centimeters; most of them are less than about 3 cm thick. Such thin layers show mostly normal grading from very coarse sand-size at the bottom to medium sand-size at the top. The abundance of such thin layers presumably result from the large number of short and small scale eruption. The main constituents of the ash deposits are finely crushed solidifying lavas which preserve groundmass texture and are poorly vesiculated. This fact indicates that the Ushinosune ash deposit may be a product of typical vulcanian eruption.

The Ushinosune ash deposit is conveniently divided into the two parts, with reference to the presence of K-Ah, upper and lower parts. The isopach map of each part is shown in Fig.28 C and D. As shown in the figure, the isopachs of the upper and lower parts form circular patterns which exhibit a striking contrast to the fan-shaped pattern of typical plinian eruption-related deposits such as the Mi-ike pumice fall deposits (Fig.15). In general, the distribution pattern of the fallout tephra sheets shows wide variation between two end-member patterns, circular patter and fan-shaped pattern : circular patterns form from rather low eruption columns under calm winds, while elliptical or fan-shaped patterns from high eruption columns that encounter strong unidirectional winds such as westerlies. However, the most dominant distribution pattern of single tephra sheets is fan-shaped with the apex at the source, even if the height of eruption columns is not so high. The low eruption columns would be affected by a seasonal wind. On the other hand, circular isopach patterns of multicomponent sheets are probably due to unstable low velocity winds blowing below the height of a few km throughout all seasons and also due to relatively long eruption duration, during which the wind direction can change.

The total volume of the Ushinosune ash deposit is 1.218 km^3 whose volume approximates to the median value (1.2 km^3) of Holocene Japanese plinian deposits(Hayakawa, 1985).

Duration of Eruption

Fig.27 demonstrates the areal correlation of the Ushinosune ash deposit. Eight columnar sections in this figure are selected to surround the summit crater and arranged from right to left as the distance from the source increases. It is noticeable that the weathered ash and/or humus layers occur in the ash deposit. In the cross section of TCV101 and KVG102 which are close to the vent, the development of humus layer is not recognized in the lower part of the ash deposit. Even a weathered ash layer dose not exist in the lower one of the cross section of TCV101. While the columnar sections of KVG103 to KVG112 which are away from the vent are characterized by the presence of humus layer with several centimeter thick. Such paleosol layers can be traced in the field 360° around the summit crater and through KVG. These field evidences show that the paleosol layers pass into the weathered ash layers as distance from the source decrease and finally disappear into the bluish ash deposits at the neighborhood of the crater. According to Nakamura's(1964) definition on member which has no weathered zone within itself, the lower part of the Ushinosune ash deposit consists of one member near the source, while it is composed of a few members at a long distance from the source. Such unusual mode of occurrence of the ash deposit can not be explained by the concept of member defined by Nakamura(1964), which has been established on the basis of the fallout tephras of Oshima Volcano which is characterized by simple strombolian eruptions.

The mode of occurrence of the Ushinosune ash deposit implies that, while the formation of humus surface was proceeding, small vulcanian eruptions intermittently continued and fallout ashes were accumulated concentrically only around the vicinity of the source. Looking at it from a different angle, it is said that the formation of the ash deposit consumed a long period of time, which may be far longer than several ten years when considering the presence of humus and weathered ash layers within the ash deposit.

On the basis of the field relationships between the Ushinosune ash deposit and the lava flows constituting Old-Takachiho Volcano, Inoue(1988) concluded that Old-Takachiho Volcanoes formed within the time span of the eruptions which produced the Ushinosune ash deposit, indicating that the ash deposit is a product of eruptive epoch(Fisher and Schmincke, 1984) that lasted for several hundreds to a thousand of years. The unusual mode of occurrence of the Ushinosune ash deposit may be a general phenomenon of vulcanian eruptions.

Kikai-Akahoya ash (K-Ah)

The Kikai-Akahoya ash, which wa defined by Machida and Arai(1978), is a widespread tephra derived from the Kikai caldera, 80 km south of KVG. More than thirty radiocarbon dates have been obtained for the ash deposit , and the

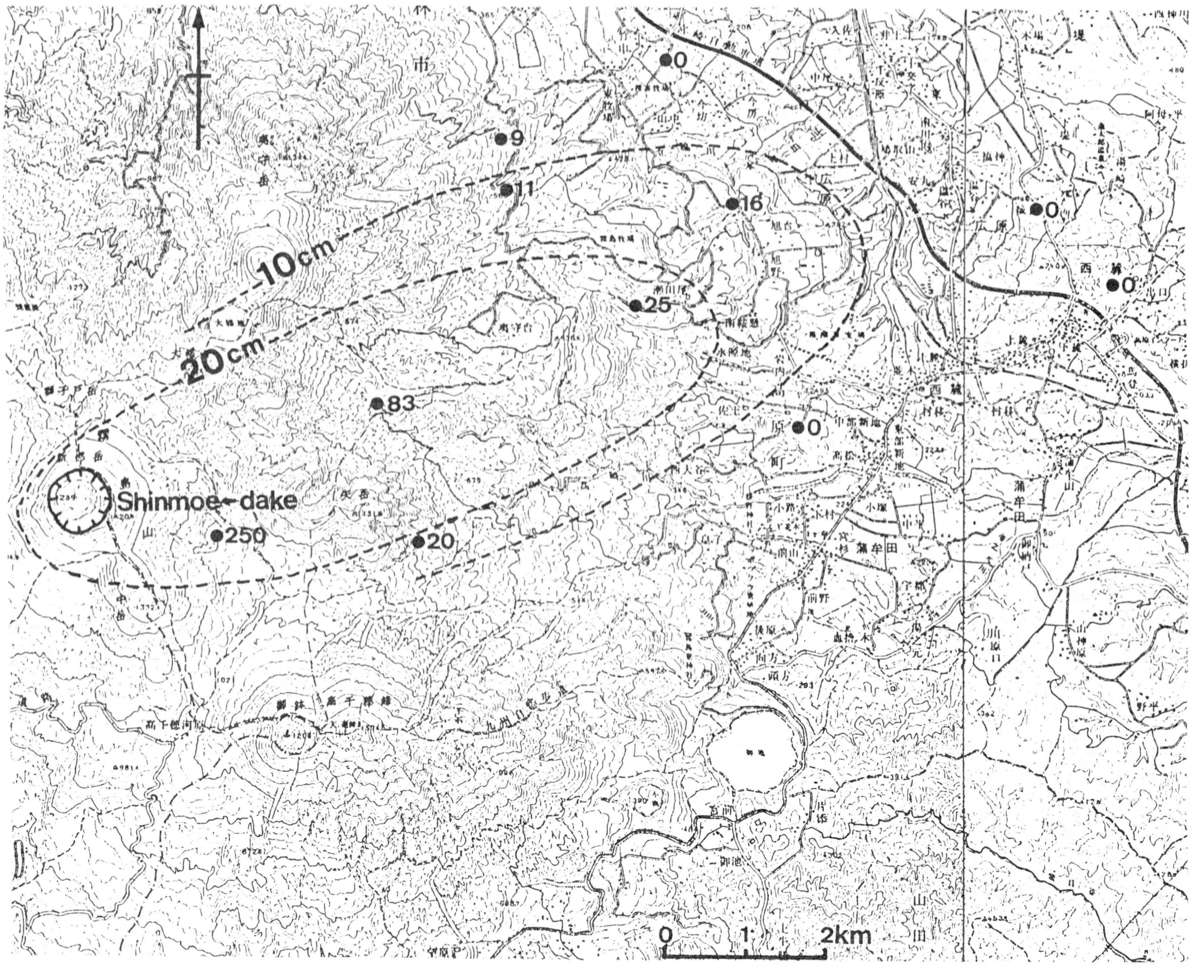

Fig. 25. Isopach map of the Setao pumice deposit(STP). Contour values in centimeters.

average is around 6,300 y.B.P.

The ash deposit consists of fine glass shards with orange color and contains abundant accretionary lapilli of less than 5 mm in diameter at its bottom. The ash bed is always intercalated in the Ushinosune ash deposit and its orange color exhibits a striking contrast to the dark bluish color of the Ushinosune ash deposit. The set of the Kikai-Akahoya and Ushinosune ash deposits is therefore useful as a key bed for the correlation purpose in proximal area.

Mochiharu ash deposit(MHA)

This ash deposit(Inoue, 1988) is the oldest fallout tephra of Takachiho-no-mine Volcano and is underlain by the Old-Takachiho lava. It is well exposed at the 1 km northwest of Mi-ike elementary school(TCV101 in Fig,24), where its thickness is 18 cm and its bottom part is reddish purple color, though the rest part is bluish gray color. The ash deposit is a tight bed with enclosed air bubbles and may be a product of a typical vulcanian eruption. It is characterized by the thinly laminated structure, suggesting relatively long eruption duration, say, a week or a month, but a year. This is because no layer of fallen leaves or soil is found within it and further its isopach(Fig.28,E) dose not form circular pattern such as that of the Ushinosune ash deposit. The total volume of the deposit is 0.02 Km^3.

Ohji scoria deposit(OJS)

The Ohji scoria deposit(Inoue, 1988) is the last fallout tephra of Takachiho-no-mine Volcano. It is composed of alternating beds of reddish brown scoria lapilli and bluish gray ash. The type section of the Ohji scoria deposit is a roadcut at the southern slope of Futagoishi Volcano(TCV101 in Fig, 24) where its total thickness is 41 cm:

18 cm reddish brown scoria intervening a thin layer of black ash, MS 2.0 cm

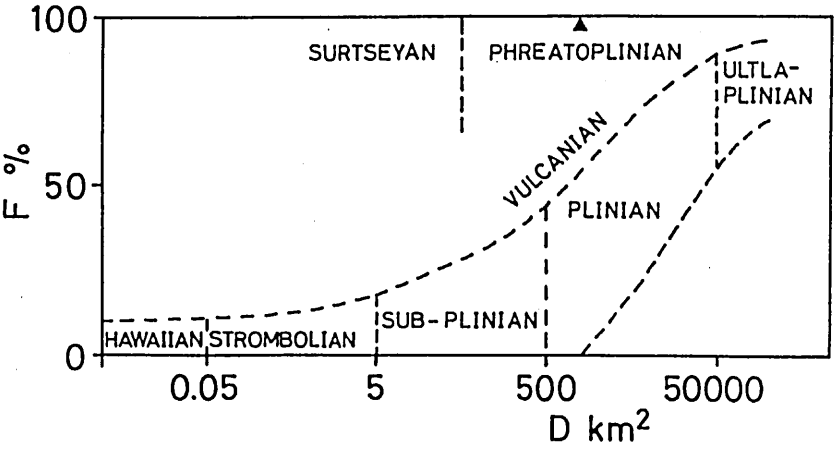

Fig. 26. Walker's(1973) classification of pyroclastic fall deposits. F % is weight percent of deposit finer than 1 mm along dispersal axis where it is crossed by isopach line which is 10 % of the maximum thickness(0.1 Tmax); D is the area enclosed by the (0.01 Tmax) isopach line. Phreatoplinian introduced by Self and Sparks(1978); ultraplinian introduced by Walker(1980). (after Wright et al., 1980).
▲: Lower part of the Ushinosune ash deposit.

5 cm	bluish gray ash
1 cm	pale brown colored weathered ash
3 cm	reddish brown scoria lapilli
5 cm	bluish gray ash
5 cm	reddish brown scoria lapilli
5 cm	bluish gray ash

The main constituents of the bluish ash deposit are finely crushed solidifying lavas, indicating that it is a typical product of vulcanian eruption. The two dispersal fans are recognized : one is remarkably elongated toward N70°E and the other is N130°E(Fig.28,F). The isopach map faithfully reflects the distribution of the reddish brown scoria. The total thickness of the deposit is 0.027 km^3.

Maeyama pumice deposit(MYP)

The distribution of the Maeyama pumice deposit(Inoue, 1988) is restricted to a narrow zone of the eastern side of Shinmoe-dake Volcano and its thickness increases toward Shinmoe-dake Volcano, suggesting a possibility that its source is Shinmoe-dake Volcano. The pumice fragments have a pale brown to reddish brown color and are well vesiculated.

Mi-ike pumice deposit (MIP)

The Mi-ike pumice deposit(Kuwano et al., 1956), which was called by Kuwano et al.(1959), has already been in detail described in the previous section.

Oh1(pale brown colored fine ash deposit)

Oh1 is the oldest fallout tephra of Ohachi Volcano origin and is composed of pale brown colored fine ash which is soft containing scattered lithic fragments(less than 1 cm in diameter). The distribution of this tephra is restricted to the southern foot of TCV, suggesting a possibility that this fallout tephra is of Ohachi Volcano origin.

Oh2(black ash deposit)

Oh2 is an ash deposit distributed at the southern foot of TCV and its thickness increases toward Ohachi Volcano. Also the deposit is directly underlain by the Ohachi lava II and is covered by the Ohachi lava III. These facts suggest that the ash deposit is of Ohachi Volcano origin. The constituents of the ash deposit are finely crushed solidifying lavas.

Oh3 (pale brown colored fine ash deposit)

Oh3 is composed of pale brown colored fine ash bed which is soft and contains scattered reddish brown scoria. The scoria lapilli are less than 1.0 cm in diameter and tend to be concentrated in the upper part of the deposit.

As already stated in the previous section, this ash deposit is not a time-rock unit showing a short period in stratigraphy, but useful as a key bed for the correlation purpose, because it can be laterally traced throughout TCV.

Oh4 (Katazoe scoria deposit: KZS)

The type section of Oh4 is a road-cut at the 750 m northwest of the Mi-ike elementary school(Fig.24, KVG102), where it consists of three fall units and its total thickness is 25 cm :

5 cm	dark brown fine ash with scattered brown scoria fragments; MS 0.8 cm
5 cm	dark brown scoriaceous ash ; faint reverse grading from fine size to medium size ash
15 cm	dark brown scoriaceous ash ; faint reverse grading from medium size ash to scoria lapilli, MS 1.0 cm

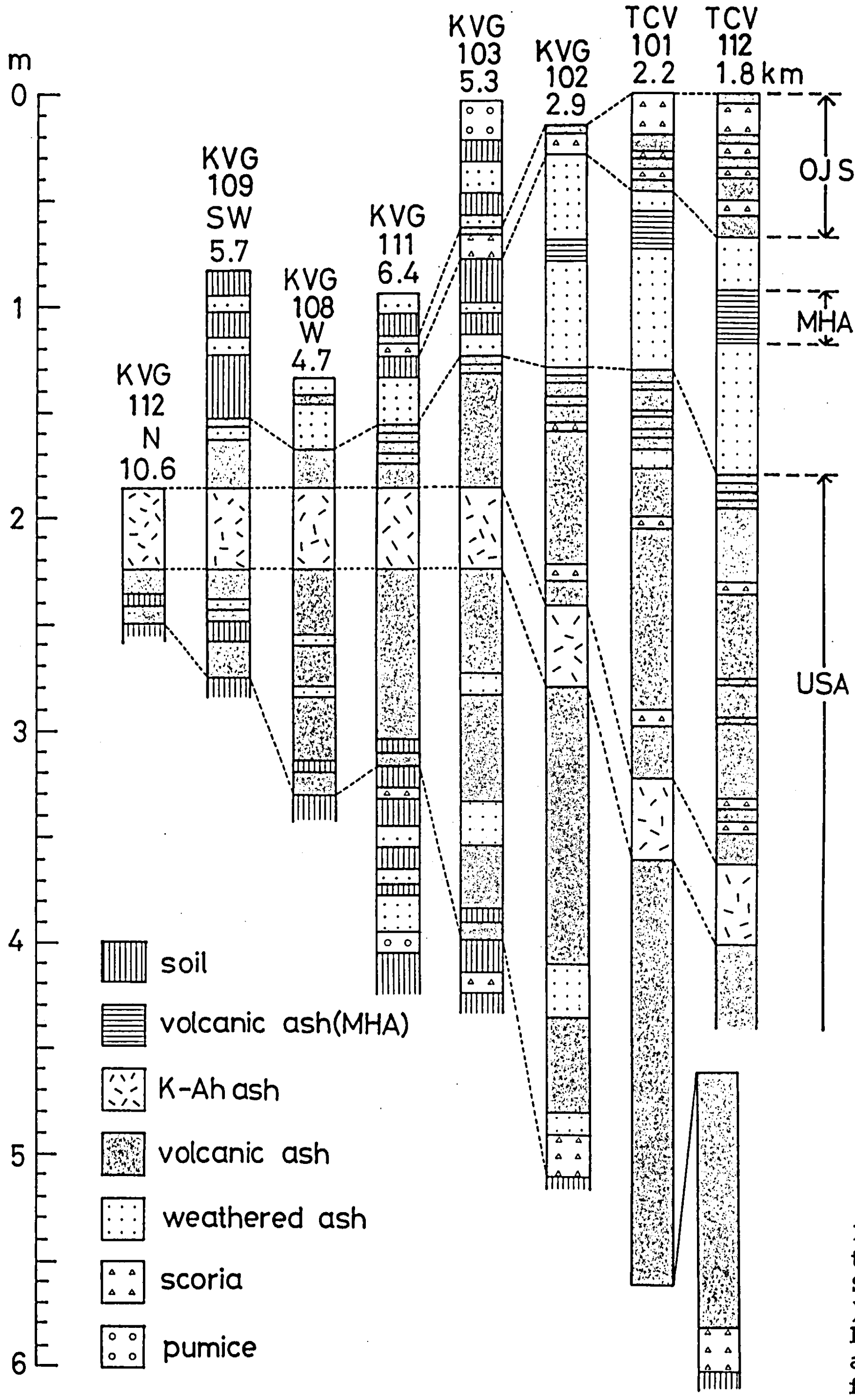

Fig. 27. Areal correlation of the Ushinosune ash deposit (See Fig.24 for data locations). Dashed lines indicate layer correlation. Numerals above columns are the distance from the source in kms.

On the basis of the Walker's(1973b) classification, the Katazoe scoria deposit is a product of sub-plinian eruption and its volume is 0.037 km^3. As shown in Fig.28 G, its isopachs have a fan-shaped form and three dispersal axes are recognized. Following the eruption of this fallout scoria, a small-scale scoria flow flowed out to the southern flank of Ohachi Volcano(Fig.12, TCV107). However, the distribution of the scoria flow deposit is not drawn on the geological map, because its distribution area is so narrow.

Oh5 (reddish purple fine ash)

Oh5 is composed of reddish purple fine ash and its distribution is restricted to the narrow elongated zone. It is well exposed at a roadcut around the Sano shrine.

Oh6 (Miyasugi ash deposit: MSA)

Miyasugi ash deposit, which was defined by Inoue(1988), is the second largest-volume tephra of Ohachi Volcano origin. As shown in Fig.28. H, the isopach pattern of the deposit consists of two dispersal fans : One extends to N70°E and is composed mainly of scoriaceous ash deposit. The other is elongated toward N140°E and is made up three fall units of scoriaceous materials. The well exposure of this deposit is preserved at a roadcut northwest of Mi-ike elementary school(Fig.24, TCV123), where its total thickness is 44 cm:

16 cm	bluish gray scoriaceous ash with ill-defined lamination; abundant fallen leaves with white color
17 cm	black scoria lapilli with scattered lithic fragments; poorly vesiculated; MS 3.5 cm
1 cm	brown color weathered fine ash
10 cm	bluish gray scoriaceous ash with ill-defined lamination

The distribution of scoria lapilli is restricted to the dispersal fan extending to N140°E. The total volume of the Miyasugi ash deposit is 0.051 km^3.

Oh7 (Takaharu scoria deposit: THS)

Takaharu scoria, which was called by Endo et al.(1969), is the largest-volume tephra of Ohachi Volcano origin and its volume is 0.257 km^3. As shown in Fig.28 I, its isopachs are of asymmetrical fan-shaped pattern and two distinct dispersal axes are recognized : One is oriented in a direction of N60°E and the other is in a direction of N95°E. The type section of this deposit is established at a roadcut northwest of the Mi-ike maar(Fig.24, TCV124), where the deposit consists of five fall units and its total thickness is 115 cm:

55 cm	black scoria lapilli; MS 5 cm
25 cm	coarser black to reddish purple scoria lapilli withscattered white and banded pumice fragments; poorly sorted; MS 25 cm
19 cm	black scoria lapilli ; MS 3.5 cm
6 cm	black scoriaceous ash ; coarse sand size
10 cm	brown scoria lapilli ; well vesiculated ; well sorted; MS 3 cm

Based upon the Walker's(1973b) classification, the Takaharu scoria deposit is plotted in the area of subplinian eruption.

As shown in Fig.23(TCV102), the Takaharu scoria deposit is overlain by the Shinmoe-dake pumice deposit which is a product of the 1716-1717 A.D. activity of Shinmoe-dake Volcano. Before the eruption of 1716-1717 A.D., more than 20 times of eruptions have been recorded on an old document (Omori, 1918). According to the old document, the eruption of 788 A.D. is characterized by the accumulation of black pyroclastic materials and its thickness attained to 60 cm at the eastern foot of KVG. This description is conformable with the mode of occurrence of the Takaharu scoria deposit, that is, it is of black color and its thickness is from 70 cm to 50 cm at the eastern foot of KVG. Therefore, the member of the Takaharu scoria deposit can be assigned to the eruptive activity of 788 A.D. Okada(1985) have reported the radiocarbon date of 1,050 y.B.P. from this scoria deposit.

Of all the scoria deposits of Ohachi Volcano origin, white pumice fragments were contained only in the Takaharu scoria deposit, and they are useful to distinguish the Takaharu scoria deposit from the other scoria deposits. Within the crater wall of Ohachi Volcano, the white pumice fragments have been found from the place situated about 5 m below the top of the crater rim (Inoue, 1988). This fact suggests that, when the eruption of the Takaharu scoria took place, the height of Ohachi Volcano had already attained to the present state. In other word, the eruptive activity of Takaharu scoria did not contributed to the growth of volcanic edifice of Ohachi Volcano.

Oh8 (Ohachi ash deposit: OHA)

Oh8 is composed of black fine ash with ill-defined lamination, which was named Ohachi ash deposit(Inoue, 1988). As shown in Fig.28 J, the ash deposit is mainly distributed in the southern and northeastern foot of TCV. Because its thickness increases toward Ohachi Volcano, the source of this ash deposit may be Ohachi Volcano. Its estimated volume is 0.022 km^3.

Oh9 (light gray scoria deposit)

Oh9 member consists of light gray scoria lapilli(less than 5 mm in diameter) and is overlain by the Shinmoe-dake scoria deposit with the intervening soil layer. Owing to no presence of isopach map, the source of this deposit is not confirmed enough, but there is a strong possibility for it to be Ohachi Volcano .

Shinmoe-dake scoria deposit(SMS)

SMS is the youngest fallout tephra distributed in the eastern area of KVG and is intercalated in the black humic soil about 15 cm below the present surface. This scoria deposit thickens toward Shinmoe-dake Volcano and passes into the alternation of fallout tephra deposits and scoria flow or base surge deposits at the eastern flank of Shinmoe-dake Volcano, indicating that this scoria deposit is of Shinmoe-dake Volcano origin.

One of the best exposures of the

scoria deposit is a roadcut at the northeastern foot of Yatake Volcano, where the deposit is composed of several fall units and its thickness is 59 cm :

10 cm	gray color scoria with abundant accidental lithic fragments ; MP 6 cm
2 cm	bright yellow very fine ash
13 cm	reversely graded gray scoria with abundant accidental lithic fragments ; MS 5 cm ; reddish purple scoria block(up to 20 cm in diameter) emplaced ballistically into this layer
3 cm	bright yellow fine ash with weak lamination
20-cm	pale brown coarse scoria with abundant large lithic fragments; ML(Maximum lithic size) 6 cm
5 cm	sky bluish and light gray very fine ash with well developed lamination structure
7 cm	inversely graded gray color scoria ; well sorted ; MP 1.0 cm

According to an old document(Omori, 1918), the Shinmoe-dake scoria deposit can be assigned to the eruptive activity of 1716-1717 A.D. Also, this scoria deposit is correlated with the Shinmoe-dake lapilli defined by Nakamura(1987) on the basis of stratigraphy and lithology.

i. Growth-history of Takachiho Compound Volcano(TCV)

The growth-history of TCV can be divided into four stages on the basis of field geology and tephrochronology. The first stage is briefly summarized, while the following three stages are described in detail because of their importance in clarifying the nature of eruptive activity of Ohachi Volcano.

As shown in Fig.28, the first stage activity of TCV began at the graben developed between Yatake Volcano and the basement rocks of the Shimanto Supergroup, in which a conical stratovolcano, Futagoishi, was built up. This volcano is composed of an alternation of pyroclastic beds and lava flows. The activity age and mode of explosion of the volcano are poorly known because of the lack of informations from fallout tephras. Judging from the fact that no fallout tephra of Futagoishi Volcano origin exists in the piles of air-fall ejecta overlying the Ito pyroclastic flow deposit(IPF) from the Aira caldera, it is concluded that the activity of Futagoishi Volcano ended before the eruption of IPF(22,000 y.B.P.).

The second stage of TCV growth probably began with the formation of the Uramuta scoria which was expelled from a vent situated about 500 m west of the vent of Futagoishi Volcano(Fig.28 B). The Uramuta scoria deposit is underlain by the Satsuma tephra(11,220 y.B.P.) with intervening paleosol layer. The thickness of the paleosol layer is nearly equal to that of humus layer developed between the Satsuma Tephra and the underlying Kobayashi pumice deposit(13,000-14,000 y.B.P.). On the basis of the assumption that the apparent weathering speeds of the tephra are constant, it may be inferred that the beginning age of the second stage is less than 9,000 y.B.P., after a repose of more than 13,000 years. Following the activity of the Uramuta scoria, voluminous lava flows, called Natsuo lava flow, were extruded to form a lava plateau of small size at the southern foot of Futagoishi Volcano(Fig.28,B). There is no evidence for pyroclastic materials associated with this lava eruption. These lavas are pasty and thick with andesitic composition(SiO_2= 59 wt%).

Interposing a short quiescence, the nature of the eruptive activity changed to the vulcanian eruptions which are characterized by a cluster of abundant small-scale eruptions and continued semi-persistently through a long period of more than a thousand years. During this period a small stratovolcano, Old-Takachiho, was built up on the western flank of Futagoishi Volcano, concentrically accumulating a large amount of volcanic ash(Ushinosune ash deposit) and lavas around the Old-Takachiho Volcano(Fig.28 C). The lavas consisting the cone of Old-Takachiho Volcano were fluidal and thin lava flows, the feature of which is a great contrast to that of the Natsuo lava flow. At the middle stage of this activity, the Kikai-Akahoya ash (6,300 y.B.P.) was intercalated in the Ushinosune ash deposit, indicating that the vulcanian eruptions of the second stage continued until the age of 6,000 y.B.P. The last activity of the second stage was the extrusion of Old-Takachiho lava flow which thinly covered the volcano and filled up its top crater (Fig.28 D).

The third stage activity is characterized by the repeated eruptions of several thin lava flows and scoria fragments from a vent close to that of Old-Takachiho Volcano(Fig.28 E). This activity continued for a short period as compared with the active duration of Old-Takachiho Volcano and resulted in the formation of a small conical stratovolcano, Takachiho-no-mine, on the western slope of Old-Takachiho Volcano. The Mochiharu ash and Ohji scoria deposit are products of the third stage activity. At the end of this stage, enormous lava flows were successively effused from the top crater and flowed downward widely. The latest lava flows, however, did not reached the foot of the

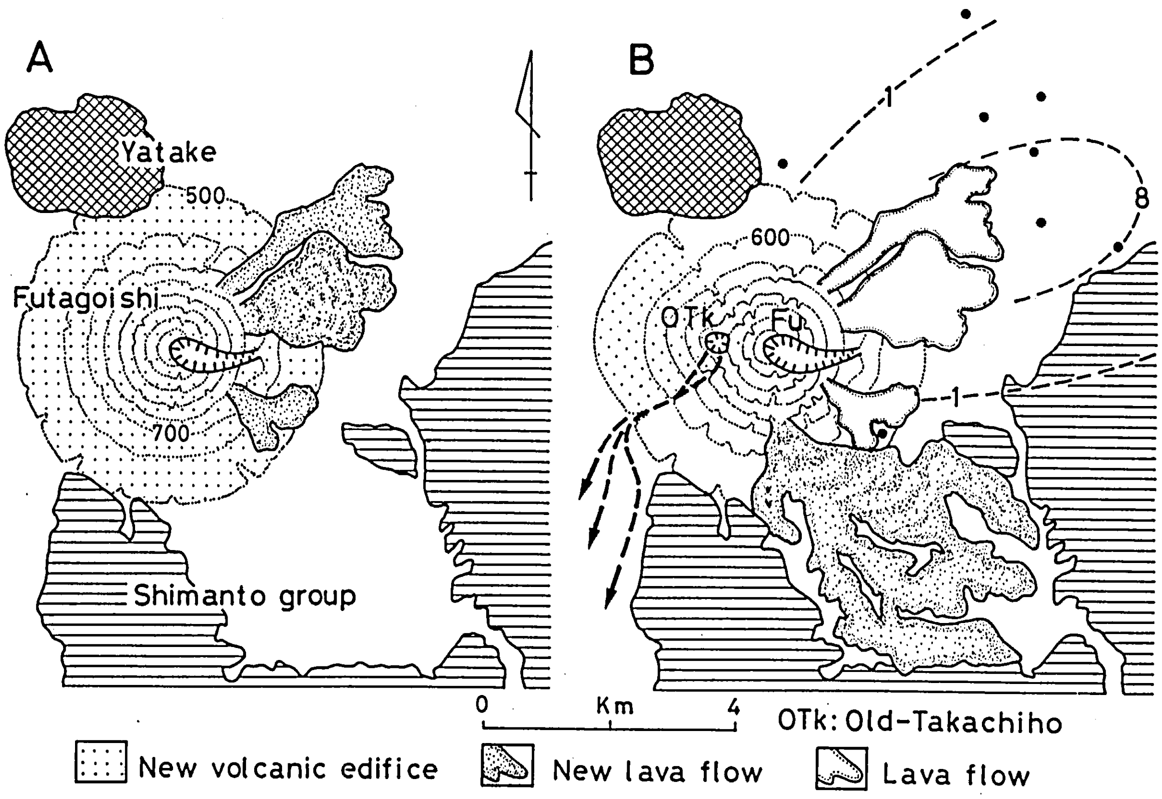

Fig. 28. Diagram showing geomorphic development of Takachiho Compound Volcano during the last 9,000 years.

(A) Futagoishi Volcano was built up at the graben developed between Yatake Volcano and the basement rocks of the Shimanto Supergroup. The activity of the volcano ended before the eruption of IPF(22,000 Y.B.P.) from the Aira caldera. Contour interval is every 100 meters.
(B). About 9,000 y.B.P., the Uramuta scoria deposit was was expelled from a new vent opened at the western flank of Futagoishi Volcano and then the Natsuo lava flow were extruded. Isopachs of the scoria thickness(in centimeter) are shown by dashed lines.

slope due to decrease in effusion rate and were piled up around the crater, resulting in the construction of an exogenous lava dome on the summit(Fig.28 F).

An obvious long repose, which was responsible for well developed humus layers, separates the third stage from the fourth. During this quiescence, however, catastrophic plinian eruption occurred suddenly at the eastern foot of Futagoishi Volcano, and vast amount of pumice fragments was accumulated mainly on the eastern area of KVG, forming Mi-ike maar(Fig.28 G). A large number of base surge deposits derived from phreatomagmatic outbursts formed broad fans radiating from the Mi-ike.

After several hundred years of quiescence, the present stage activity began about 2,500 years ago(Fig.28 G). The (forth) stage activity is composed of ten stratigraphic members from Oh1 to Oh10, which are grouped into two eruptive sequence according to the difference of magma composition. The first sequence, which is a set of from Oh1 to Oh3, is characterized by the emission of fine volcanic ash and the extrusion of pasty and thick lava flows. These eruptives are of high-silica andesite magma origin. The second sequence, which is composed of six stratigraphic members from Oh4 to Oh9, is characterized by typical sub-plinian eruptions(Fig.28 G,H), accompaning the effusion of fluidal thin lava flows, whose eruptive materials are of basalt magma origin. Of all the lava flows of the first sequence, however, the Ohachi lava flow IV, which flowed out following the Ohachi lava flow III without any repose-time, is of basalt magma origin. Thus the change of magma batch controlling each explosion took place between the eruptions of the Ohachi lava flow

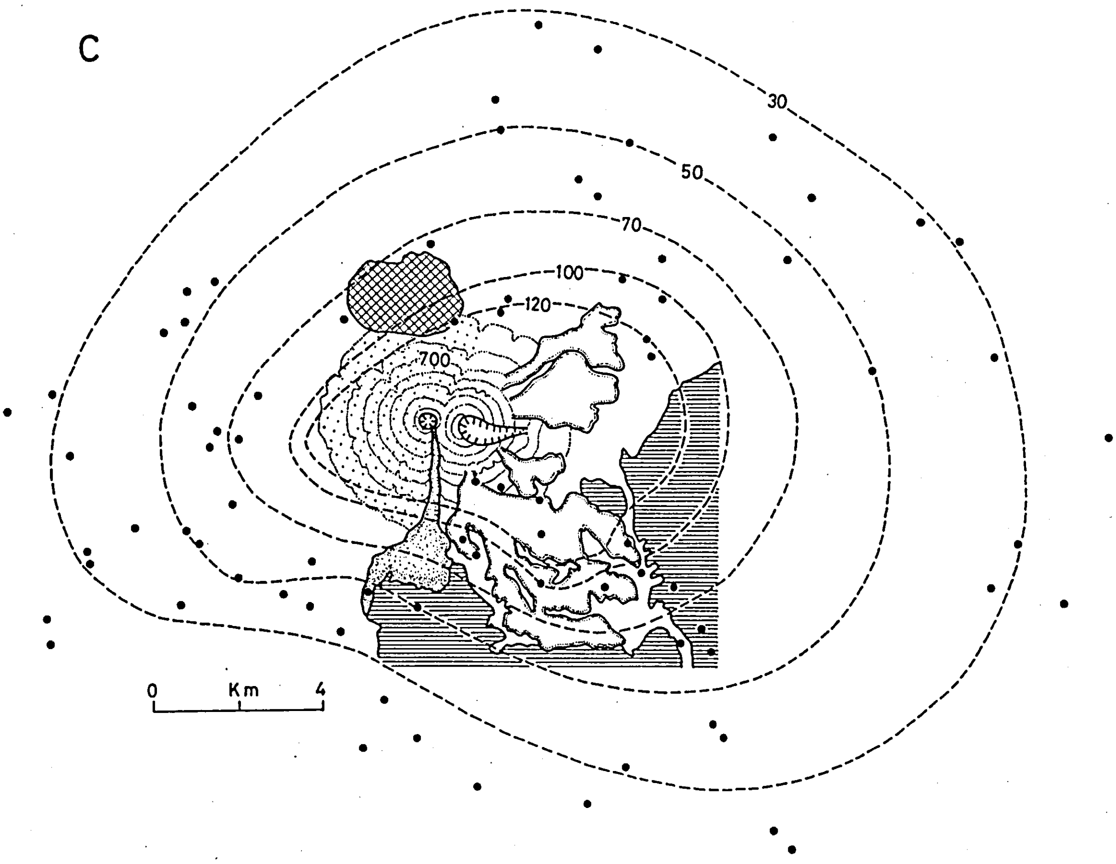

Fig. 28.(continued)

(C) Between ca. 9,000 and 6,300 y.B.P., typical vulcanian eruption had continued. The eruption of great volume of pyroclastic materials and thin lava flows was repeated. Consequently, the western half of Futagoishi Volcano was buried under Old-Takachiho Volcano. The Tonokuchi lavas flowed down from the top crater along the boundary of two volcanoes. The concentric dashed lines show the Ushinosune ash deposit(lower part), and its thickness is given in centimeters.

III and IV, both of which are constituents of the Oh3 member.

No presence of abundant fallout scoria, coupled with the presence of pale brown fine ash for the first sequence, suggests that its mode of eruption was vulcanian without any strombolian eruptions. Judging from the fact that no pyroclastic materials of high-silica andesite composition are founded at the crater wall, it is considered that the eruptive activity of this sequence preceded the construction of main scoria cone of Ohachi Volcano.

The activity of the second sequence occurred intermittently and produced thick scoria and ash beds on the eastern foot of TCV. By repeated accumulation of a great volume of scoria and thin lava flows with basalt composition near the vent, a new volcano, Ohachi, was born on the western flank of Takachiho-no-mine Volcano. Reflecting the large-scale eruptions such as the Katazoe and Takaharu scoria, Ohachi Volcano formed a truncated cone with large crater-pit at the top. When the eruption of Takaharu scoria (Oh7 member) took place, the height of Ohachi Volcano have already attained to the present state, suggesting that the volcanic edifice of Ohachi Volcano was constructed for a short period-time from Oh4 to Oh6.

The lavas of Oh10 member, the Ohachi lava VIII and the bombs of recent eruptions, as well as the products of the first sequence, are of high-silica contents, indicating that the magma batch controlling the recent eruptions changed once more from basalt magma to high-silica andesite magma.

J. Summary and Conclusion

The growth-history of Takachiho Compound Volcano revealed the following features :

1. During the last 9,000 years, the three volcanoes, Old-Takachiho, Takachi-

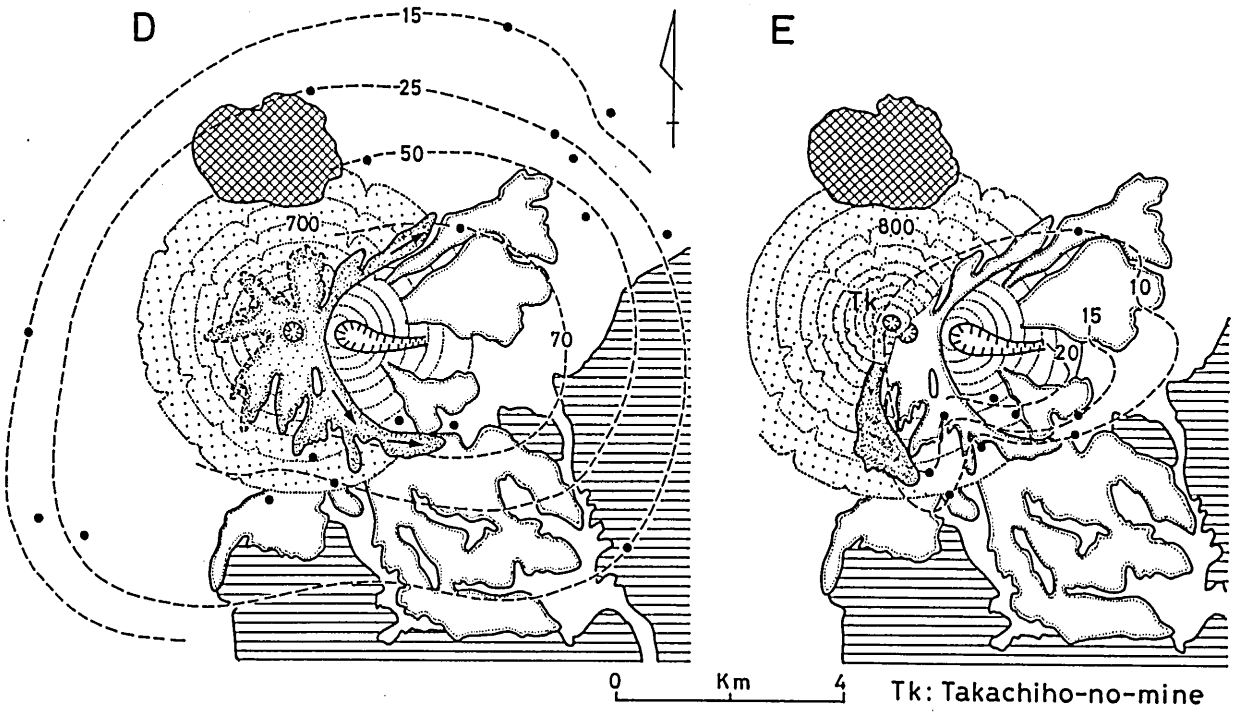

Fig. 28.(continued)

(D) In the time interval of 6,300 to ca.3,000 Y,.B.P., the geomorphic development of TCV has proceeded in the following order: D, E and F. The eruptive activity of Old-takachiho Volcano ended with the extrusion of Old-Takachiho lavas which form far-reaching flows along the boundary of two volcanoes. The upper part of the Ushinosune ash deposit is shown by dashed lines and its thickness is given in centimeters.

(E) A new vent opened at the northwest side of the vent of Old-takachiho Volcano. From the new vent, the Mochiharu ash deposit was expelled(centimeter in thickness) and the eruptive activity of Takachiho-no-mine Volcano began.

Fig. 28.(continued)

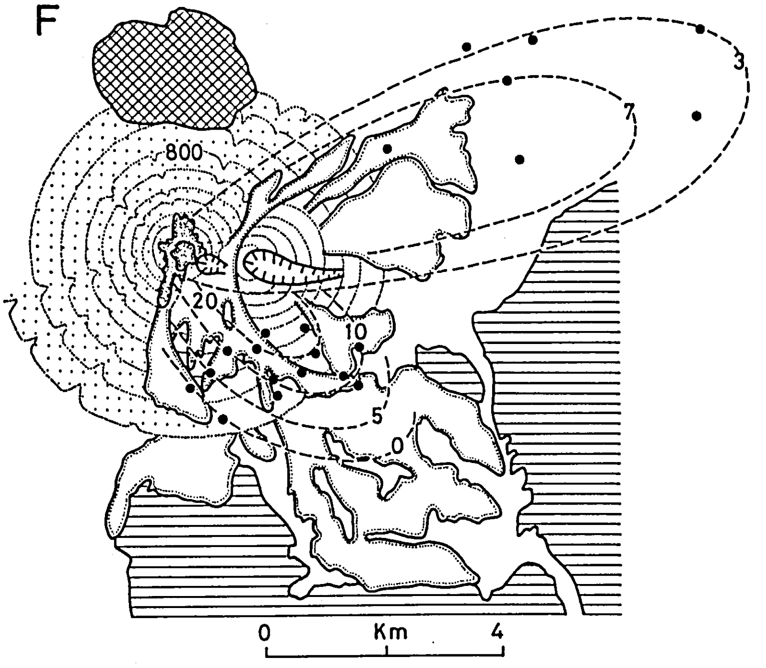

Fig. 28.(continued)

(F) The late stage activity of Takachiho-no-mine Volcano was characterized by the explsoive eruption of abundant scoria(Ohji scoria deposit). The thickness of the deposit is given in centimeters. At the end of activity of the volcano, enormous lava flows were successively effused from the top crater and flowed downward widely. The latest lava flows were, however, piled up around the crater, resulting in the construction of an exogenous lava dome on the summit.

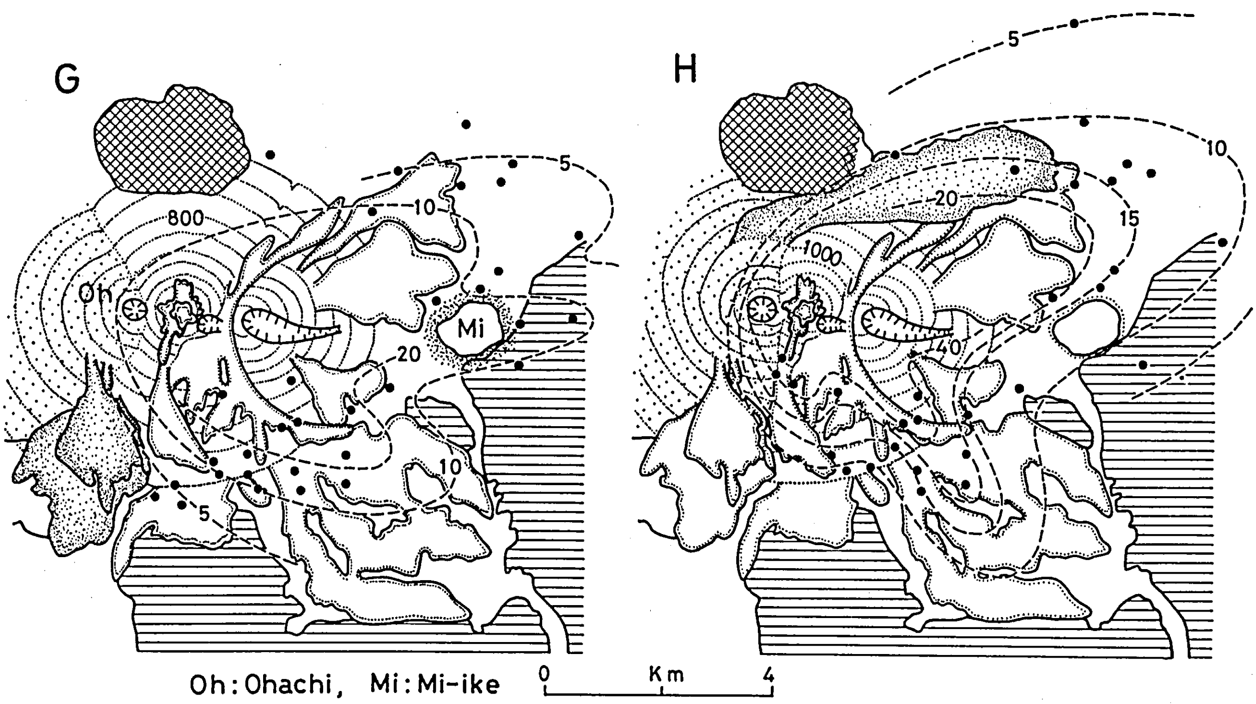

Fig. 28.(continued)

(G) About 3,000 y.B.P., the Mi-ike pumice fall deposit was catastrophically emplaced. Base surge deposits are interbeded with the air-fall pumice near the source, indicating the phreatomagmatic nature of the eruption. The last 2,500 years are marked by a new eruptive activity of Ohachi Volcano which was constructed on the western slope of Takachiho-no-mine Volcano. The initial activity of the volcano is characterized by the extrusion of pasty and thick lava flows of high silica andesite composition(Ohachi lava I-III). Extrusion of basaltic lavas followed(Ohachi lava IV) and a thick scoria deposit was produced(Katazoe scoria deposit, centimeters in thickness).
(H) The Miyasugi ash deposit was emplaced on the eastern foot of TCV and its thickness is given in centimeters.

ho-no-mine and Ohachi Volcano, and one explosion crater, Mi-ike maar, appeared in the southeastern end of KVG.
2. Owing to the migration of activity toward the west, the four cones of TCV are aligned in E-W direction and partly overlap each other. They become younger in generation age toward the west.
3. Including the Mi-ike maar, five volcanic centers are arranged in a direction of E-W, indicating that the volcanic activity of this area may has been controlled by underlying fractures of E-W direction.
4. The volcanic activity, which postdated semi-longer pauses of the order of a few hundred years, is characterized by the extrusion of dominant pasty and acid lava flows such as the Natsuo lava and Ohachi lava I. While the activity related to the construction of each cone of TCV is characterized by the repeated eruptions of a great volume of pyroclastic materials and fluidal thin lava flows without any longer pauses.
5. Comparing the volume percentage of the two kinds of fallout deposits derived from three volcanoes(Fig.7 B), the volume ratio of scoria to the whole fallout deposits increase with time from Old-Takachiho Volcano to Ohachi one. This result is in harmony with the conclusion that the styles of explosive activity of TCV had gradually changed with time from vulcanian eruption of Old-Takachiho Volcano to sub-plinian one of Ohachi Volcano.

3. Naka-dake Volcano

a. General statements

Naka-dake Volcano is a lava volcano built up almost entirely of overlapping and interfingering andesitic lava flows and lies at the northwestern area adja-

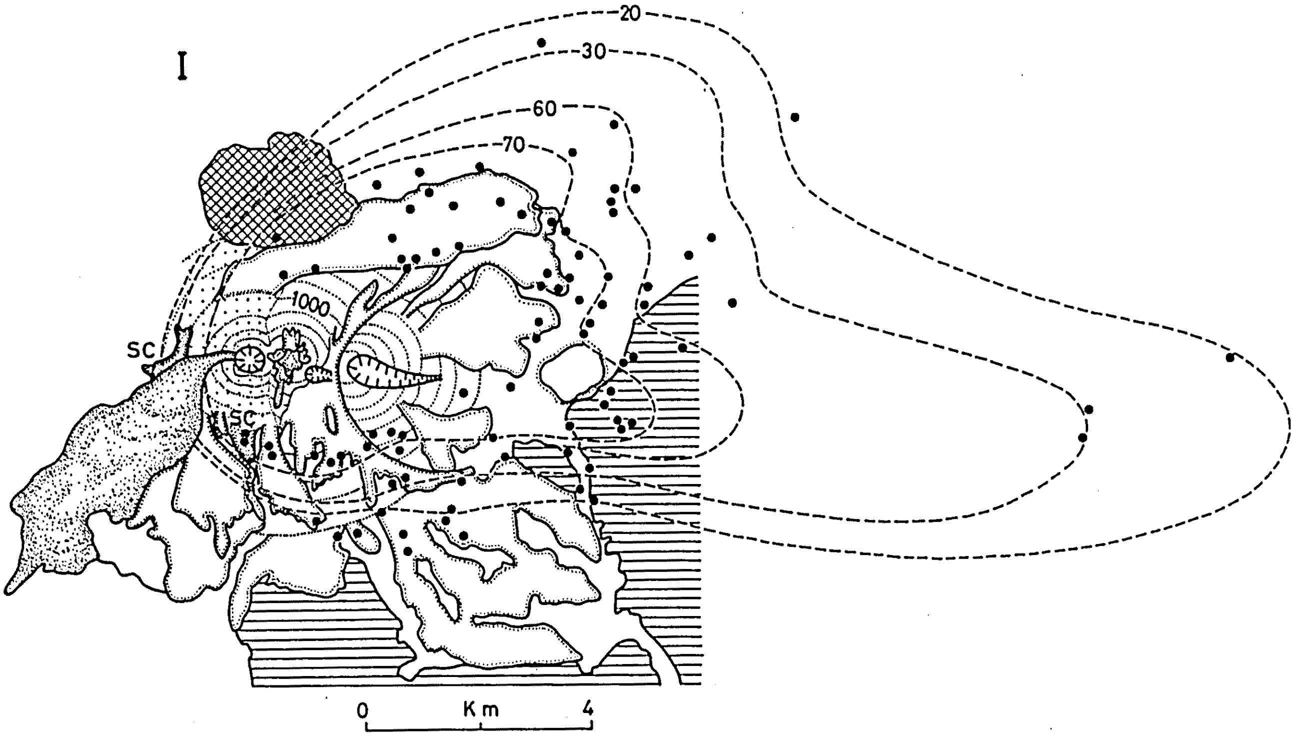

Fig. 28.(continued)

(I) The 788 A.D. activity of Ohachi Volcano produced the most voluminous Takaharu scoria deposit(in centimeters in thickness). The extrusion of scoria flow followed.

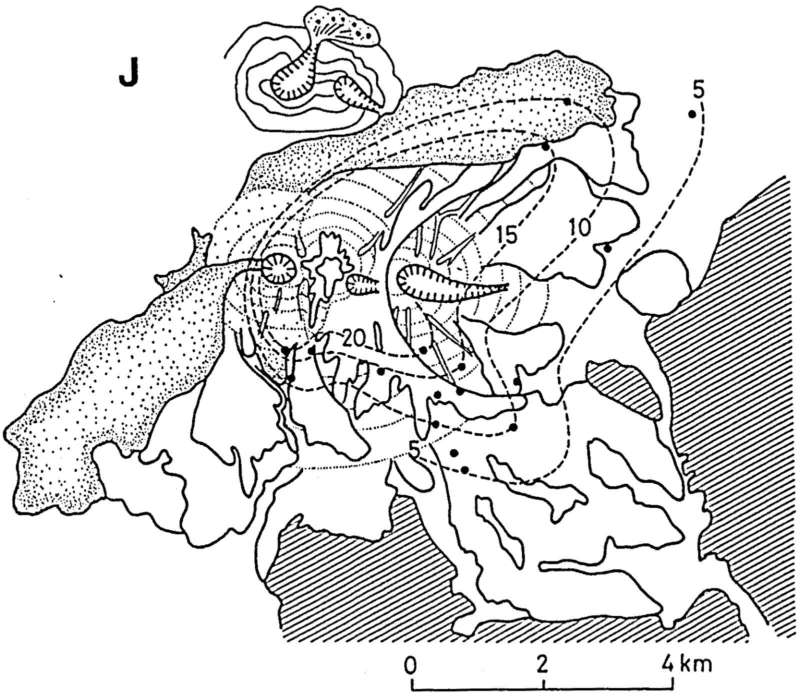

Fig.28.(continued)

J) Isopach map of Ohachi ash deposit(centimeters in thickness).

cent to Ohachi Volcano(Fig.3). As viewed from the south, the rugged, long grass-covered slopes of Naka-dake Volcano that forms its substructure are seen to be crowned by the steep, relatively smooth slopes of a small top cone, sides of which are as steep as 25°(Fig.29). This cone represents the somma of Naka-dake volcano, in which a younger central cone was built up at the latest eruptive time(Sawamura and Matsui,1957). From this inner cone, a few lava flows issued and climbed over the outer rim of the somma, and flowed downward widely.

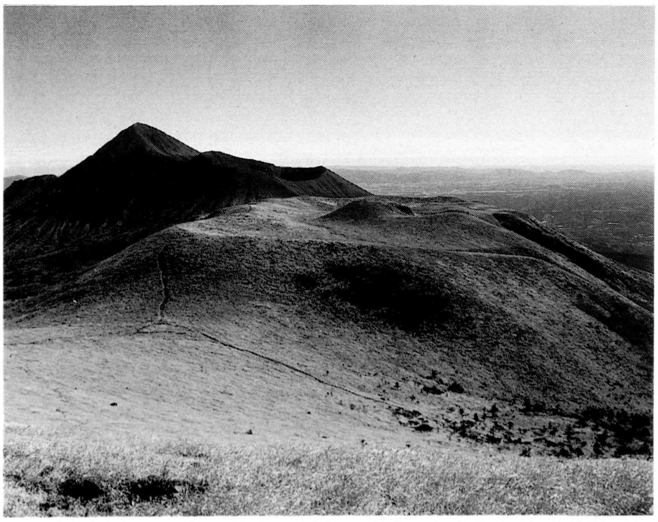

Fig. 29. Naka-dake Volcano, seen from northwest. A small lava dome appears in the central part of the outer crater and the viscous lava which overflowed from the top crater is just visible in the right side of the crater.

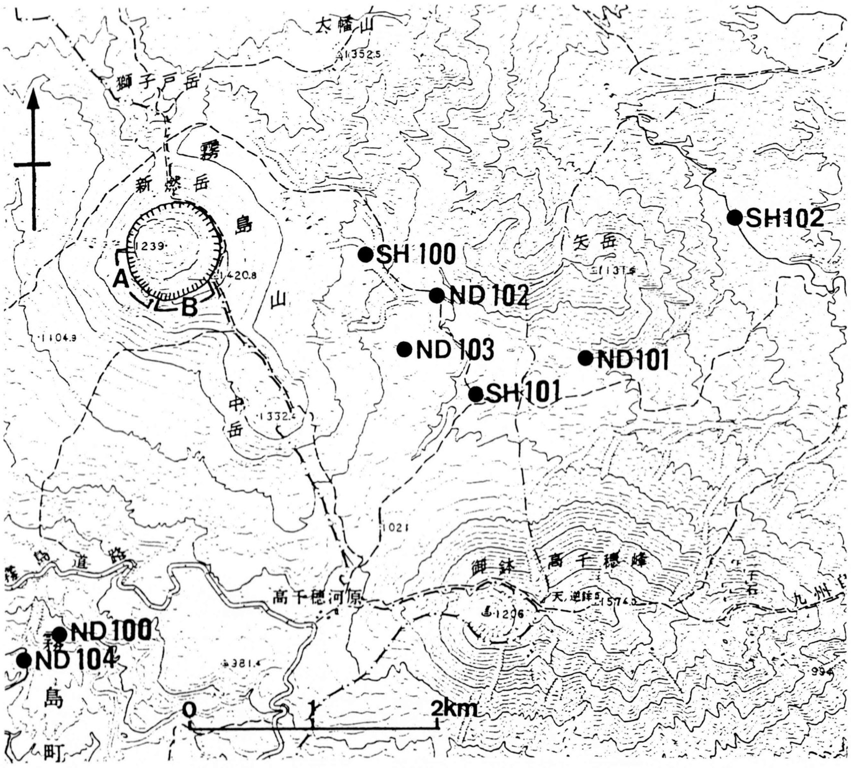

Fig. 30. Topographic map of Naka-dake and Shinmoe-dake Volcano. Naked numeral with ND and SH indicate the localities of columnar sections in

Oda(1921) pointed out that there is a possibility for these lava flows to be a product of the eruption in historic times.

b. Geology of Naka-dake Volcano

As pointed out by Sawamura and Matsui (1957), Naka-dake Volcano is a double volcano which is built up of somma and inner cone. The somma volcano consists largely of andesitic lava flows and subordinate pyroclastic materials which are the only constituents of the top cone with a elongated crater. Including the lava flows effused from the inner crater, all lava flows of Naka-dake Volcano are named Nd1 to Nd12 in a upward sequence.

The lavas of Nd1 to Nd7 are of the somma stage and are overlain by the top cone. From the topographic relationship at the southwestern slope of the volcano, the Nd1 lava is covered by the Nd2 lava flow which is traced from the top crater down to the foot of the volcano. The Nd1 and Nd2 lavas resemble each other in appearance, showing black color with abundant visible phenocrysts of plagioclase, which is from 0.5 to 2 mm in size. In many places, the Nd2 lava

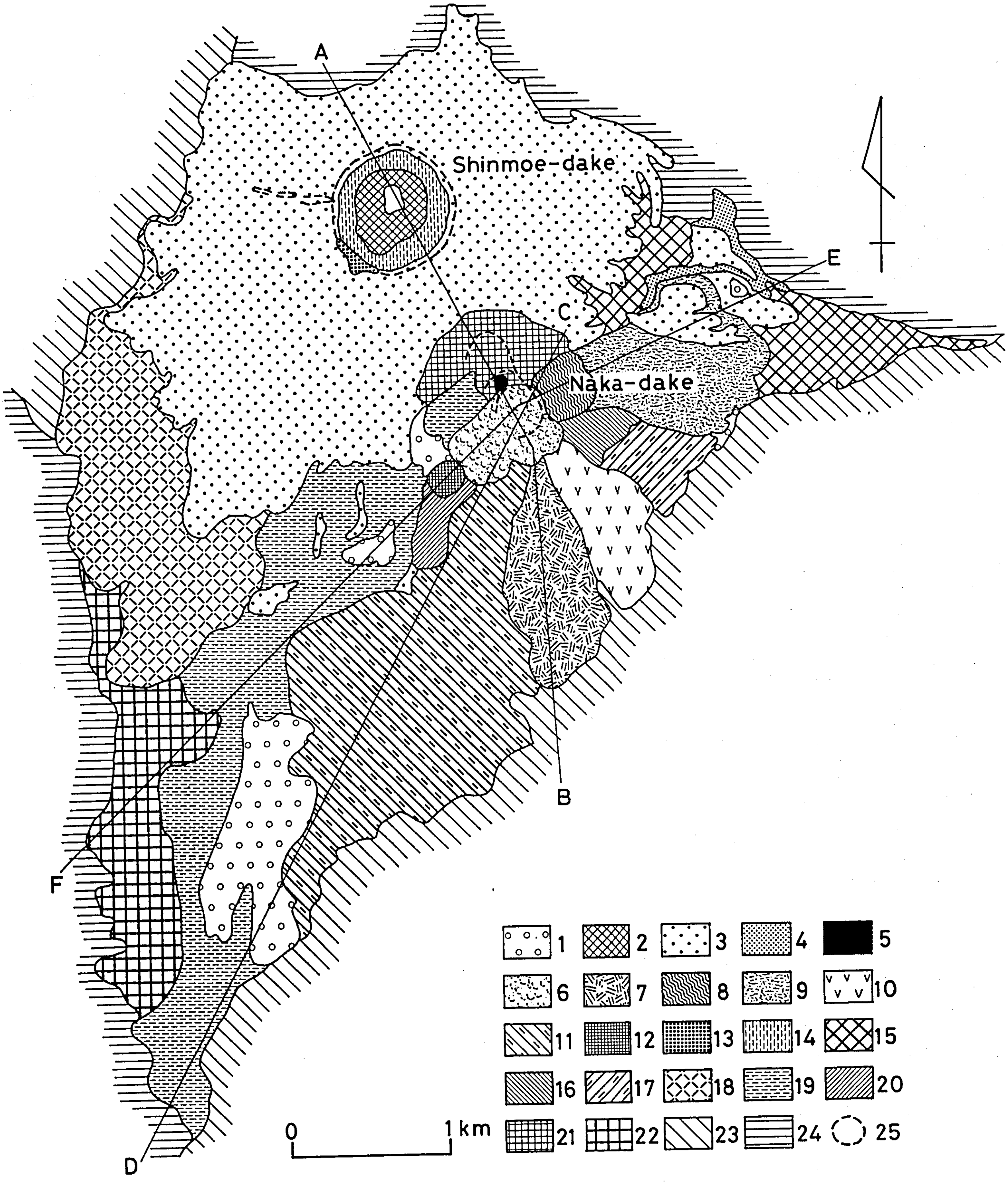

Fig.31. Geological map of Naka-dake and Shinmoe-dake Volcano. A-B, C-D and E-F lines show the positions of the geological cross sections in Fig.36. (1) debris flow deposit, (2) Sh6 lava flow, (3) Shinmoe-dake scoria flow deposit(A.D. 1716-1717 activity), (4) pyroclastic and debris flow deposits(A.D. 1716-1717 activity, Unit B), (5) Nd12 lava flow, (6) Nd11 lava flow, (7) Nd10 lava flow, (8) Nd9 lava flow, (9) Nd8 lava flow, (10) Nd7 lava flow, (11) Nd6 lava flow, (12) Nd5 lava dome, (13) Sh5 lava flow, (14) Sh4 member(lava flow and pyroclastic rocks), (15) Sh3 lava flow, (16) Nd4 lava flow, (17) Nd3 lava flow, (18) Sh2 lava flow, (19) Nd2 lava flow, (20) Nd1 lava flow, (21) pyroclastic cone of the third stage activity, (22) Sh1 lava flow, (23) eruptive products of the third stage activity, (24) eruptive products of the first stage activity, (25) crater.

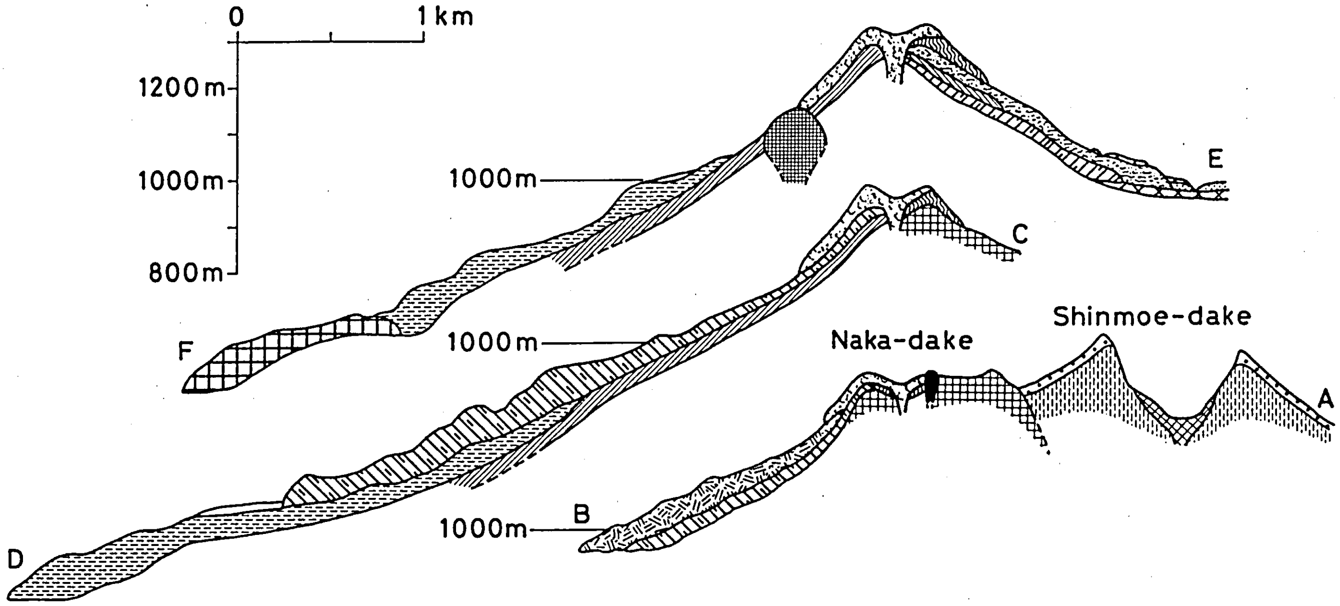

Fig. 32. Geological cross sections of Naka-dake and Shinmoe-dake Volcano. See Fig. 31 for explanation of symbols.

flow is overlain by the Ushinosune ash deposit with the intervening thick paleosol deposits. As the cross section of ND100 in Fig.33 shows, the thickness of the paleosol deposits which are intercalated between the Ushinosune ash deposit and the Nd2 lava flow is larger than that of the weathered ash layer developed between the Ushinosune ash deposit and the Uramuta scoria deposit(Fig.23, KVG102). The eruptive age of the Uramuta scoria was estimated to be around 9,000 years old in the foregoing paragraph, so that the eruptive age of the Nd2 lava flow is definitely older than that of the Uramuta scoria. As shown in geologic map(Fig.31), the outer rim of the top cone is cut through by the Nd2 lava flow, suggesting that, when the extrusion of the Nd2 lava flow took place, the height of Naka-dake Volcano had already attained to the present state.

The Nd3 and Nd4 lava flows are exposed on the eastern side of the somma volcano and are overlain by the Nd8 lava flows. Because tephras overlying these lava flows are not found, the eruptive age of the lavas is only poorly known. Judging from the amount of erosion, they are apparently older than the Nd6 lava flow which well preserves its flow morphology such as lava levee.

The Nd5 lava is a small lava dome, diameter of which is 250 m. Its net height attains 20 m or more. This lava dome is exposed at the southwestern slope of the volcano and its outlines are easily discriminated by the use of aerial photographs. The lava is glassy and grayish with visible abundant plagioclase and pyroxene aggregate crystals.

On the southern slope of Naka-dake Volcano, there is a wide terrace made up of a thick lava flow of Nd6. The upper rim of the terrace is situated in the altitude of 980 m to 960 m and the relative thickness of the lava is 80 m or less. As shown in Fig.31, the Nd6 lava flow issued from the southern rim of the top crater and was widely distributed. The southeastern part of the lava flow is completely covered by the Ohachi lava flow VI and VII. The Nd6 lava is black in color with visible plagioclase and pyroxene crystals.

Because the K-Ah ash deposit is not found on the lava flow of Nd5 and Nd6, they are obviously younger than the K-Ah ash deposit(6,300 y.B.P.), but their eruptive ages are not precisely confirmed. Of all the lava flows constituting the somma volcano, the Nd1, Nd2, Nd4 and Nd5 lavas are olivine- bearing two pyroxene andesite, and the rest is two pyroxene andesite.

Moderately dissected lava flow of Nd7 lies on the southeastern slope of the volcano and shapes like a tongue. Flow morphology such as lava wrinkle is still apparent, though fairly strongly eroded, in the ridge-top remnants of the lava. A maximum thickness of the lava is about 20 m. The lava is porous augite-hypersthene andesite with dark gray appearance. Abundant plagioclase and pyroxene crystals are visible in hand specimen.

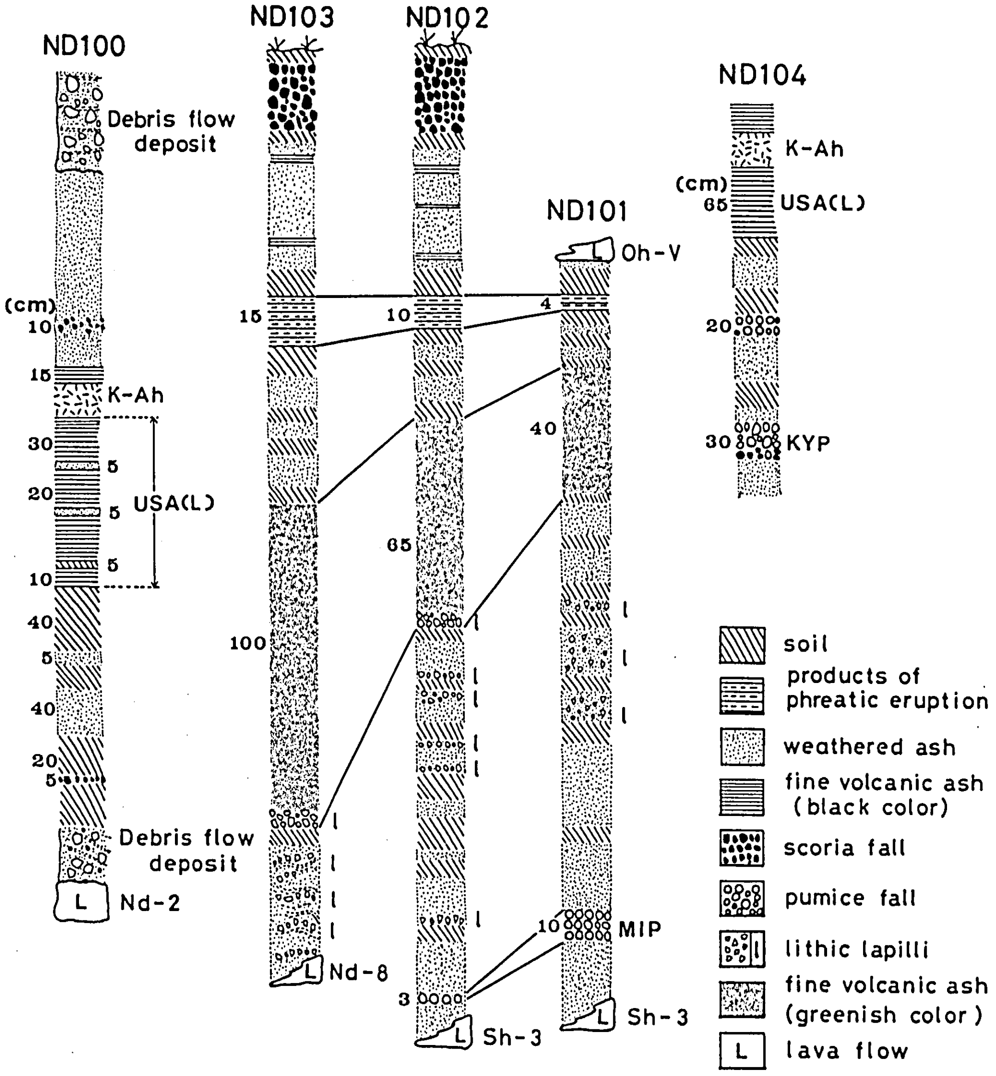

Fig. 33. Diagram showing correlation of the stratigraphic sections of the fallout deposit of the southwestern and eastern foot of Naka-dake Volcano. See Fig. 30 for localities of those sections.

A later explosive episode produced the inner cone with a large crater within the elongated top crater of the somma. The highest point of the inner cone is as much as 1,335 m in altitude and is about 20 m lower than the top of the outer crater. The preceding repose-time was not probably so long. The lava flows ejected from the inner crater are from Nd8 to Nd11.

On the eastern foot of Naka-dake Volcano, there is a wide, distinct terrace made up of a thick lava terminal of Nd8. The lava flow descended the steep slope of the top cone and stopped as it reached the flat area developed among the three volcanoes; Naka-dake, Ohachi and Yatake Volcano. It is about 40 m in apparent thickness at the eastern terminal. The lava is compact and dark-grayish in color with visible augite, hypersthene, and plagioclase crystals.

The terrace is underlain by another thick lava flow(Sh3) of Shinmoe-dake Volcano origin. The lava flowed down from the top crater of Shinmoe-dake Volcano toward the southeast and stopped at the point about 3.8 km in horizontal distance from the crater. As shown in Fig.33(ND101), the Sh3 lava is overlain by a thick sequence of tephra layers including the Mi-ike pumice fall deposit(ca. 3,000 y.B.P..). No soil layer is present between the Sh3 lava and the Mi-ike pumice fall deposit, indicating a very short time gap between the two deposits. Any thin layer of the Mi-ike pumice is not found in the thick tephra deposits that cover the terrace of Nd8 lava flow (Fig.33(ND103)). The number of soil layers developed within the tephra deposits on the Nd8 lava is less than that of soil layer in the tephras overlying the Sh3 lava flow(Fig.33, ND102 and ND103). These field evidences indicate that the eruptive age of the Nd8 lava flow may be younger than the age of about 3,000 y.B.P.

A small andesitic lava flow of Nd9 crops out on the eastern, steep slope of the top cone and is underlain by the Nd8 lava flow. The lava apparently issued quietly from the crater of inner cone and flowed eastward down the top cone for about 350m. The lava is glassy, porous and grayish rocks, containing many irregular, flattened vesicles. Sparse plagioclase phenocrysts and considerable pyroxene are set in a glassy groundmass.

As shown in geologic map(Fig.31), the Nd10 lava flow shapes like a tongue and is emplaced on the southern slope of Naka-dake Volcano. This lava flow is distinguished from the adjoining lavas by its clear outline, fresh appearance and rugged surface. And the lava retains its original surface features such as lava wrinkles and frontal scarps. It is massive, dark-gray andesite with abundance of fine vesicles. Phenocrysts of plagioclase and pyroxene are abundantly found in some hand specimens.

Judging from the topographic feature, the Nd10 lava was probably extruded from a small lateral vent of less than 100 m in diameter, which opened in the altitude of 1,200 m on the southern slope of the top cone. The distance from the source to the terminal of the lava flow is 1.4 km and its width varies from 100 m to 650 m. The maximum thickness of the lava flow may attain 50 m or more.

The Nd11 lava flow is a product of the latest eruption of Naka-dake Volcano and lies on the southwestern part of the top cone. As seen from the geologic map, the lava issued from the crater of the inner cone and flowed southwestward down the top cone for about 350 m. Consequently, the inner cone including the crater was completely filled up with the Nd11 lava flow. The thickness of this lava flow, as seen from the topography, may well exceed 25 m. Its rock is black in color color and contains conspicuous phenocrysts of plagioclase and pyroxene.

A small lava dome of Nd12 stands at the central part of the outer crater and has an shape like a spine. The plan of the dome has an outline of square rather close to a circle with a diagonal line of about 80 m at the base. The net height of the dome may reach 10 m or more. The rock constituting the dome is augite-hypersthene andesite with more or less vesicular and glassy groundmass. Its eruptive age is only poorly known.

c. Fall out tephra deposits

A thick layer(usually a few meter thick) consisting of black, pale brown and greenish-gray fine ash deposits is frequently observed in some sections on the eastern foot of Naka-dake Volcano. Columnar sections of the representative outcrops of the fallout deposits are shown in Figure 33, in which immediately below the humus of the present surface is the scoria fall deposit of the 1716-1717 A.D. activity of Shinmoe-dake Volcano.

Below the Shinmoe-dake scoria fall deposit occur alternately accumulated deposits of two kind beds, weathered ash or paleosol beds and stratified fresh ash beds. The former beds are generally brown or black in color probably due to oxidation on the surface and to the presence of humus, although the color varies slightly with horizon. They are 3 to 40 cm thick with almost negligible local difference. Marked or slight but regional unconformities are found between the lower weathered ash or soil deposits and the upper fresh ash deposits. Judging from the number of them developed within the cross sections, it is concluded that twelve times of dormancy existed between the Mi-ike pumice fall deposit and the Shinmoe-dake scoria fall deposit.

The fresh ash deposits are massive or well stratified fine ash. The individual ash bed is usually several to a hundred centimeters thick and colored pale brown, greenish gray, or yellow by the presence of altered materials. Some of the deposits contains abundant lithic fragments that are lapilli of fresh lavas and altered rocks, which is from 0.2 to 10 cm in size. As seen from the cross sections, the lithic fragments tend to be concentrated at the bottom of individual ash beds. In some places the deposits contain pieces of charcoal several millimeters in diameter.

The isopach map of each ash deposit is hardly known because of the limited exposures, resulting in that the precise source of each one is not confirmed. However, the thickness of each deposit and maximum particle size of lithic fragments increase as the distances from Naka-dake and Shinmoe-dake Volcano decrease(Fig.33), indicating that most of the ash deposits in question may be of Naka-dake and Shinmoe-dake Volcano origin. Also no presence of juvenile clasts, coupled with the lithologic features of the ash deposits, suggests that the nature of the eruption of Naka-dake and Shinmoe-dake Volcano was vulcanian type, but not sub-plinian type eruption which is comparable with that of Ohachi Volcano.

d. Internal structure of Naka-dake Volcano

The inner structure of Naka-dake Volcano is diagrammatically shown in the geologic sections of Figure 32. The volcano is composed of many lava flow units, which overlap or are superposed one on another to form a lava volcano. No pyroclastic layer is present between the flow units. Pyroclastic materials are the only constituents of the top cone. Thus the internal structure of Naka-dake Volcano is relatively simple, and largely reflect its mode of eruption.

4. Shinmoe-dake Volcano

a. General statements

Shinmoe-dake Volcano is an andesitic stratovolcano with a large top crater, where several fumaroles exist, and rises to the height of 1,421 m above the sea level. The volcano is situated at the central part of KVG and its southeastern part is continuation of the slope of Naka-dake Volcano.

The topography of Shinmoe-dake Volcano is a low symmetric, truncated cone with smooth slope (Fig.30, 34). Its surface is thickly covered by loose pyroclastic ejecta projected in the 1716-1717 A.D. activity. Huge fissures up to 60 m in width, which show fumarolic activity, are common on the western slope and extend to a length of 650 m in a direction of N 65° W. The fissures were formed by phreatic eruptions in the 1959 A.D. activity.

The top crater has a circular-shaped appearance of 800 m in diameter and 162 m in maximum depth. The crater is surrounded by steep walls of less than 100 m in relative height(Fig.35). On the southwestern part of the crater rim, there are small double projections made up of a thick lava flow, which are called Usagi-no-mimi (meaning ears of rabbit). Also at the bottom of the crater lies a small lake with greenish water.

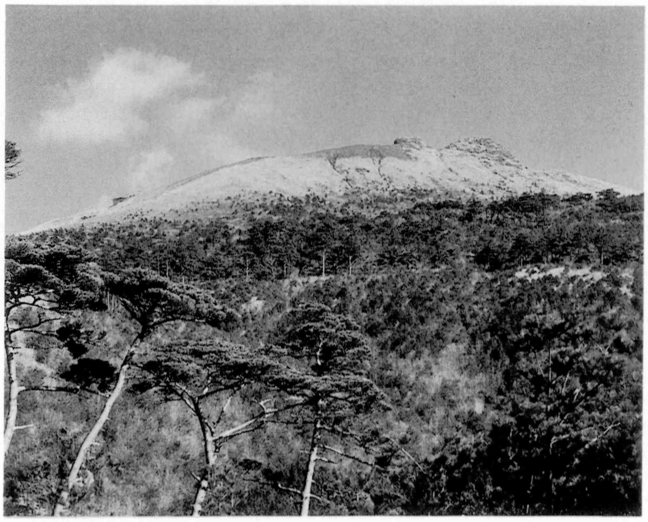

Fig. 34. Shinmoe-dake Volcano, seen from the west. Stream is shown venting from the fissures of the A.D.1959 activity(left side of the volcano). Note the double projection on the summit of the volcano(Usagi-no-mimi).

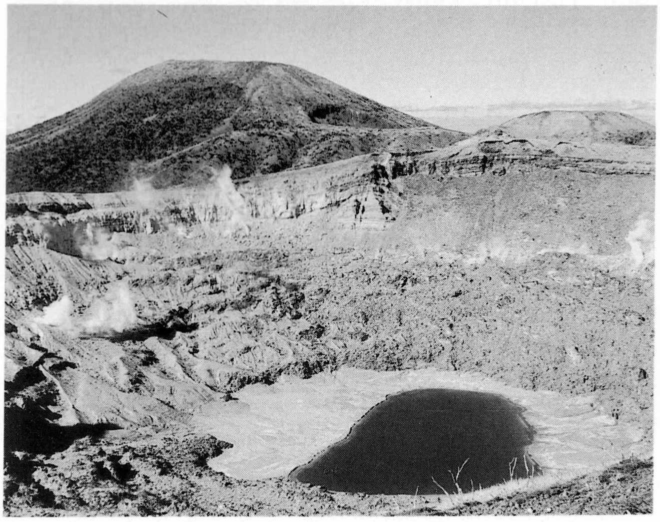

Fig. 35. Inside view of Shinmoe-dake crater.

b. Previous geological work

The first comprehensive study on the geology of Shinmoe-dake Volcano was made by Oda(1921). He reported a plug occupying the small pit-crater which lies in the bottom of the top crater, but the pit-crater is completely filled up with sand and gravel at present. Explanatory text of the geological map of KVG published by Sawamura and Matsui(1957) is another and the last comprehensive study of the geology of KVG. According to their geologic map, Shinmoe-dake Volcano is represented by a single lava, showing that its internal structure can not be inferred from the geologic map. Indeed, it is very difficult to infer the internal structure of the volcano, because of a thick blanket of pyroclastic ejecta covering its most part(Fig.31). Sawamura and Matsui clarified also first the presence of scoria flow deposit around Shinmoe-dake Volcano, but its distribution is not drawn in their geologic map.

c. Geology of Shinmoe-dake Volcano

c-1. Lava flows constituting the main cone

The geological map of Shinmoe-dake Volcano(Fig.31) is not enough for the comprehensive study of the growth-history of the volcano. As shown in this figure, Shinmoe-dake Volcano consists mainly of andesitic lava flows, pyroclastic rocks and subordinate pyroclastic flow deposits. All the lava flows are named Sh1 to Sh6 in ascending order.

On the southern slope of Shinmoe-dake Volcano and the west of the Nd2 lava flow, there is a terrace made up of Sh1 lava flow which has a rectangle outline(Fig.31). The west side of the terrace is cut by a deep gorge, Kirishima River, on the left bank of which a thick section of the Sh1 lava is exposed. The lava is compact augite-hypersthene andesite with dark gray appearance.

The Sh1 lava flow is the oldest product of Shinmoe-dake Volcano and is overlain by the Nd2 lava flow being older than the age of 9,000 y.B.P. On the other hand, at the locality ND104 of Figure 30, close to the west edge of the Nd2 lava flow, a thick sequence of tephra layers is found on the Sh1 lava flow(Fig.31). The tephra deposits contain two distinct pumice layers and the Ushinosune ash deposit. The two pumice layers are overlain by the Ushinosune ash deposit with a few intervening thick soil layers. Judging from lithologic property of pumice fragments such as, for example, content of crystals and degree of vesiculation, the lower pumice fall deposit is probably correlated with the Kobayashi pumice deposit derived from Karakuni-dake Volcano. As already stated, the eruptive age of the pumice deposit is around 13,000-14,000 y.B.P. Therefore, the eruptive age of the Sh1 lava flow is older than the age of 13,000-14,000 y.B.P.

Just on the north of the Sh1 lava flow and on the eastern banks of the River Kirishima there are several terraces made up of the original landforms of the Sh2 lava flow. These terraces, as seen from the topographic map(Fig.30), have a wide variety of sizes and types, suggesting that the Sh2 lava flow is a group of several lava flows produced through multiple eruptive activities. However, these lava flows are generally so homogeneous in petrography, that the discrimination of each flow unit is difficult. They are scoriaceous augite-hypersthene andesite with dark gray appearance. Some of the lava flows are overlain by the K-Ah ash deposit, but the others are intercalated in the upper part of the Ushinosune ash deposit which is underlain by the K-Ah ash deposit. This fact is in accord with the conclusion that the Sh2 lava flow is a product of multiple activities. Although the eruptive ages of the lavas show a wide range, most of them are probably gathered around the age of the K-Ah ash deposit(6,300 y.B.P.).

On the eastern slope of Shinmoe-dake Volcano, there is a wide, distinct terrace with a semi-circular outline, which has a steep front facing toward the east(Fig.30). The upper rim of the steep front is traced in the altitude of 1,175 m and its foot from 1,050 m to 1,000 m in rough approximation. The relative height of the steep front attains 150 m or more. The rock exposed at the front is a lava flow only of Sh3 which is dark grayish augite-hypersthene andesite with abundant plagioclase and pyroxene as phenocrysts. As shown in geological map (Fig.31), the Sh3 lava flow descended the steep front and traveled toward the east about 2 km in horizontal distance from the foot of the front. Thus the terrace does not represent a flow front of the Sh3 lava flow. The steep front continues to the eastern slope of the other old volcano which lies on the north of the terrace. These facts show a possibility that the terrace reflect a topography of the remnant of Old Shinmoe-dake Volcano. However, it is completely covered by the Sh3 lava flow and the loose pyroclastic ejecta of the 1716-1717 A.D. activity.

At the locality ND102 and ND102 in Fig.33, the Sh3 lava flow is overlain by a thick sequence of tephra layers including the Mi-ike pumice fall deposit(ca. 3,000 y.B.P.), in which no soil layer is present between the Sh3 lava flow and the pumice deposit, indicating that the eruptive age of the lava is close to that of the Mi-ike pumice fall deposit.

c-2. Crater wall of Shinmoe-dake Volcano

The geological feature of Shinmoe-dake Volcano, specially part of altitude of higher than about 1,150 m , is mostly concealed by the loose pyroclastic ejecta of the 1716-1717 A.D. activity. Therefore, the geological map of Shinmoe-dake Volcano is not very for the understanding of its internal structure. In order to overcome this difficulty, it is necessary to obtain the geological information from the crater wall of the volcano.

Fig.30 shows a topographic map of Shinmoe-dake Volcano, in which an alphabetical code is assigned to positions of photographs of its crater wall. Fig.36 is a photograph of the crater wall of the position A. Lower part of the scarp is now covered by recent talus. At the central part of the photograph there are two broad projections on the crater rim, which are called Usagi-no-mimi. Oda(1921) and Sawamura and Matsui(1957) were misled into the conclusion that the Usagi-no-mimi is a sort of feeder dike(or spine), which continues from the crater rim down to the bottom of the crater. However, detailed observation

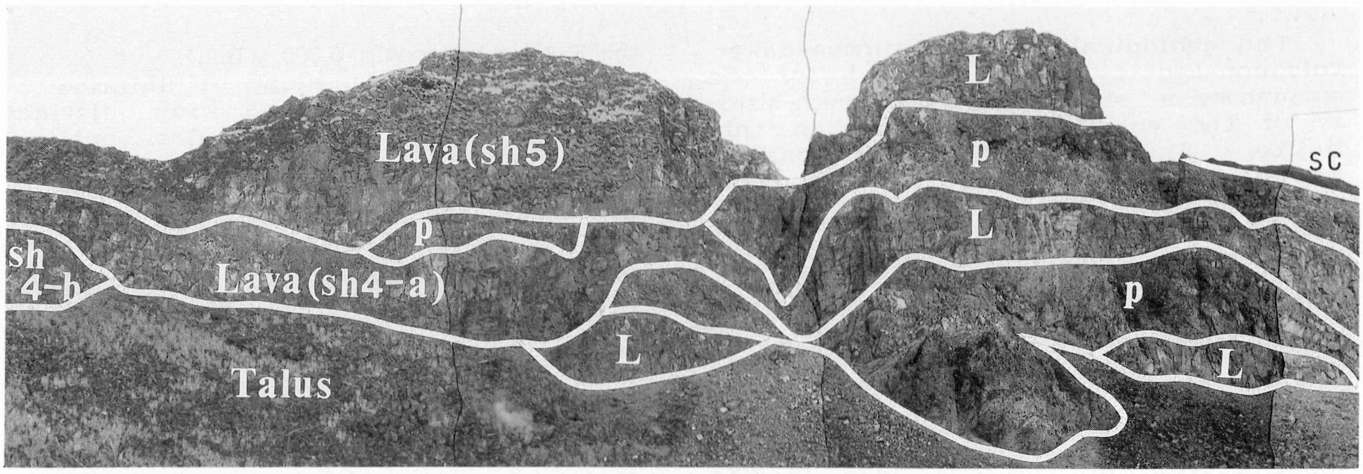

Fig. 36. Inside view of the top crater of Shinmoe-dake Volcano showing the structure of the position A in Fig.30. The double projections in the central of the photograph are Usagi-no-mimi which is composed of thick lava flow(Sh5).
L: Lava, p: pyroclastics, sc: scoria flow deposit.

of the exposures shown in the photograph A indicates that the tops of the projections consist of a thick lava flow(Sh5) of andesitic composition with an underlying thick layer of pyroclastic rocks. Below the pyroclastics layer there are two lava flow layers, one pyroclastic rocks layer and one altered rocks one in descending order.

The same type of volcanic rock succession is clearly followed on the main part of the scarp of the photograph A. Most of the pyroclastic rocks are essential tuff breccia and volcanic breccia with much coarser fragments of lavas. Some of the tuff breccia grade into agglomerate with bread-crust bombs as coarse constituents.

In the right half of the photograph A is found a layer of black scoria with thickness of several meters forming the top of the crater rim. The scoria layer is weakly welded and is underlain by a layer of yellow brownish pyroclastic ejecta which are loose, ill-sorted and rich in fine materials.

The lavas and pyroclastic rocks, which constitute the main part of the crater wall except for the Sh5 lava flow and loose pyroclastic ejecta, are collectively called here Sh4 member. The lava of Sh4-a is dark grayish compact andesite with visible pyroxene and plagioclase crystals. The Sh4-b lava is porous augite-hypersthene andesite with light gray appearance. While the Sh5 lava is dark grayish augite-hypersthene andesite with glassy groundmass, and glomeroporphyritic aggregates of pyroxene and plagioclase minerals are found in hand specimens. The Sh5 lava flowed down on the slope toward the southwest to some extent(Fig.31). Generally speaking, the amount of lava flows is greater than that of pyroclastic rocks and their average ratio may approach to 3:2.

The Sh6 lava is the youngest product distributed in Shinmoe-dake Volcano and is exposed on the bottom of the crater with a feature of concentric depressed surface(Fig.35), showing that it is a fossil of lava lake. The lava is quartz-hornblende-bearing augite-hypersthene andesite with light gray appearance.

d. Products of the 1716-1717 A.D. activity

d-1. Age relation

The Loose pyroclastic ejecta that cover much of the outer slopes of Shinmoe-dake Volcano are of its 1716-1717 A.D. activity. The Shinmoe-dake scoria deposit corresponds to their air-fall part. In geologic map(Fig.31), the distribution of the loose pyroclastic deposits is represented by that of the scoria flow deposits.

The deposits of the 1716-1717 A.D. activity have the maximum thickness of about 970 cm at an outcrop(Sh100 in Fig.30) on the eastern slope of Shinmoe-dake Volcano and thins out up to 160 cm(SH101 in Fig.30). It smoothed irregularities of the pre-1716 A.D. eruption surface, especially above an altitude of 1250 m of the volcano, filling valleys to depths of several meters and covering thinly most bedrock spurs between valleys.

The pyroclastic deposits comprise five principal stratigraphic units : in an upward succession, beds of well sorted scoria and fine ash(Unit A), thick deposits of unsorted pyroclastic and debris flow(Unit B), several thin layers of unsorted base surge deposit(Unit C), a few beds of scoria flow with black color(Unit D) and well sorted pumice and ash(Unit E). These units, except for the unit B and E, are traceable into the layers of the Shinmoe-dake scoria deposit.

As shown in the cross sections of Fig.37, the five unit stratigraphy comprise more than 19 distinctive layers and each unit lies conformably without any soil layer, indicating a very short time gap among individual units. The deposits are overlain by the fragmental ejecta and ashes of the 1959 A.D. eruption with an intervening soil layer of 15 cm thick. These field evidence indicates that the loose pyroclastic deposits are products of a series of big explosive eruptions and is the second youngest products in the eruptive history of Shinmoe-dake Volcano. According to the old documents(Omori, 1918), the second youngest record of eruption of Shinmoe-dake Volcano appears as January 12, 1822 A.D., but the eruption was too mild to be compared with that related to the formation of the pyroclastic deposits in question. Prior to 1822 A.D. are recorded two larger-scale eruptions, 1771-1772 and 1716-1717 A.D. eruptions, both of which are characterized by abundant pyroclastic ejecta of lapilli size. Judging from the content of the old documents such as petrographic features of deposit, the 1716-1717 A.D. eruption appears to be comparable with that for the Shinmoe-dake scoria deposit. For example, the old documents gives such information that, owing to the continuation of falling of volcanic ash during a few years it looked as if the distant hills were veiled in a spring mist. That would most felicitously express the state of falling of the light gray fine ash of the Shinmoe-dake scoria. Therefore, it may safely be said that most parts of the loose pyroclastic deposits are products of the 1716-1717 A.D. eruption. However, there is a possibility that the 1771-1772 A.D. eruptions had played a role in the formation of the deposit.

d-2. Profile of the deposits

A typical geological section for the deposits of the 1716-1717 A.D. activity is given below. An alphabetical code is assigned to their constituent units in a upward sequence(Fig.37).

25 cm (E3) light gray pumice lapilli with angular appearance; MP 8 cm

10 cm (E2) brown to dark brown ash with parallel laminations and cross laminations occurring in bedding set (Fig.37); gradational contact with unit below

35 cm (E2) light gray pumice lapilli with abundant fresh and altered lithic fragments, all in fine dark brown ash matrix; gradational contact with the underlying unit

25 cm (E2) brown to dark brown ash with parallel and cross laminations

25 cm (E1) similar to the fall unit E3

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175 cm (D3) black scoria flow deposit ; non-welded ; shows a cross section of lenses composed of coarser scoria fragments

150 cm (D2) mixture of pale brown scoria and poorly vesiculated black scoria; contains abundant altered lithic fragments ; well sorted

120 cm (D1) weakly welded scoria flow deposit; contains dark scoria fragments, very minor lithic fragments and carbonized woods; upper part of the bed alters from black color to reddish brown color due to the high-temperature oxidation

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20 cm (C6) mixture of light gray and black scoria with abundant angular lithic fragments , all in fine scoriaceous ash matrix; MS 3 cm, ML 4 cm

4 cm (C5) reddish purple fine ash with parallel laminations

25 cm (C5) mixture of pale brown and gray scoria with abundant altered lithic fragments, all in fine scoriaceous ash matrix

15 cm (C4) laminated bright yellow ash with scattered lithic fragments and gray scoria lapilli in the lower half; faint normal grading from coarse sand size to fine sand size in the matrix ash; the ash is of hydrothermally altered materials origin; gradational contact with the underlying bed

20 cm (C4) gray scoria lapilli and lithic fragments with pale brown color, all in coarse scoriaceous ash matrix

30 cm (C3) bright yellow ash with scattered lithic fragments, some of which are completely altered, and minor amount of

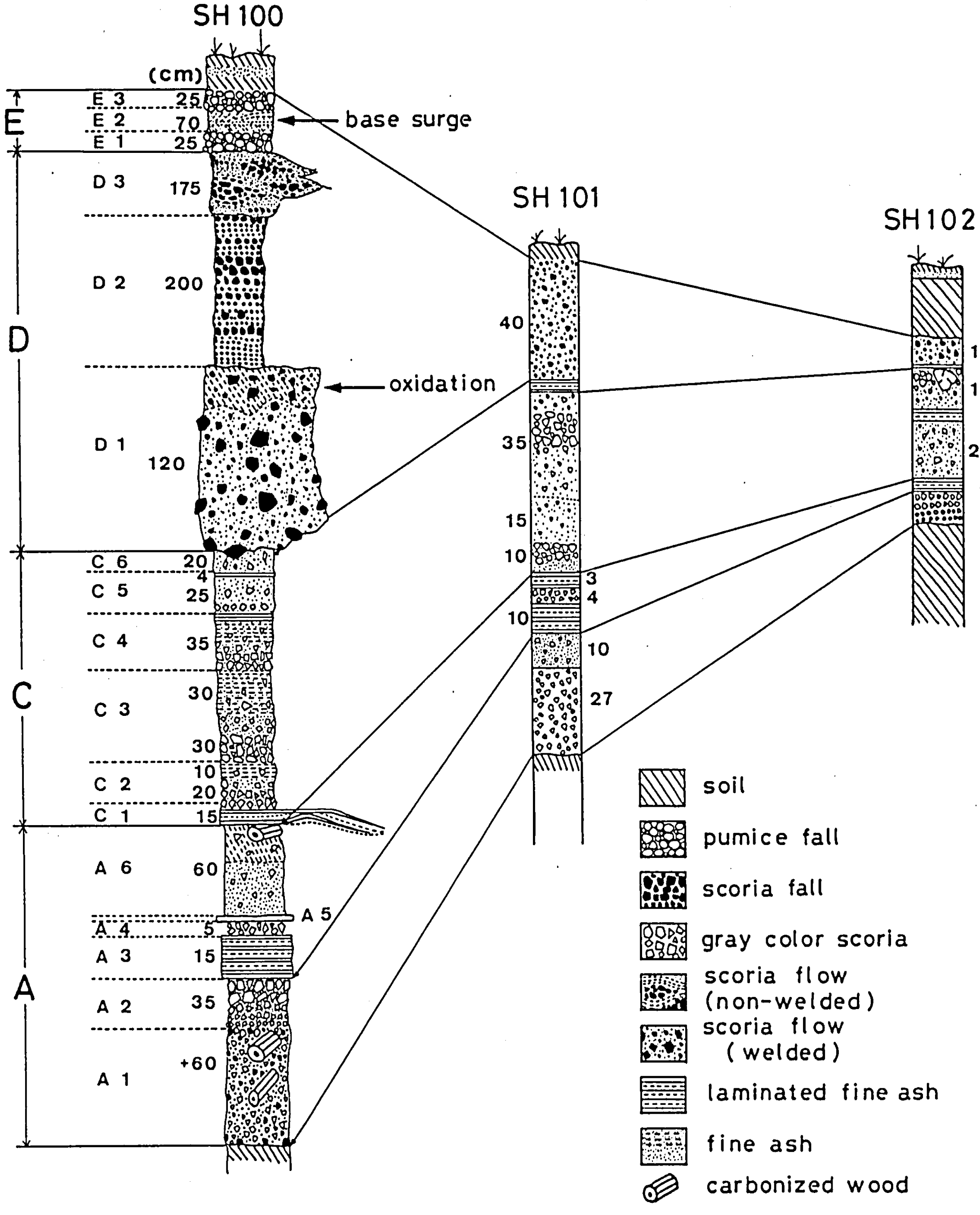

Fig. 37. Diagram showing representative stratigraphic sections of the products of the 1716-1717 A.D. activity(See Fig.30 for their locations). The section of SH102 represents the sequence of Shinmoe-dake scoria deposit.

gray scoria; platy lithic fragments show subhorizontal orientation; gradational contact with the underlying bed

30 cm (C3) gray scoria lapilli with lithic fragments, all in coarse scoriaceous ash matrix

10 cm (C2) bright yellow ash with ill-defined laminations; contains granular lithic fragments; ML 2 cm

20 cm (C2) gray scoria lapilli with scattered lithic fragments, all in coarse scoriaceous ash matrix

15 cm (C1) thinly-bedded bright yellow fine ash; intercalating thin layers of scoria lapilli and lithic fragments; forms frequently antidune bedding (Fig.39)

Fig. 38. Close up of a sequence of Unit E near the source. Note the sandy bed just under the pumice bed of E3, in which there lie cross laminations occurring in bedding sets 4 cm thick. current form left of right. small-scale "convolute lamination"(arrow) in E2 layer. scale in 10 cm intervals.

Fig. 39. Relatively symmetrical antiduens lie in center of photograph(lift of which 1 m long scale is resting). Current from right of left.

Fig. 40. Soft sediment deformation structure in Unit A. Note inversely graded bed in the middle part of A3 layer. Scale in 10 cm interval.

+6 m (B) pyroclastic flow deposit with pale brown color;consists of black scoria, banded pumice, altered lithic fragments and many debris, all in coarse compact ash matrix; contains many weakly carbonized woods which are more than two meter in length

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20 cm (A6) pale brown fine ash with scattered lithic fragments; contains a small carbonized wood; gradational contact with the underlying bed

40 cm (A6) sky blue fine ash with scatlithic fragments(mudflow ?) ; sometimes thining out; ML 2 cm

1 cm (A5) sky blue silt layer

5 cm (A4) gray scoria lapilli with angular appearance; well sorted; MS 3 cm

15 cm (A3) a sequence of thinly-bedded volcanic silt, ash and scoria lapilli; each layer shows typical normal grading; lower and upper parts of the sequence are sky blue color, and the rest bright yellow color; association with soft sediment deformation structures(Fig.40)

35 cm (A2) inversely graded gray scoria lapilli with abundant angular lithic fragments; poorly vesiculated; well sorted; MS 4 cm

+60 cm (A1) dark gray scoria lapilli with abundant altered lithic fragments, all in coarse friable ash matrix made up of mixture of scoriaceous and altered materials; contains branches of carbonized woods with a random distribution; scoria lapilli is poorly vesiculated and has angular appearance

d-3. Lateral variations

Unit A: Layers A1 and A2 , whose constituents become thinner- and finer-grained away from the volcano, merge into a single basal scoria of the Shinmoe-dake scoria deposit at a distance place(SH102 in Fig.37). The rest four layers from A3 to A6 are characterized by abundant fine ash and marked sky blue color. Their constituents become finer grained downwind and their internal stratigraphy so disappears progressively, that, beyond about 4 km (Sh102), the layers A3, A4, A5 and A6 become only a single banded layer. In this banded layer exist three parts of sky blue, which correspond to the lower and upper part of A3 layer and the A5 layer respectively.

Unit B: Unit B is composed of two flow deposits at least. The one is exposed on both banks of the main valley on the eastern foot of Shinmoe-dake Volcano and contains abundant debris ranging up to one meter in diameter, in sandy matrix(Fig.31). Most of the debris are concentrated to the upper part of the flow unit, indicating that the deposit is of debris flow origin. Another flow deposit appears to have been erupted just after the emplacement of the debris flow deposit, because the matrix of the former is similar in grain size and identical in color to the matrix of the latter. This flow deposit contains abundant fragments of vesiculated scoria and many scorched tree fragments standing together, indicating that it is a high-temperature pyroclastic flow deposit.

Unit C: Constituent layers of Unit C, except for layers C1 and C6, consists of two major beds: coarse basal bed and fine upper bed, whose constituents systematically become finer-grained and better sorted away from the source.

The coarse basal bed is the most voluminous and consists principally of gray scoria and scoriaceous ash matrix. Owing to the dominance of scoriaceous materials, the bed is tinged with dark gray color near the source, making a marked contrast with a bright yellow color of the fine upper bed. The coarse basal bed consists of a massive, ill-sorted, matrix- to clast- supported bed that grades to a well-sorted or slightly inverse graded, clast-supported bed with progressive depletion of sand- to silt-sized ash as distance from the source increases.

The fine upper bed generally grades into the coarse basal bed. It, particularly in the upper part, is better sorted and more thinly laminated. Dune structures with very low amplitude are sometimes observed in the upper part of the bed, in which coarse well-sorted lenses of scoria occur on the lee side of the crest. The bed contains also platy fragments which are aligned roughly parallel to bedding surfaces or are imbricated. These features suggest that the fine upper bed was emplaced by flow processes. As the fine upper bed becomes thinner away from the source, the scoria and lithic fragments and internal structures progressively disappear, so that, on the volcano flanks, the bed grades into a thin ash bed with thickness of less than a few cm.

The stratigraphic sequence made of the coarse basal bed and fine upper bed may correspond to a inner structure of one flow unit of pyroclastic flow deposits and is maintained on the eastern slope of Shinmoe-dake Volcano.

Layer C1 consists of laminated ash beds with a bright yellow color, which are sequences of thinly-bedded volcanic silt, ash and lapilli. Commonly, dune structures and cross-bedding are observed in the layer C1(Fig.39). The dunes are characterized by relatively symmetrical shapes, fine-grained materials, and minor lee-side built-up. Most materials are deposited on the extensive lee slopes which dip at low angles toward downstream commonly 10^{o} or less. Such dunes may develop above plane beds without initial obstructions and upstream migration of the crests is common. These features suggest that the layer C1 was emplaced by high energy flow processes such as base surges from phreatomagmatic eruptions.

Unit D: At least two times eruptions of scoria flow took place(D1 and D3). These scoria flows flowed in all directions down the slopes, so that the distribution of the scoria flows can be traced in the field 360^{o} around the summit crater of Shinmoe-dake Volcano(Fig.31). From the characteristic distribution of them, it can readily be imagined that the scoria flows were not produced by gravitational collapse of an overloaded vertical column but formed by the " boiling-over" of a highly gas-charged magma from an open vent.

It is beyond the scope of this paper to discuss in detail the course of the A.D.1716-1717 events. However, the author wish to describe the following remarks :

1. During the last 3,000 years of activity of Shinmoe-dake Volcano(Fig.33), the 1716-1717 A.D. eruption produced the largest volume of materials and covered

the largest area.

2. The three fine ash beds within the Shinmoe-dake scoria falls suggest that the 1716-1717 A.D. eruption consists of four eruptive phases(SH102 in Fig.37). On the other hand, according to the old documents(Omori, 1918), the 1716-1717 A.D. activity is divided into four active terms by the short quiescence. However, the relationship of the four active terms to the four eruptive phases is only poorly understood at present.

3. The scoria lapilli of Unit A is poorly vesiculated and its surface is considerably compact. While the fragments of scoria and pumice of Unit C,D and E are moderately vesiculated and their surfaces touch rough owing to the presence of many vesicles. This fact suggests that the vesiculation degree of magma abruptly increased with time.

4. The A3 layer in the Shinmoe-dake scoria falls is so firm, although it consists of fine ash materials. In many places the A3 layer demonstrates soft sediment deformation structures as shown in Fig.40. These phenomena are attributed to cohesion provided by condensed water on grain surfaces. The amount of water necessary for soft sediment deformation in fine grained sediment is about 15-20 % (Heiken, 1971), being far greater than saturation values for magmatic gases in andesitic magmas(Sakuyama and Kushiro, 1979). Thus, the water must be mostly or entirely nonmagmatic.

5. The fallout event for Unit A was followed by the mudflow(A6) and debris flow(B), suggesting that the volcanic activity of the period from Unit A to B took place under wet conditions.

6. The explosions for the deposit of Unit C were all periodic and pulsating, and many base surges were produced. These surge deposits form thin sheets composed of unconsolidated, well-stratified materials. Typical dune structures are observed in the C1 layer proximal to the vent(Fig.39). These phenomena are typical features of dry-surge deposits.

7. Outcrops of A3 and A6 layers and Unit C are usually sky blue to tan or brown in color containing abundant hydrothermally altered fine materials. While the color of Unit D and E usually indicates that for their original composition, black to light gray.

8. The explosions related to Unit D are characterized by the outburst of voluminous scoria flow. The scoria flow deposit are well welded, and its upper part alters from black color to reddish brown due to the high temperature oxidation.

These observations suggest that the deposits of the 1716-1717 A.D. activity were formed by phreatomagmatic eruptions and a variety of their structures and features provide good evidence for the interaction of external water with magma. The change in the character of the deposits throughout the eruption indicates the presence of an eruption cycle that is related to an decrease in hydromagmatic component with time. The cycle starts with a scoria-fall beds with low vescularity and then proceed to mudflow or debris flow beds. These deposits are overlain by dry surge beds and capped by a cycle-ending scoria flow and scoria-fall beds with high vesicularity.

The above-described result of the eruption cycle for the 1716-1717 A.D. activity is not throughgoing enough, but reconstruction of eruption cycle in terms of water-magma mixing is extremely useful in modeling of eruption processes and evaluation of risk at active volcanoes.

5. Volcanic landforms and internal structures of the third stages volcanoes

a. General statement

Study on various kinds of volcanic activity and of internal structure for volcanoes reveals that they both are closely linked. Therefore, to clarify the internal structure of volcanoes is the most important work in volcanology. As valleys do not cut deeply enough the slopes of modern volcanoes to let us see the insides of volcanic edifice, however, their internal structures may be a matter of conjecture. The internal structures of volcanoes may also not be inferred from the geological map, because the great parts of their outer slopes are thickly covered by recent pyroclastic ejecta. Shinmoe-dake Volcano is just this case.

On the other hand, it is considered that landforms for volcanoes reflect the processes of their development. Thus the study of volcanic landforms may give an important clue to understanding of the internal structures of volcanoes. In this section, therefore, the author will consider the relationship between volcanic landform and internal structure for the third stage volcanoes of KVG with reference to their geological maps. Comparing the difference between the internal structures of those volcanoes, the variety of their eruption styles is discussed.

b. Takachiho Compound Volcano (TCV)

Fig.41 shows the topographic cross sections of three volcanoes of TCV, which are arranged in the following order from up to down : Ohachi, Takachiho-no-mine and Old-Takachiho Volcano. In these cross sections number represents the angle of the slope. As already stated, these volcanoes are small stratovolcanoes with relatively short life span of less than several thousands years. The morphology of the volcanoes is only characterized by a conical form with or without a large top crater, and the inclination of the main slope becomes greater with increasing elevation, attaining to more than 35° at their summits(Fig.41).

On the other hand, Ohachi, Takachiho-no-mine and Old-Takachiho Volcano differ in internal structure from one another. For example, Old-Takachiho and Takachiho-no-mine Volcano are symmetrical cones with steeply dipping pyroclastic deposits interbedded with thin and short lava flows(Fig.7(A)). While Ohachi Volcano consists of an alternation of agglutinates(or welded air-fall tuffs) and non-welded pyroclastic materials(Fig.7(A)) without lava flows. Ohachi Volcano is characterized by relatively wide top crater for its basal diameter, which shows the violent nature of eruption style. Judging from the information on the tephra, the difference in internal structure between those volcanoes is probably ascribed to that in nature of eruption style between them. Ohachi Volcano is a product of repeated subplinian and strombolian eruptions, while the rest two volcanoes are related to repeated strombolian and vulcanian ones.

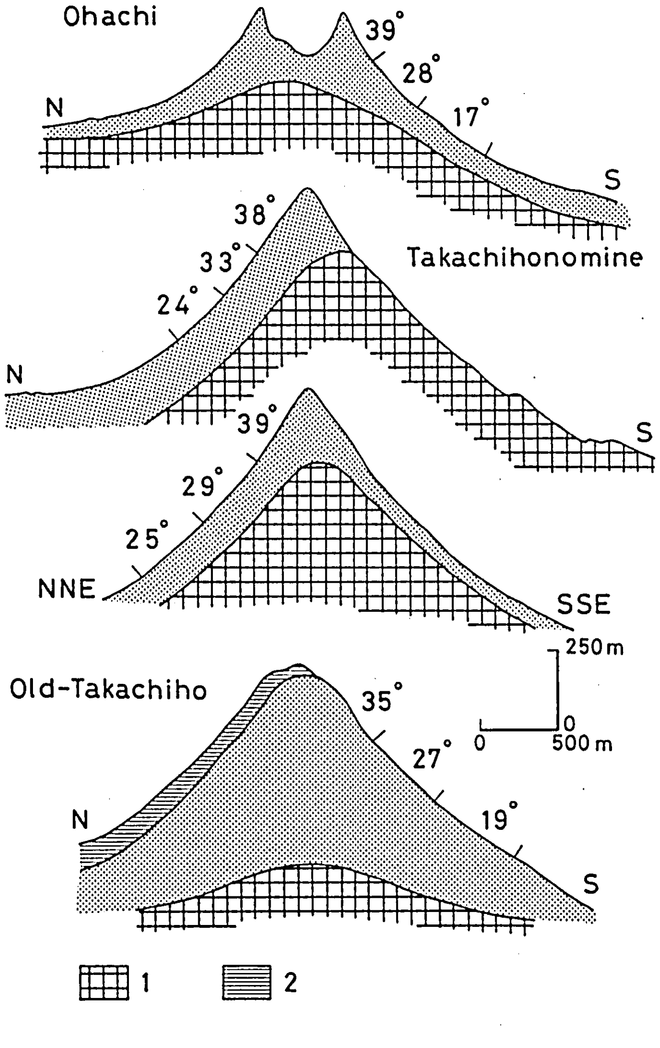

Fig. 41. Topographic cross sections of the cone of TCV. Numerals on the slope of each cone represent the angle of slopes. (1) underlying volcano, (2) overlying volcano.

As viewed from the inclination angles of their slopes, the three volcanoes appear to have the same property, indicating that the inclination angles for them range from 35° to 39° and are controlled by the other factor than by the internal structure. As shown in Fig.41, the inclination angles of the slopes are close to the maximum repose angle at which loose, cohesionless materials remain in stable. They for natural slopes commonly range between 33° and 37°. Because pyroclastic deposits are volumetrically essential in those volcanoes occupying 70-80 % or more of their constituents, their slop inclination angles appear to correspond to the repose angle of the cohesionless pyroclastic materials.

c. Naka-dake, Shinmoe-dake and Karakuni-dake Volcano

Fig.42 shows the topographic cross section of three volcanoes : Naka-dake, Shinmoe-dake and Karakuni-dake Volcano. In these cross sections number represents slope angles. As shown in this figure, the appearance of Shinmoe-dake Volcano is strikingly similar to that of Karakuni-dake Volcano for the presence of large top craters. However, the inclination angle of the southwestern slope of Shinmoe-dake Volcano is closely similar to that of Naka-dake Volcano rather than that of Karakuni-dake Volcano. It can also be noted that the angles of the slopes close to the summits of Naka-dake and Shinmoe-dake Volcano, ranging from 24° to 28°, is too small as compared with a repose angle of cohesionless pyroclastic materials.

As shown in Fig.32, the geologic cross sections of Naka-dake Volcano suggest that it is composed of the accumulated lava flows. Many lavas overflowed from the top crater were piled up high around the summit. Thus the internal structure of the volcano is relatively simple and characterized by predominance of lava flows. This feature is in contrast in a striking way with the internal structures of TCV.

On the other hand, the information on the tephra suggests for Naka-dake Volcano that the nature of the eruption was of vulcanian type accompaning abun-

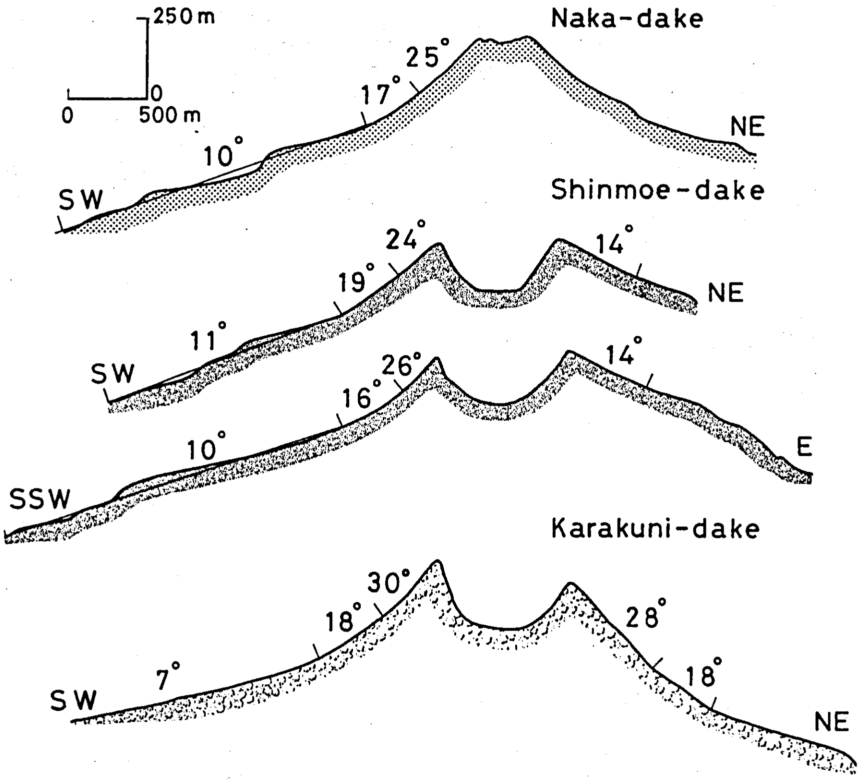

Fig.42. Topographic cross sections of Naka-dake, Shinmoe-dake and Karakuni-dake Volcanoes. Numerals on the slope of each volcano indicate the angle of slopes.

dant extrusion of lava flows but not of sub-plinian or strombolian type such as the eruption of TCV. From the above-mentioned features, it is concluded that the inclination angle of the slopes of Naka-dake Volcano is controlled by the accumulation of thick lava flows, so that the dip of the slope close to the summit is smaller than the repose angle of cohesionless pyroclastic materials.

The most parts of the outer slopes of Shinmoe-dake Volcano are so thickly covered by recent pyroclastic ejecta, that it is difficult to infer its internal structure from the geological map(Fig.31). However, the fact that the main slopes of Naka-dake and Shinmoe-dake Volcano have similar values of dip angle leads to the inference that Shinmoe-dake Volcano is mainly made up of lava flows with subordinate pyroclastic materials. This inference is in harmony with the result obtained from the observation of the Shinmoe-dake crater wall, where the amount of lava flows is greater than that of pyroclastic materials and the average ratio of the former to the latter may approach to 3 : 2.

Well, how about is the internal structure of Karakuni-dake Volcano ? Fig.43 shows large cliff formed on the lateral flank of Karakuni-dake Volcano, in which two-thirds or more of its geologic cross section is exposed. It actually consists of three successive walls with zones of talus between them. Each wall is made up of a single cooling sheet of densely welded pyroclastics of andesitic composition which show marked columnar joints and welded banding. These pyroclastics are of the greatest thickness and most densely welded near the vent. Therefore, the inclination of the slopes of Karakuni-dake Volcano becomes greater toward the vent. The amount of non-welded pyroclastics is surprisingly less than that of welded equivalents, and lava flows are mostly found in the lower slopes of Karakuni-dake Volcano(Kobayashi, 1981).

On the basis of the above-described evidence and consideration, it would be concluded that the inclination angles of the slopes of Karakuni-dake Volcano is controlled by the way of piling of the welded pyroclastics layers but not by the repose angle of cohesionless pyroclastic materials and the mode of accumulation of thick lava flows, unlike the case of Ohachi and Naka-dake Volcano. This is the reason why the dip of the slope of Karakuni-dake Volcano is different from that of Naka-dake and Ohachi Volcano(Fig.41 and 42). According to Imura and Kobayashi(1987), the welded pyroclastic layers, which constitute the most parts of Karakuni-dake Volcano, could be comparable with the Kobayashi pumice deposit whose isopach map is typical for plinian fallout deposit. This fact indicates that the eruption style of Karakuni-dake Volcano is characterized by repeated plinian eruptions and its formation period is equivalent to that of the Kobayashi pumice fall deposit which was very short.

Fig. 43. Diagram showing the large cliff formed on the lateral flank of Karakuni-dake Volcano, in which two-thirds or more of the geological cross section is exposed.

d. Crowded monogenetic volcanoes situated on the north-west side of Karakuni-dake Volcano

As shown in the geologic map of KVG(Fig.3), the northwestern area of Karakuni-dake Volcano is crowded with five monogenetic volcanoes and one small stratovolcano. Of all those volcanoes, Byakushi-ike and Fudo-ike are pit craters, from which narrow lava flows of andesitic composition are traced to the northern foot of Shiratoriyama Volcano. The Byakushi-ike lava flow is older in eruption age than the Ushinosune ash deposits, but Fudo-ike lavas are younger than the latter. In Fudo-ike took place extrusion of lava flow in two times. Rokkannon-miike is a explosion crater with a low rim composed of black scoria, which is older than the Ushinosune ash deposits. The above three craters are filled with water fed from groundwater. Iwō-yama is a small lava dome with a short coulee extending toward the north-west, which is of 1768 A.D. eruption.

6. Summary : Eruptive History of the Kirishima Volcano Group during the Last 18,000 years

In order to understand the distribution of the eruption products of the third stage volcanoes of KVG in time and space, the stage is conveniently subdivided into three periods by two pyroclastic deposits, Ushinosune ash deposits (ca. 9,000 y.B.P.) and Mi-ike pumice fall deposits (ca. 3,000 y.B.P.)(Fig.44).

The third stage of activity began with the plinian eruption of Karakuni-dake scoria about 18,000 years ago after a repose of more than about 10,000 years. The scoria deposit was derived from Old-Karakunidake Volcano which is now completely overlain by Karakuni-dake Volcano. The north-west portion of KVG becomes a site of intense volcanism(Fig.44 (A)) during the phase between 18,000 and 9,000 y.B.P., forming Karakuni-dake, Koshiki-dake, Rokkannon-miike, Byakushi-ike and Iimori-yama Volcano. The life span of all these volcanoes, except for Koshiki-dake Volcano, was much shorter than the repose times. The eruptive activity of Shinmoe-dake Volcano began in this period.

In the time interval of 9,000 to 3,000 y.B.P., the site of volcanism moved to the south-east portion of KVG(Fig.44 (B)). Shinmoe-dake and Naka-dake Volcano repeated the extrusion of thick lava flows from the top craters, forming two stratovolcanoes rich in lava flows. On the other hand, the sequence of activity of TCV situated at the southeastern end of KVG began with explosive eruptions of tephra, and vast amount of volcanic ashes and scoriae was accumulated mainly on the eastern foot of KVG. By repeated eruptions during this activity, two stratovolcanoes rich in pyroclastic materials, Old-Takachiho and Takachiho-no-mine Volcano, were built up on the western slope of the previously formed volcano. Their shapes are steeper than that of stratovolcano rich in lava flows such as Naka-dake.

About 3,000 y.B.P., catastrophic plinian eruption occurred suddenly at the eastern end of KVG, accompaning the formation of the Mi-ike maar. During the period from 3,000 y.B.P. to the present, the main activity has occurred at the south-east portion of KVG(Fig.44 (c)), exception for the eruptions which extruded the Fudo-ike and Iwohyama lava flows. The extrusion of lava flows from the top crater of Naka-dake Volcano continued on into this period, but the volcanism became weak in comparison with that of the preceding period. While the volcanic activity of TCV increased in violence during this period and was marked by the intermittently repeated sub-plinian eruptions of scoria lapilli and ash. As a result of these eruptions, the small stratovolcano of Ohachi was born on the western slope of Takachiho-no-mine Volcano.

Since 742 A.D., more than 40 eruptions have been documented, and they occurred mostly at Ohachi and Shinmoe-dake Volcano, except in 1768, when a small lava issued at Iwōyama. Activities in 788, 1566 and 1716-1717 A.D. were extraordinary violent and caused great disasters. However, the details of such disasters have not been described in the literature.

Two important points arise from the

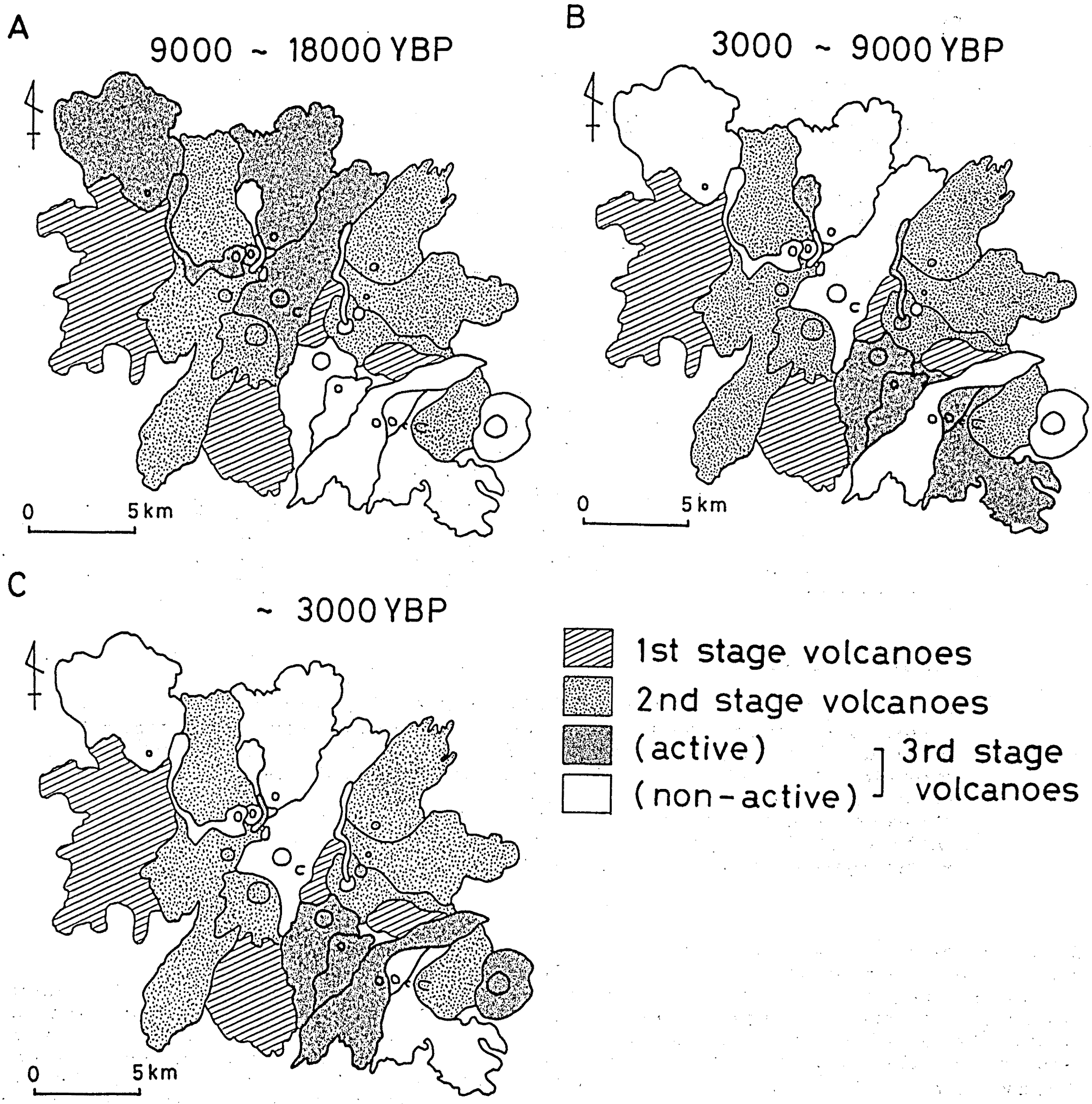

Fig. 44. Distribution of erupted products of the third stage volcanoes of KVG in time and space.

(A) Between ca.18,000 and ca.9,000 yY.B.P., the north-west portion of KVG became a site of intense volcanism.
(B) During the following 6,000 years, the site of intensive volcanism moved to the south-east portion of KVG.
(C) About 3,000 y.B.P., catastrophic plinian eruption occurred at the eastern end of KVG, forming the Mi-ike maar(Mi).

eruptive histories of the third stage volcanoes of KVG. Firstly most of the volcanic centers of this stage are concentrated in a linear zone of NW-SE direction(Fig.44 (D)), resulting in that the distribution of KVG is elongated in the NW-SE direction. Sakurajima Volcano and Ibusuki Volcano Group, which are situated to the south of KVG, have also linear flank volcanoes zone and post-caldera cones trending approximately in a NW-SE direction. Based on thses phenomena, Nakamura(1977) concluded that NW-SE direction in south Kyushu is

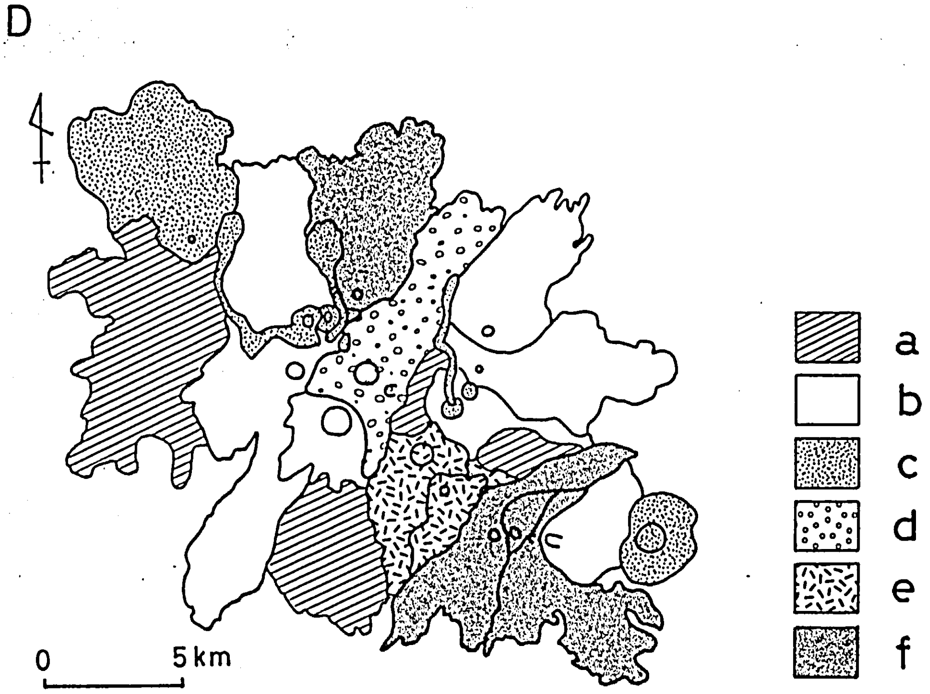

Fig.44.(continued)

(D) Volcanoes of the third stage of KVG are concentrated in a linear zone with NW-SE direction. Judging from the internal structure of volcanic edifice and the mode of eruption, the following four kinds of volcanoes are discriminated : (1) small stratovolcanoes rich in loose pyroclastic ejecta, (2) small stratovolcanoes rich in thick lava flows, (3) small stratovolcano with short life span, which is composed of the piling of the welded pyroclastic layers, (4) monogenetic volcanoes.

regarded as the direction of the maximum horizontal compression. This NW-SE direction is parallel to the moving direction of the Philippine Sea plate(N50°W, Seno, 1977) and obliques at high angles to the volcanic front of the Ryukyu arc. Therefore, it is safely said that the elongation direction of KVG is related to the subducted slab and is in accord with the across direction of the Ryukyu volcanic arc.

Secondly, the volcanoes of the third stage are divided into four groups on the basis of their internal structure and eruption style. The four groups, which appear to have resulted from the difference of the nature of magma, are aligned in the following order from SE side to NW side of KVG(Fig.44 (D)) : 1) small stratovolcanoes rich in loose pyroclastic materials(Old-Takachiho, Takachiho-no-mine and Ohachi Volcano), 2)small stratovolcanoes rich in thick lava flows(Naka-dake and Shinmoe-dake Volcano), 3) a large pumice cone with wide top crater, which is characterized by the piling of welded pyroclastics layers(Karakuni-dake Volcano), and 4) crowded monogenetic volcanoes.

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