A RECONSTRUCTION OF SMALL-SCALE ERUPTIONS USING PYROCLASTIC DEPOSITS

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Abstract Sedimentological and stratigraphical studies of the deposits accumulated by recent eruptions on Sakurajima volcano have clarified some features of the deposit of small-scale eruptions, and led to a method for reconstruction of those eruptive activity using the pyroclastic deposits. Depositional facies, bulk density and carbon content of the deposit are reflections of the accumulation rate of pyroclastic materials. The sequence of small-scale eruptive activity manifests by the different depositional facies in the proximal area. Laminated and/or massive volcanic sand layer usually indicates a period of highly active volcanism; brownish loamy volcanic sand layer a less active one and brownish loam and/or humic soil a dormant or inactive one. The duration of these periods of volcanic activity can be estimated from recent fallout ash data. This method is fed back to the deposits of Sakurajima volcano after the 1914 eruption and also applied to those of Suwanosejima volcano after the 1813-1814 eruption. It is ascertained that this method is useful in understanding of non-recorded small-scale eruptive activities. A pre-historical eruptive activity of Old-Takachiho volcano, one of the Kirishima volcanoes, is reconstructed by means of this method.

Key words: small-scale eruption, pyroclastic deposit, Sakurajima volcano, volcanic sand, accumulation rate

1. Introduction

Purpose of this study

Over the last few decades, a considerable number of papers have been written on pyroclastic deposits. They have contributed to volcanology. However, most of these studies were carried out on the basis of the deposits of comparatively large-scale eruptions such as plinian or pyroclastic flow eruptions. On the contrary, few studies have so far been made on the deposits of small-scale eruptions of vulcanian and/or minor strombolian type. Small-scale eruptions leave little or no deposits which can be now recognized as discrete geological units, because they are usually so thin and fine-grained that they are soon eroded by wind and water. The purpose of this study is to establish a method for reconstruction of small-scale eruptive activity using pyroclastic deposits.

Sakurajima volcano is one of the world's most active volcanoes. It has displayed virtually continues small-scale eruptions of vulcanian type since 1955. Such activity is well documented by Japan Meteorological Agency (JMA), Sakurajima Volcanological Observatory (SVO) of Kyoto University and Kagoshima Prefectural Government (KPG). This volcano is a reliable "working laboratory" for studying small-scale eruptive activity. In this paper, characteristics of the deposits accumulated by small-scale eruptions of Sakurajima volcano since 1914 are described first. Then, the problems concerning the relationship between the features of deposits and the documented eruptive activity are discussed. The method for reconstruction of small-scale eruptions based on the deposits is presented next. I will discuss the problem of this method can be fed back to the deposits of Sakurajima volcano after the 1914 eruption and applied to those of Suwanosejima volcano after the 1813-1814 eruption. Lastly, a pre-historical eruptive activity of Old-Takachiho volcano, one of the Kirishima volcanoes, is reconstructed using this method.

Significance

The present-day eruptions of Sakurajima volcano are rather small in scale, with Volcanic Explosivity Index (VEI) of 2 (Simkin *et al.*, 1981; McClelland *et al.*, 1989). Such an eruptive style (*i.e.*, vulcanian type) is very common at many active andesitic stratovolcanoes clustered along subducting plate margins (*e.g.*, Self *et al.*, 1979; Walker, 1982). Thus, understanding of these eruptive activities may offer a key to interpretation of arc volcanism. In addition, this study should contribute to understand the eruptive history of the volcano in more detail.

Like earthquakes, the frequency of eruption increases with decreasing size, *i.e.*, there are a lot of small ones and not so many large ones (Simkin, 1988). But, even small-scale eruptions may cause great disasters nowadays, because many people live in areas of high volcanic hazard. Thus, this study is also important for reducing volcanic hazards.

Previous work

Many studies of comparatively large-scale eruptions have been performed on many volcanoes and numerous ancient pyroclastic deposits (*e.g.*, Walker, 1981; Walker, 1983). These studies are compiled in two excellent text books, *i.e.*, *"Pyroclastic Rocks"* by Fisher and Schmincke (1984) and *"Volcanic Successions"* by Cas and Wright (1987). On the other hand, small-scale eruptions have been studied particularly on the physical eruptive mechanism and the fallout model of the ashes on the basis of some recent activities (*e.g.*, Rose, Jr. *et al.*, 1973; Self, 1974; Self *et al.*, 1979; Iguchi and Kamo, 1984; Suzuki *et al.*, 1980; Gilbert *et al.*, 1991; Lane and Gilbert, 1992). There are few studies on the deposits of small-scale eruptions from the sedimentological and stratigraphical view.

Murata *et al.* (1966) described the eruptive activity of Irazú volcano in 1963-1965. Although they clarified the depositional facies and grain-size distributions of ash deposits accumulated through the activity, the complicated dynamics of transportation, deposition and erosion of the ash were not mentioned.

Kobayashi (1986a) studied the volcanic ash layers formed by intermittent eruptions of Sakurajima, Satsuma-Iwojima and Kirishima volcanoes, and discussed the relationship between the intermittent eruptive activity and the growth history of the volcanic edifice. He expressed the distributions and sedimentary processes of deposits by small-scale eruptions. However, there is no quantitative description about the deposits.

The eruptive histories including the small-scale eruptions have been constructed for several volcanoes (*e.g.*, Kobayashi *et al.*, 1988; Hayakawa and Imura, 1991). However, little is known about the details of eruptive activity such as magnitude, sequence and length of an eruptive episode.

Imura (1991) described the deposits of Suwanosejima volcano accumulated during the last 200 years. He suggested that the small-scale eruptive activity can be reconstructed from the succession of volcanic sand beds, although the relationship between the deposits and the eruptive activities was not presented quantitatively.

Terminology

"Volcanic ash" is used as the general term for all pyroclastics finer than 2 mm. "Coarse ash" (2-1/16 mm) and "fine ash" (< 1/16 mm) classified by Schmid (1981) are called volcanic sand and volcanic silt, respectively in this paper considering correspondence with grain-size division of non-volcanic clasts.

We can usually find abundant non-stratified brown or black ill-sorted deposits intercalated by the readily confirmed geological units such as volcanic ash, scoria and pumice layers. They are called by such terms as volcanic soil (*e.g.*, Suzuki and Hayatsu, 1991), soil (*e.g.*, Fisher and Schmincke, 1984), loam (*e.g.*, Melekestsev *et al.*, 1989), weathered ash (*e.g.*, Nakamura, 1964), Kuroboku and/or Akaboku (*e.g.*, Watanabe and Takada, 1990), paleosol and/or epiclastic (*e.g.*, Walker *et al.*, 1981), loess (*e.g.*, Hayakawa and Imura, 1991), *etc*. These terms are sometimes extended to note the origin of the deposits. In this paper, those deposits are collectively called as "loam" from the features, without consideration of the origin because there is no agreement as to the origin of the deposits (*e.g.*, Watanabe and Takada, 1990; Hayakawa, 1990). According to the *"Glossary of Geology (3rd ed.)"*, loam is defined as follows: a rich, permeable soil composed of a friable mixture of relatively equal and moderate proportions of clay, silt and sand particles, and usually containing organic matter (Bates and Jackson, 1987).

2. Deposits on Sakurajima Volcano Accumulated After the Great Eruption of 1914

Outline of Sakurajima volcano

Sakurajima volcano located in southern Kyushu, Japan (Fig. 1) is one of the most active volcanoes in the world. This volcano is a post-caldera cone of the Aira caldera which was formed as a result of large scale pyroclastic flow eruptions in the late Pleistocene age (Aramaki, 1984). The activity of Sakurajima volcano started about 20,000 years ago, as inferred from tephrochronological study (Kobayashi, 1986b).

Sakurajima volcano consists of two adjoining stratocones, the Kitadake (north peak: elev. 1,117 m) and the overlying Minamidake (south peak: elev. 1,040 m), and of several parasitic volcanoes. The major constituents of these cones are coarse pyroclastic

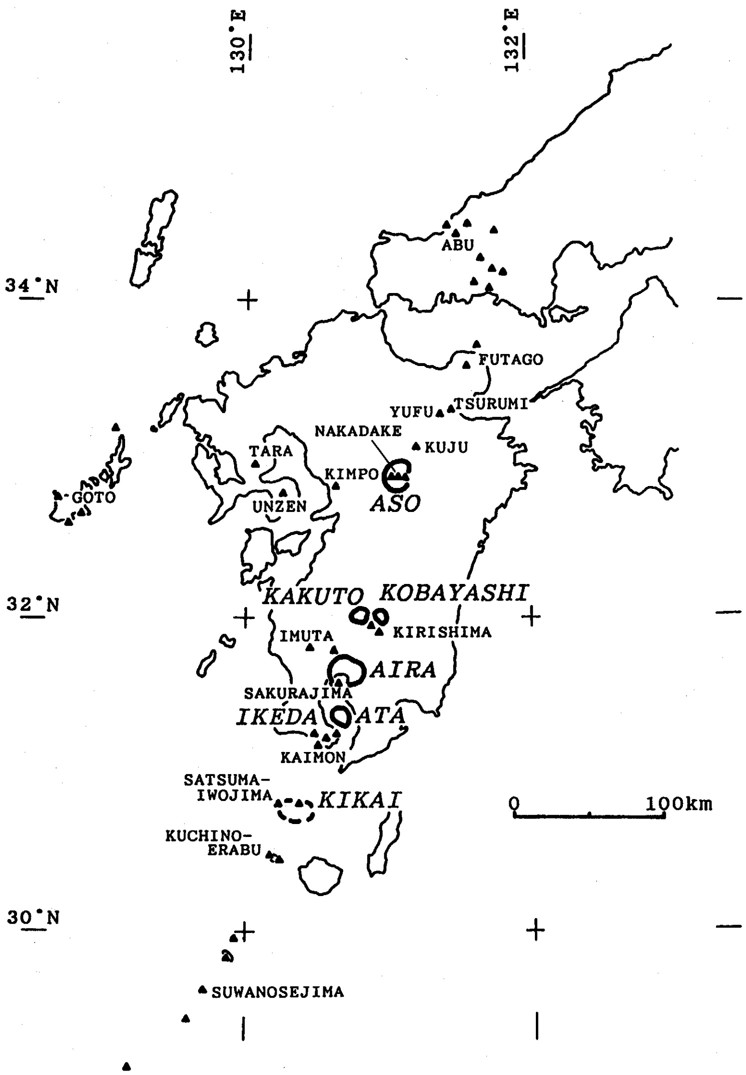

Fig. 1 Index map showing the distributions of the Quaternary volcanic centers and calderas in Kyushu
Solid triangles are the Quaternary volcanoes. Thick solid lines show outlines of calderas with names in italics (modified from Aramaki *et al.*, 1981).

materials associated with lesser amounts of lava flows. The rocks of Sakurajima volcano are augite hypersthene andesite and dacite with SiO_2 content from 57 wt.% to 67 wt.% (Fukuyama and Ono, 1981).

Since 708 A.D., more than 30 eruptions have been recorded. Large eruptions took place in 1471-1476 (Bunmei eruption), 1779-1781 (An-ei eruption) and 1914 (Taisho eruption), producing a huge amount of pyroclastics and lava flows from newly formed fissure vent (Kobayashi and Ishihara, 1988). In 1914 eruption, the Sakurajima island was converted into the Osumi peninsula by the lava flow (Taisho lava).

After the great eruption of 1914, the volcano was quiet for 21 years. Only fumaroles were found at summit crater and in several places on the flank (Hagiwara *et al.*, 1946).

Eruptive activity at the Minamidake summit crater began in September of 1935. Since that time a white plume infrequently issued from the crater. In October of 1935, an eruption took place in the new parasitic crater on the eastern flank of the Minamidake, 750 m above sea level. This eruptive activity was accompanied by small-scale pyroclastic flows. In March of 1946, lava flows (Showa lava) extruded from the parasitic crater (Hagiwara *et al.*, 1946). Since then, small explosions have occurred at the Minamidake summit crater from time to time. This activity lasted until 1950.

After the five years of dormancy, the eruptive activity of Minamidake summit crater resumed on 13 October, 1955 and has continued to the present. Most of eruptions are cannon-like explosive eruptions which generally called "vulcanian type"; small-scale pyroclastic flows are often produced. However, ash-laden smoke poured out for a few days without explosion. JMA counts the explosions using the following rules: (a) an explosive sound is heard, air shock is felt, or ejection of blocks is recognized by observers at the JMA Kagoshima Local Meteorological Observatory, 10 km west of the volcano, or (b) a typical explosion earthquake is recorded by seismographs on the island, or (c) a typical explosion air shock is recorded by a microbarograph at the Observatory.

The eruption column usually attains a height of 1,000-3,000 m above the summit crater. It rarely exceeds 5,000 m. Ejected materials are mainly bread-crust bombs, consolidated volcanic blocks, lapilli and ashes, while in violent explosions, mainly pumice is ejected. Although lava lakes or lava domes at the summit crater were repeatedly formed, they were later destroyed by explosive eruptions (Kobayashi and Ishihara, 1988). During the period from 1955 to the end of 1991, the total number of explosions exceeded 6,000 (JMA, 1992). The fallout ash covers a wide area in the Kagoshima Prefecture, and it causes great damage to agriculture and to people's daily life in the area.

Description of the deposits

Field works

The investigation of the deposits was performed as follows: the observation points were selected such that they are on the flat areas with natural vegetation and far from the main road. I made a trench to observe the deposits down to the upper layer of the Taisho pumice (1914). Samples of deposit were obtained from every 5 cm in depth using the cylindrical plastic case (5 cm depth and 3 cm in inside diameter). Field works were carried out in January, February and May 1990 and March 1991.

1) Thickness and distribution

Figure 2 shows the thickness of the deposits above the Taisho pumice (1914). The distribution of the deposits does not have depositional axis along a specific direction such as those of many plinian fallout deposits.

Kamo *et al.* (1977) and Eto and Ishihara (1979) found that the dispersal of fallout ashes from Sakurajima volcano coincides qualitatively well with leeward direction in the

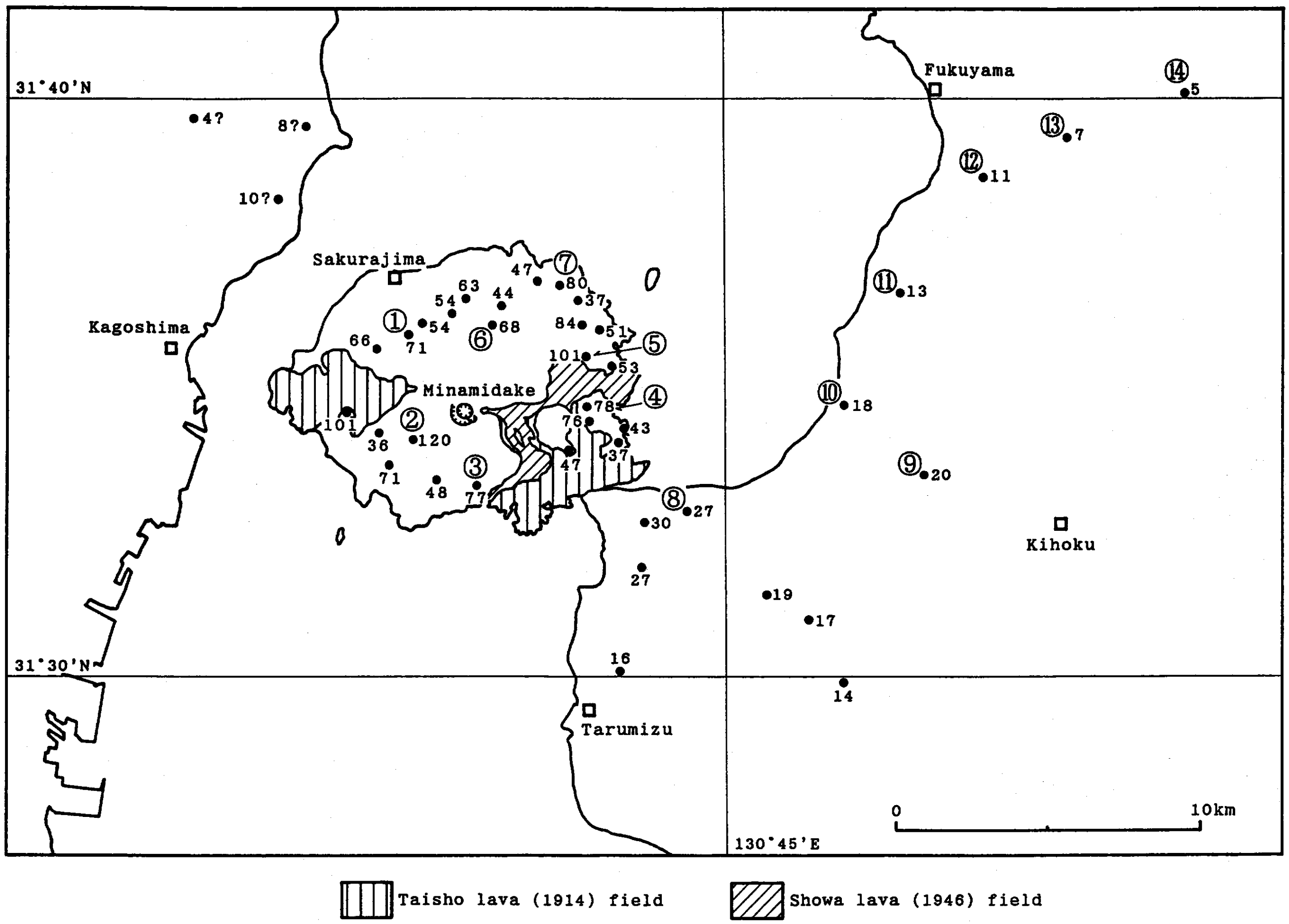

Fig. 2 Thickness of the deposit above the Taisho pumice (1914) in cm
Number with circle indicates the locality of columnar sections in Figs. 4, 6 and 16.
Open squares indicate the cities and/or towns.

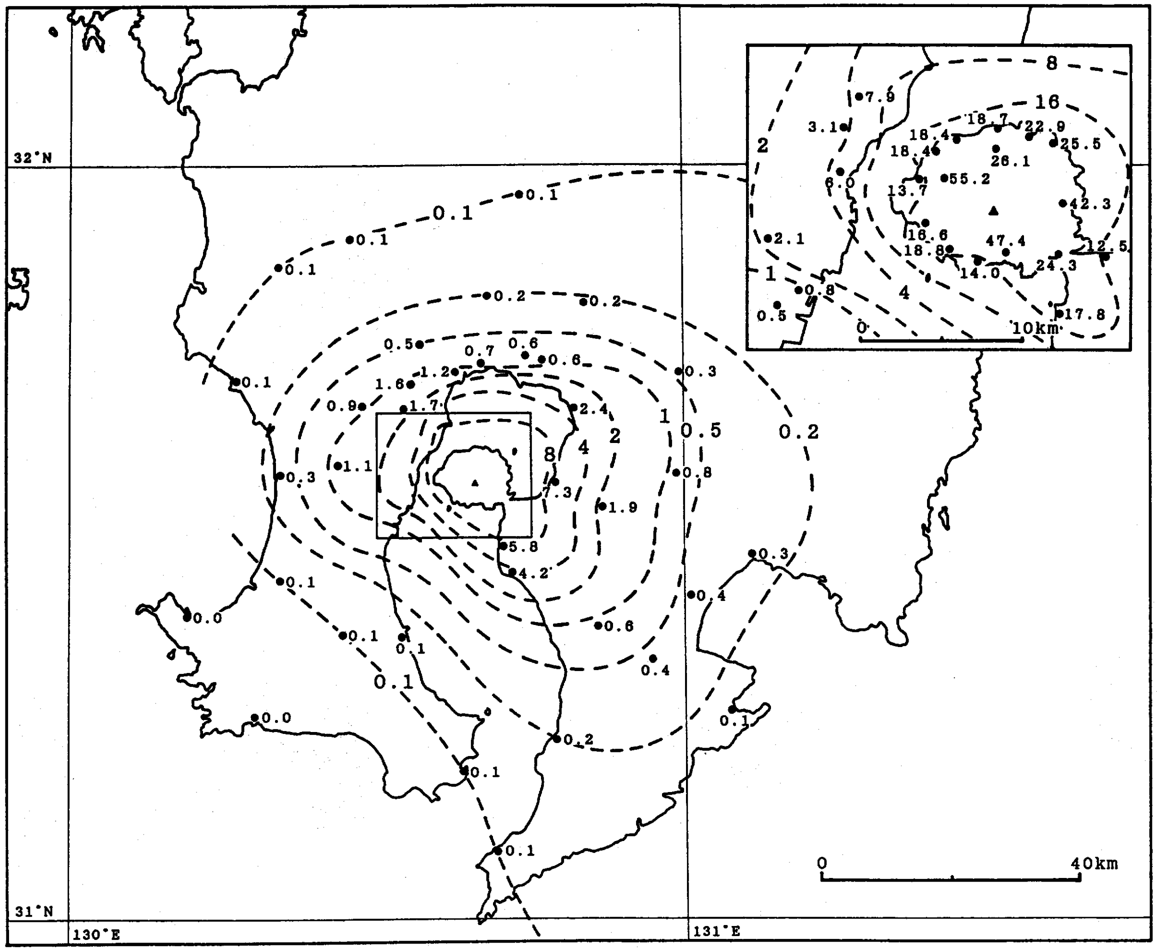

Fig. 3 Average annual amount of fallout ashes during the 10 years (1981-1990) Value in kg/m²/year. Data source: Kagoshima Prefectural Government.

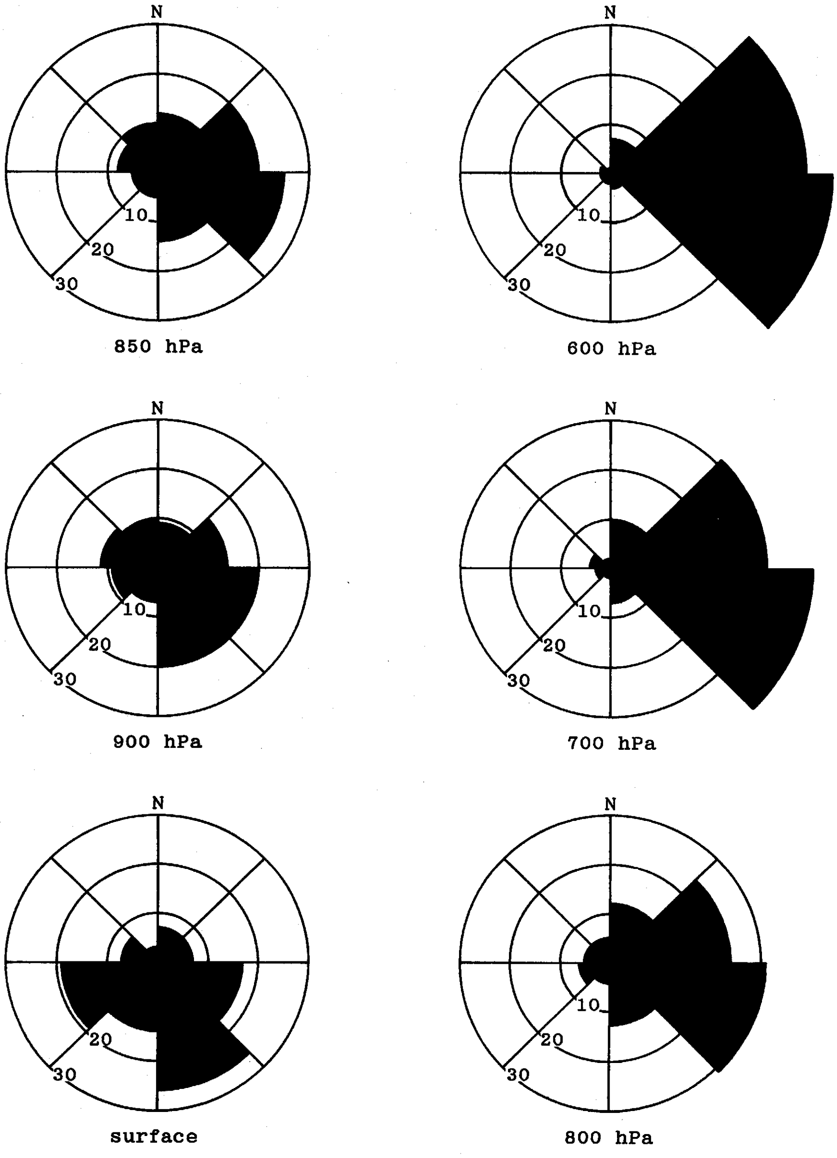

Fig. 4 The percentages of leeward direction during the 1981-1990
Data source: Kagoshima Meteorological Observatory. 900 hPa: *ca.* 1000 m high, 850 hPa: *ca.* 1500 m high, 800 hPa: *ca.* 2000 m high, 700 hPa: *ca.* 3000 m high, 600 hPa: *ca.* 4000 m high.

lower troposphere *ca.* 1,000-2,000 m (a.s.l.). On the other hand, Kobayashi (1986a) suggested that the deposits of long-term small-scale eruptions occur in concentrically circular areas. The distribution of fallout ashes during the last 10 years (1981-1990) measured by KPG (Fig. 3) approximately fits in the percentages of leeward direction in the lower troposphere *ca.* 1,000-1,500 m (Fig. 4), and it shows a nearly concentric circular pattern. Thickness distribution of the deposits observed by the present author

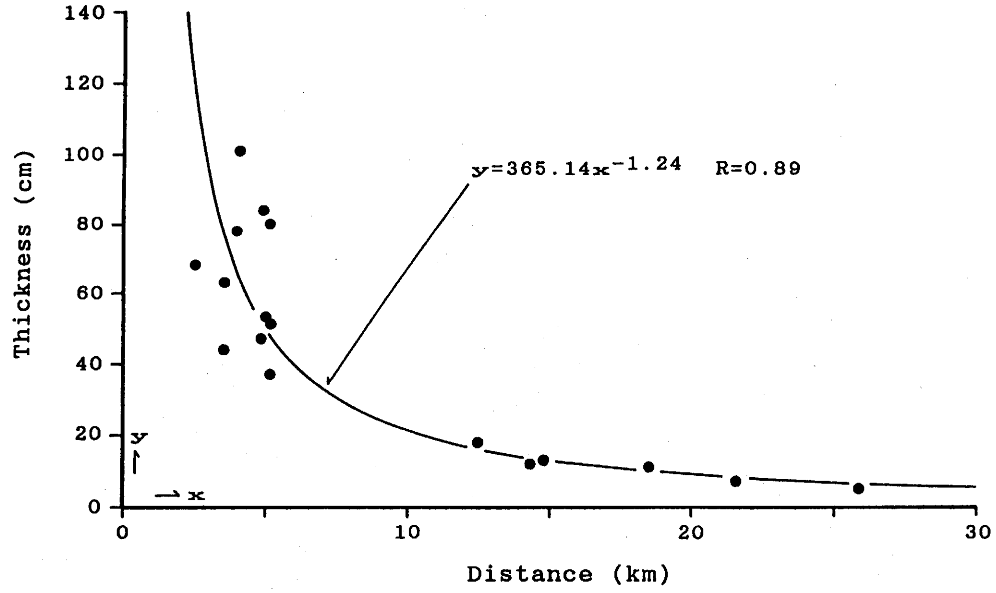

Fig. 5 Plots of the thickness of the deposit (NE-E) above the Taisho pumice (1914) against the distance from the vent

roughly corresponds to the facts mentioned above.

Total thickness of deposits increases along with decreasing distance from the Minamidake active crater (Fig. 5). In Sakurajima island, however, the distribution pattern is very complicated. For example, at place 6 in Fig. 2, the thickness changes drastically from 68 cm to 40 cm only 3 m away and 15 cm higher. The deposits do not show mantle bedding in the strict sense. This fact indicates that the accumulation of pyroclastic deposit by small-scale eruptions is strongly influenced by micro topography. In the non-vegetated areas, *i.e.*, Taisho (1914) and Showa (1946) lava fields and/or dry riverbeds, the deposits are lacking or very thin. In contrast to those areas, the deposits tend to be thicker in the adjacent areas.

These features suggest that the fallout ashes have been easily moved after the primary deposition. Aramaki and Hayakawa (1982) observed the phenomenon of ash particles were moved by surface wind after the fallout of the 1982 eruption of Asama volcano. However, there is another reason why the deposits become thicker in the places around bare areas. It depends on the condition of vegetation cover; fallout ash particles could not be trapped in the non-vegetated areas. Fallout ashes are carried by surface wind to surrounded areas covered with vegetation. Thick deposits are thus formed. Imura (1991) stressed that the vegetation played the most important role in the accumulation process of ash particles from such minor eruptions.

2) Facies and stratigraphy

Figure 6 shows representative columnar sections for the deposits above the Taisho pumice (1914). Although recent ashes accumulated with fallen leaves and rootlets at the top, horizons of humic soil are not recognized in the deposits.

The deposits are mainly composed of sand-sized and poorly vesiculated gray lava

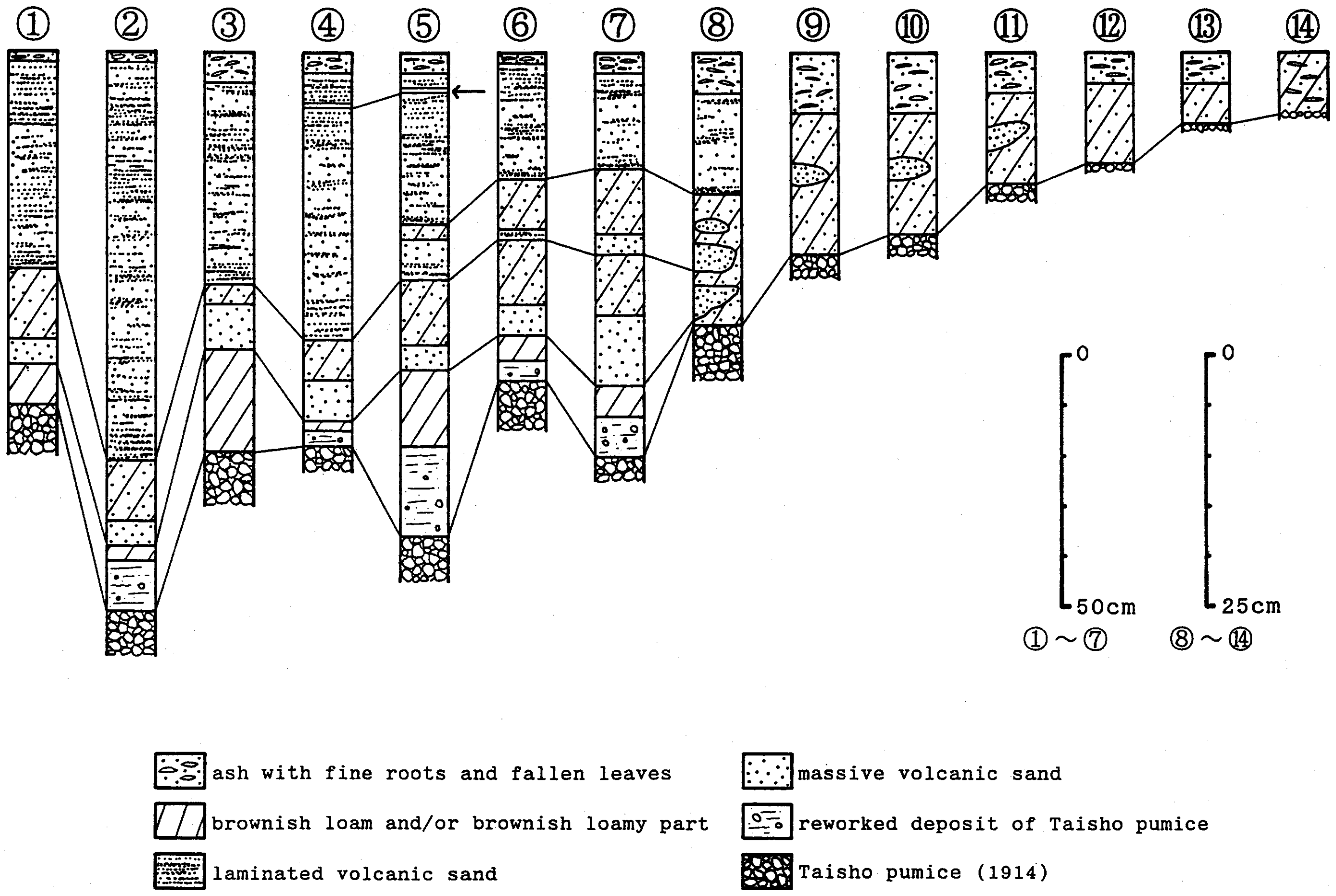

Fig. 6 Representative columnar sections of the deposit above the Taisho pumice (1914) Arrow shows the thin pumice layer deposited on 17 November, 1987.

fragments. It is very hard to identify the so-called "fall unit" (Nakamura, 1964). There are no key beds throughout the study area. However, a thin pumice layer erupted on 17 November, 1987 is observed in the northeastern part of Sakurajima island (sections 4 and 5 of Fig. 6).

In the area within *ca.* 10 km from the active crater, the deposits are divided into the following five different facies: laminated volcanic sand layer, massive volcanic sand layer, loamy volcanic sand layer, brownish loam and light colored laminated volcanic silt layer. Each of the boundaries among them are not clearly identified. In the area within 10 to 15 km from the vent, the deposits become loamy. Patchwork-like volcanic sand lenses are recognized (*e.g.*, sections 9, 10 and 11 of Fig. 6). In the area farther than 15 km, these facies could not be discriminated (*e.g.*, sections 12 and 13 of Fig. 6). Then, beyond area 25 km from the crater, the deposit is only recognized as a loam (section 14 of Fig. 6).

In the area within *ca.* 10 km from Minamidake, the successions of deposits show same stratigraphic sequences from upper to lower (Fig. 7) as follows: recent fallout ash layer (A1) which include many fallen leaves and rootlets, dark gray laminated volcanic sand layer (A2), somewhat brownish gray massive volcanic sand layer (A3), dark gray laminated volcanic sand layer (A4), brownish loamy volcanic sand layer (L1), gray massive volcanic sand layer (B) which rarely shows lamination, brownish loam (L2) containing thick roots of present trees which are not found in the other horizons, and reworked deposit of Taisho pumice (R). It is difficult to identify such stratigraphic sequences as those mentioned above in the area farther than 15 km from the vent because the depositional facies are not so clear.

Laboratory works

1) Deposit density

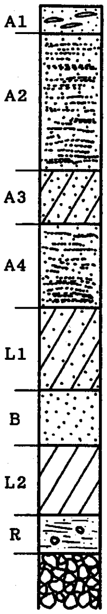

Fig. 7 Idealized columnar section of the deposit in Sakurajima island Not to scale.

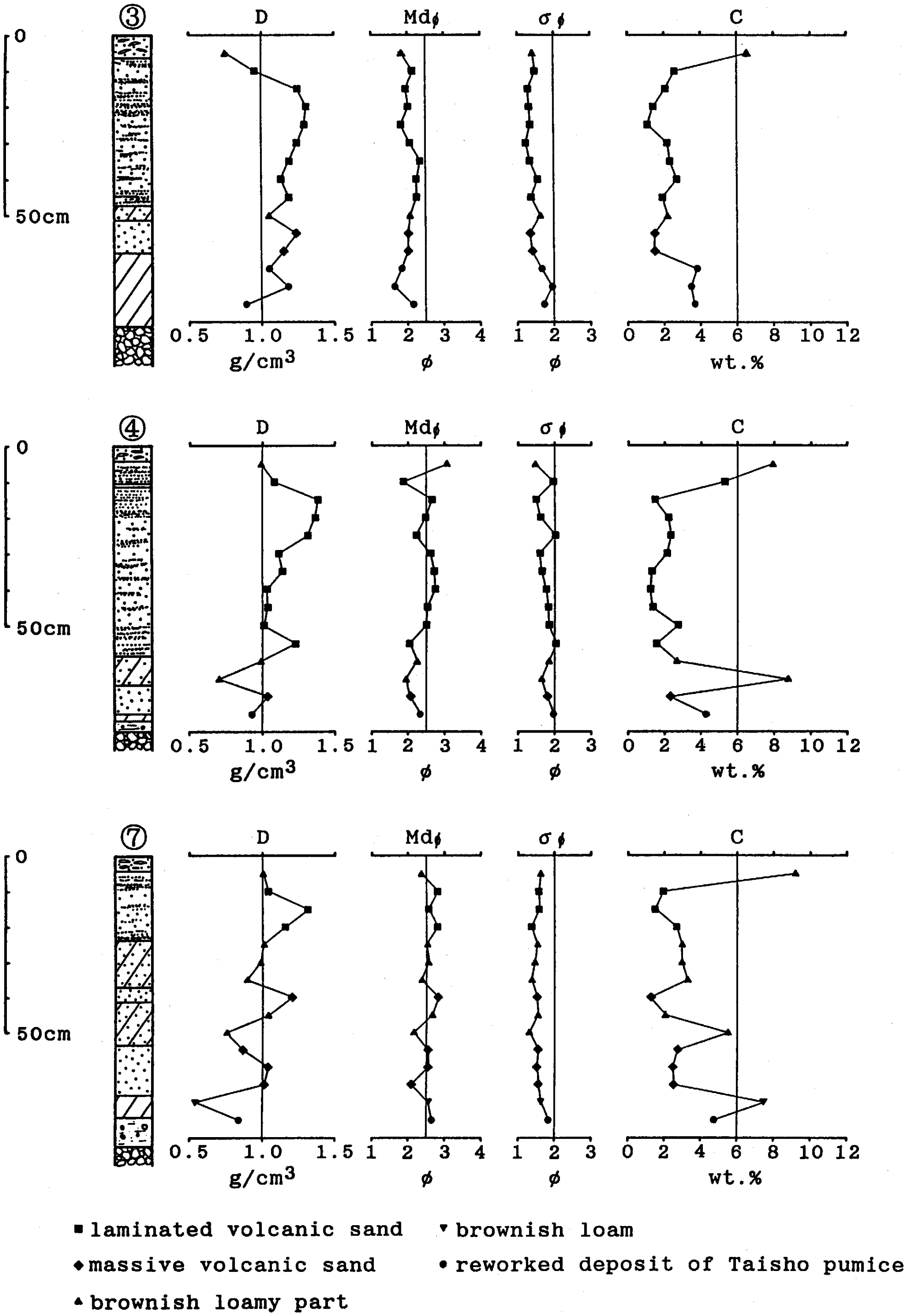

Fig. 8 Deposit density (D), median diameter (Mdϕ), sorting ($\sigma\phi$) and carbon content (C) of the deposits of Sakurajima volcano

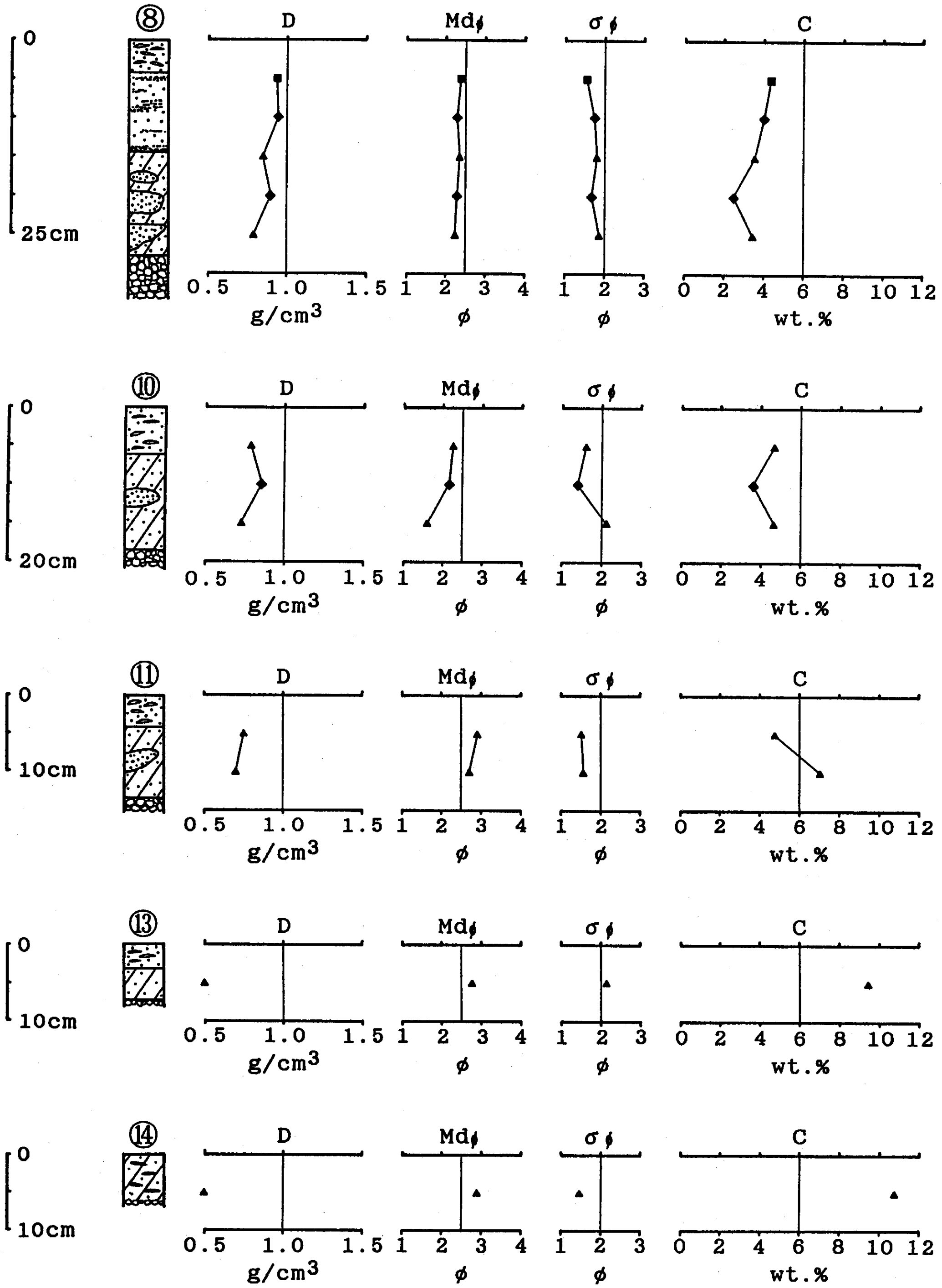

Fig. 8 Continued

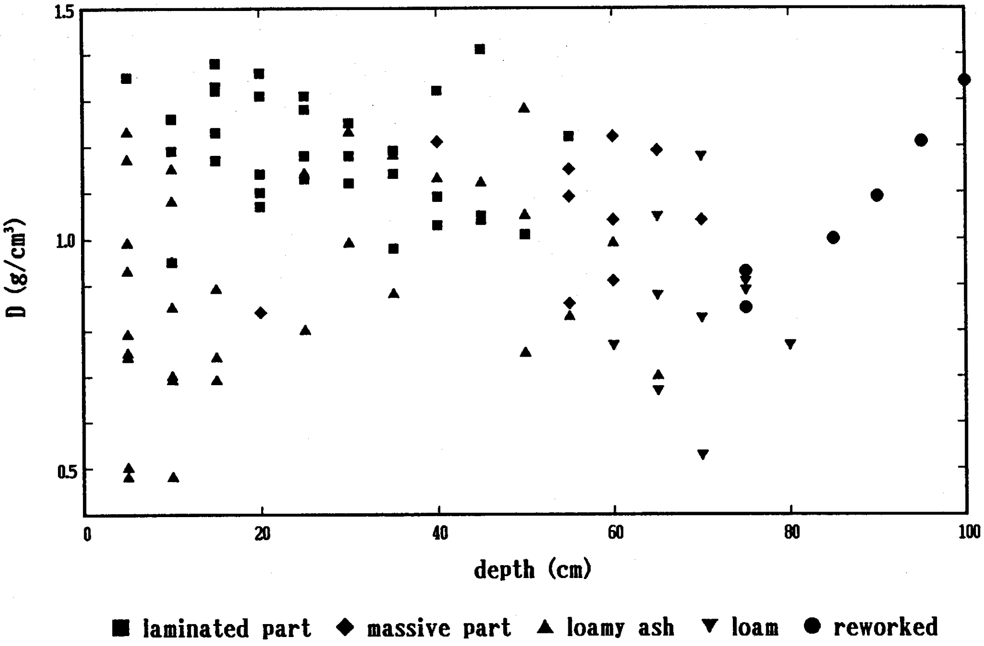

Fig. 9 Plots of the deposit density (D) against the depth

The bulk density of the deposit was determined by measuring the dry-weight of sample. Figure 8 shows the deposit density of representative sections.

Deposit density ranges from 0.5 g/cm^3 to 1.5 g/cm^3. The uppermost part of each section and loamy layers tend to show low density (0.5-1.1 g/cm^3). On the other hand, laminated and massive layers have a significantly higher density (1.1-1.5 g/cm^3) than those of former layers. It seems likely that the deposit density decreases with increasing distance from the Minamidake crater. The deposit density does not increase with depth (Fig. 9), indicating that the compaction does not proceed due to the depth. It suggest that the deposit bulk density should depend on the porosity and/or carbon content of deposits because the deposits are mainly composed of lava fragments of the same density.

2) Grain-size distribution

Collected samples were sieved with a set of sieves chosen to have one ϕ intervals (where$\phi = \log_2 d$, d being the grain-size in millimeters) and to cover the range from -4 ϕ to 4 ϕ (16 mm to 1/16 mm). The three parameters chosen to quantify the main characteristics of the cumulative curve (Walker, 1971) are median diameter (Mdϕ), graphical standard deviation ($\sigma\phi$) and first-order skewness ($\alpha\phi$) of Inman (1952). The relevant formulae are:

$$\mathrm{Md}\phi = \phi_{50}$$

$$\sigma\phi = (\phi_{84} - \phi_{16})/2$$

$$\alpha\phi = [(\phi_{84} + \phi_{16})/2 - \mathrm{Md}\phi]/\sigma\phi$$

Figure 8 shows the grain-size data of representative sections. The values of Mdϕ

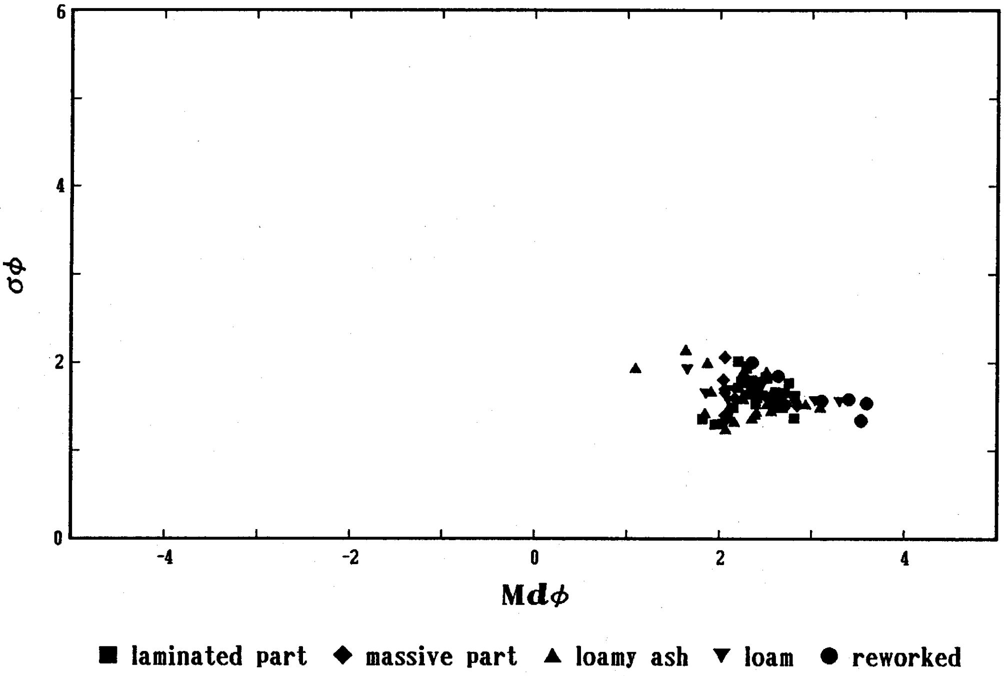

Fig. 10 Plots of sorting (σφ) against median diameter (Mdφ)

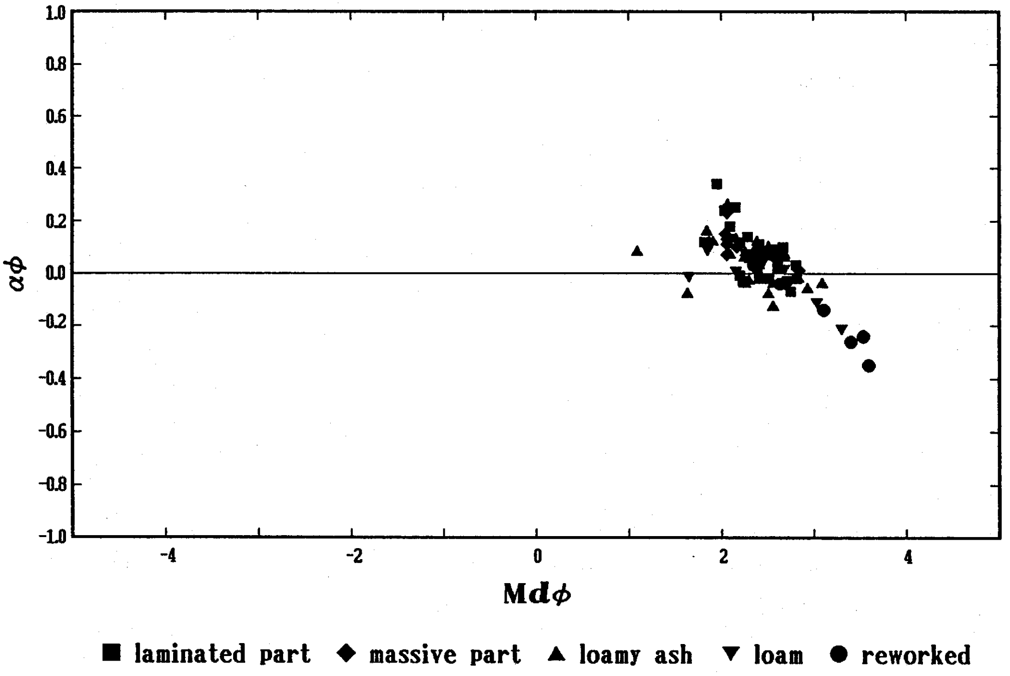

Fig. 11 Plots of skewness (αφ) against median diameter (Mdφ)

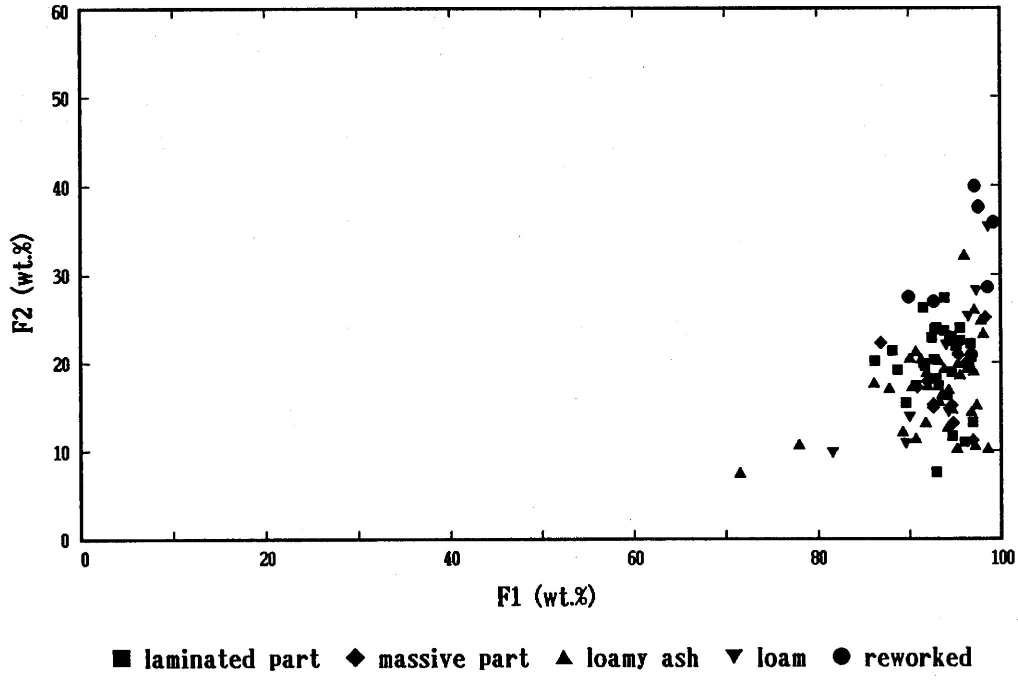

Fig. 12 Plots of F_2 (wt.% clasts finer than 1/16 mm) against F_1 (wt.% clasts finer than 1 mm)

are mostly between 2 and 3. The values of $\sigma\phi$ are mainly in the range of 1 to 2 which means they are well sorted. Then, $Md\phi/\sigma\phi$ plot shows that most of samples occupy the same field (Fig. 10). The values of $\alpha\phi$ for each sample are plotted against $Md\phi$ in Fig. 11. The $\alpha\phi$ values mainly represent positive and/or nearly symmetrical skewness. However, reworked deposit of the Taisho pumice shows significantly negative skewness. This fact may imply that the reworked deposit of Taisho pumice was affected by fluvial process, because beach sand generally displays negative skewness (Friedman, 1961). These facts indicate that the mechanisms of transportation and sedimentation of clastics did not change during the accumulation of deposits, except for the reworked deposit of Taisho pumice.

The deposits of vulcanian eruption are generally characterized by fine-grained ash (*e.g.*, Wright *et al.*, 1980). Samples of Sakurajima's pyroclastic deposits certainly contain more than 70 wt.% of clastics finer than 1 mm. Materials finer than 1/16 mm constitute 40 wt.% or less (Fig. 12).

3) Carbon content

Carbon content was measured as follows: 10 ml of hydrogen peroxide (H_2O_2) and 40 ml of water were added to 10 grams of dried sample in the beaker. The beaker was placed in hot water bath for 1 hour to decompose the organic matter. Carbon content was calculated from the weight loss. Figure 8 includes the carbon content data, ranging widely from 1 wt.% to 11 wt.%.

On Sakurajima island, uppermost parts near the surface (layer A1) have high

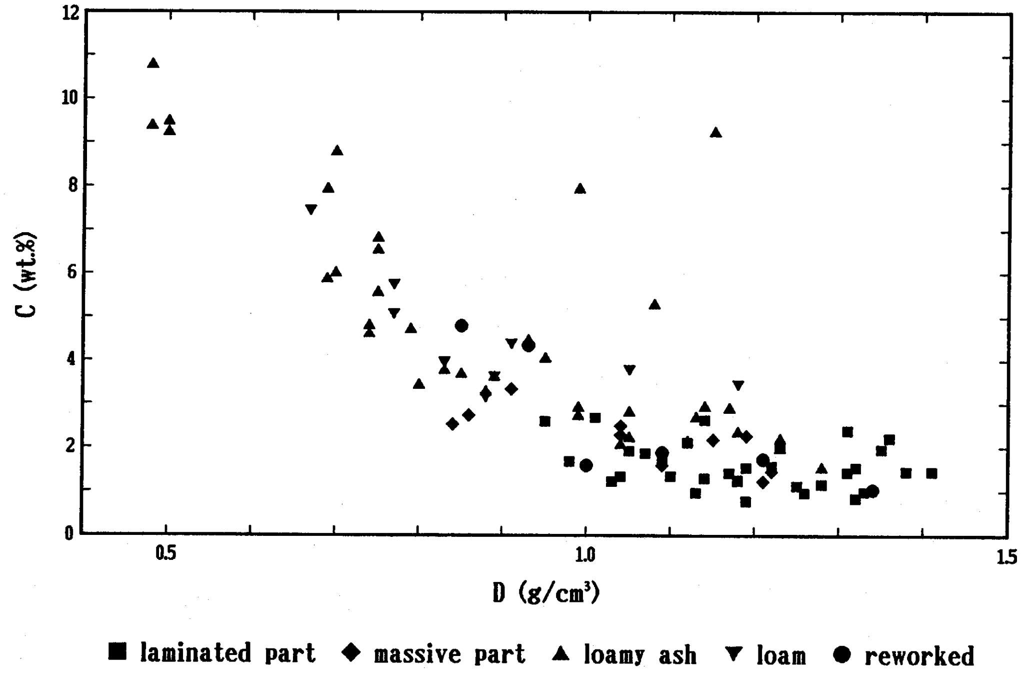

Fig. 13 Plots of the carbon content (C) against the deposit density (D)

carbon contents (4-8 wt.%), whereas the lower parts have relatively constant value of about 2 wt.%. Loamy layers such as L1 and L2 have comparatively higher carbon content than those of laminated and/or massive volcanic sand layers (Fig. 8).

It seems likely that the carbon content increases with distance from the Minamidake. At a place more than 20 km far from Minamidake crater (*e.g.*, section 14 of Fig. 8), the carbon content amounts to more than 10 wt.%. It is clearly seen that the carbon content is comparatively high in the deposits with relatively low density (Fig. 13).

3. Discussions

Depositional features and observed eruptive activity of Sakurajima volcano

Sakurajima volcano has experienced two major active periods since 1914: 1935 to 1950 and 1955 to the present. The latter is subdivided into two active periods (*i.e.*, 1955-1968 and 1973-1988), and includes the relatively tranquil period from 1969 to 1972 (Fig. 14). The changes in facies of the deposits on Sakurajima island are consistent with such sequence of observed eruptive activities (Fig. 14); two layers of laminated volcanic sand A2 and A4 would correspond to the very active periods of 1973-1988 and 1955-1968 respectively, and the layer of massive volcanic sand B would be a formation of the active period of 1935-1950. The brownish loamy volcanic sand layer A3 corresponds to the less active period of 1969-1972, and the layer of brownish loamy volcanic sand L1 may be a product of the inactive to dormant period of 1947-1954. The brownish loam layer L2

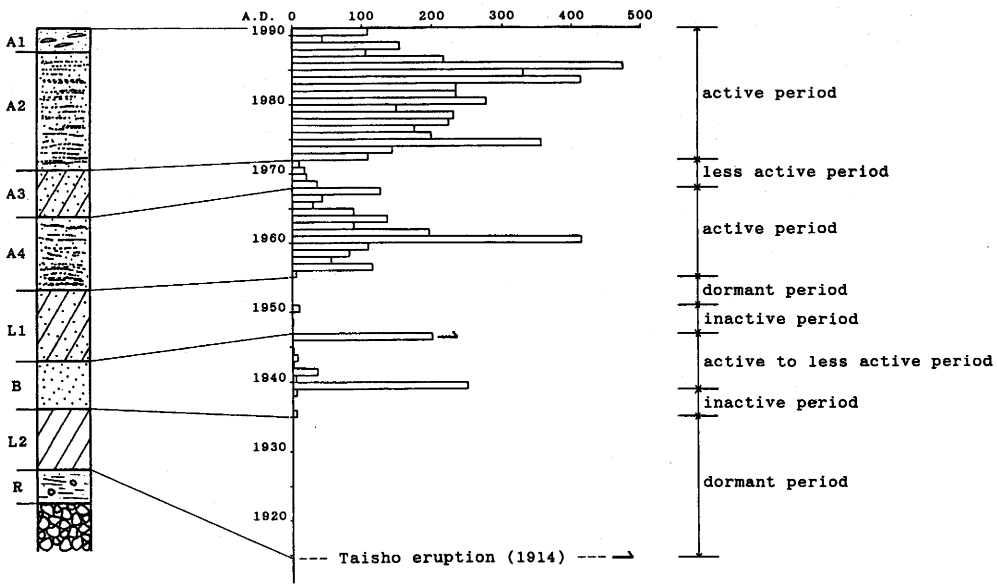

Fig. 14 Correlation between the recent activities and the depositional facies
Idealized columnar section of the deposit above the Taisho pumice (1914) in Sakurajima island (left) and annual frequencies of summit eruptions (right). Arrows indicate the emission of lava flows.

Table 1 Suggested depositional facies model for small-scale eruptive activity

	Volcanic activity			
	Active	Less active	Inactive	Dormant
Amount of fallout ashes	heavy		light	none
Accumulation rate of pyroclastics	high		low	very low
Structure of the deposit	laminated	none	none	none
Density of the deposit	high			low
Carbon content of the deposit	low			high
Depositional facies	gray laminated volcanic sand	gray massive volcanic sand	brownish loamy volcanic sand	brownish loam or humic soil

may be a deposit of dormant period of 1914-1935. We should notice that the brownish loamy layer is accumulated during the not only inactive period but also dormant period. Table 1 shows the relationship between volcanic activity, amount of fallout ashes, accumulation rate of pyroclastics, depositional structure, deposit density, carbon content and the depositional facies.

The accumulation rate of pyroclastics is relatively high during the active period when laminated and high density deposit is formed by successive settlement of fallout ashes. In contrast to this, during the less active period, the accumulation rate of pyroclastics is lower than that of active periods. Low accumulation rate of pyroclastics would not cause any depositional structure. Thus, the deposit becomes massive with relatively low density. During inactive periods, massive and low density deposit is produced by the accumulation of a lesser amount of primary fallout ashes and eolian dusts that are mainly composed of reworking pyroclastics. During dormant periods, loam and/or humic soil is formed by the very slow accumulation of only eolian dusts.

Organic matter such as fallen leaves and dead roots in the deposits are broken down by micro-organisms, and the remains are preserved as humus. Carbon content of the deposits depends on the sedimentation rate of non-organic particles and the accumulation/decay ratio of organic matters. The post-1914 activity of Sakurajima volcano has never destroyed vegetation. Thus, it may be safely assumed that the accumulation/decay ratio of organic matter was constant. Viewed in this light, carbon content of deposits is determined by the accumulation rate of clastics. Consequently, loamy layers with high carbon content indicate the period of low level eruptive activity. High value of carbon content near the uppermost part of the succession can be explained by organic matter which is not decayed enough.

It follows from what has been said that the depositional facies, bulk density and carbon content of the deposits are reflections of the accumulation rate of pyroclastic materials. To put it another way, the sequence of small-scale activities can be estimated from those features of the deposits. However, use of this analysis is restricted to an area within 10 km from the crater where the depositional facies is well observed. Because the accumulation rate of pyroclastics changes in accordance with distance from the vent even for the same eruption; the laminated volcanic sand layer gradually changes to brownish loam with increasing distance from the crater (Fig. 15).

Accumulation rate of pyroclastics that caused each depositional facies can be estimated from the measured amount of fallout ashes (Fig. 3). At sections 1 through 7 in Fig. 6, the gray laminated volcanic sand layer is found in the upper part formed in the recent several years. These sections are located in the area where fallout ashes exceed 16 $kg/m^2/year$ during the last 10 years (Fig. 3). On the other hand, at section 8 of Fig. 6, the gray massive volcanic sand layer has accumulated in recent years. This section is obtained from the area where the amount of fallout ashes is between 16 $kg/m^2/year$ and 8 $kg/m^2/year$ (Fig. 3). Then, as shown at sections 9 through 13 in Fig. 6, the brownish loamy volcanic sand layer is accumulated in the area where the amount of fallout ashes is between 8 $kg/m^2/year$ and 2 $kg/m^2/year$ (Fig. 3). At the distal section 14 in Fig. 6 (*ca.* 25 km away from the crater), the deposit is recognized as a loam, representing the fallout ashes of 2 $kg/m^2/year$ (Fig. 3). Consequently, it is concluded that the laminated volcanic sand layers, massive volcanic sand layers and loamy volcanic sand layers are formed at the accumulation rate of > 16, 16-8 and 8-2 $kg/m^2/year$, respectively. Therefore, an accumulation rate less than 2 $kg/m^2/year$ is a condition for the formation of loam or humic soil.

Considering mentioned before, the duration of small-scale eruptive activity could be estimated from the facies, thickness, deposit density and the accumulation rate. Namely,

$$T = Th \cdot D / Ar \qquad (1)$$

where T is duration of deposition in year, Th is thickness of the deposit in m, D is the deposit density in kg/m^3, and Ar is accumulation rate corresponding to the facies in $kg/m^2/year$.

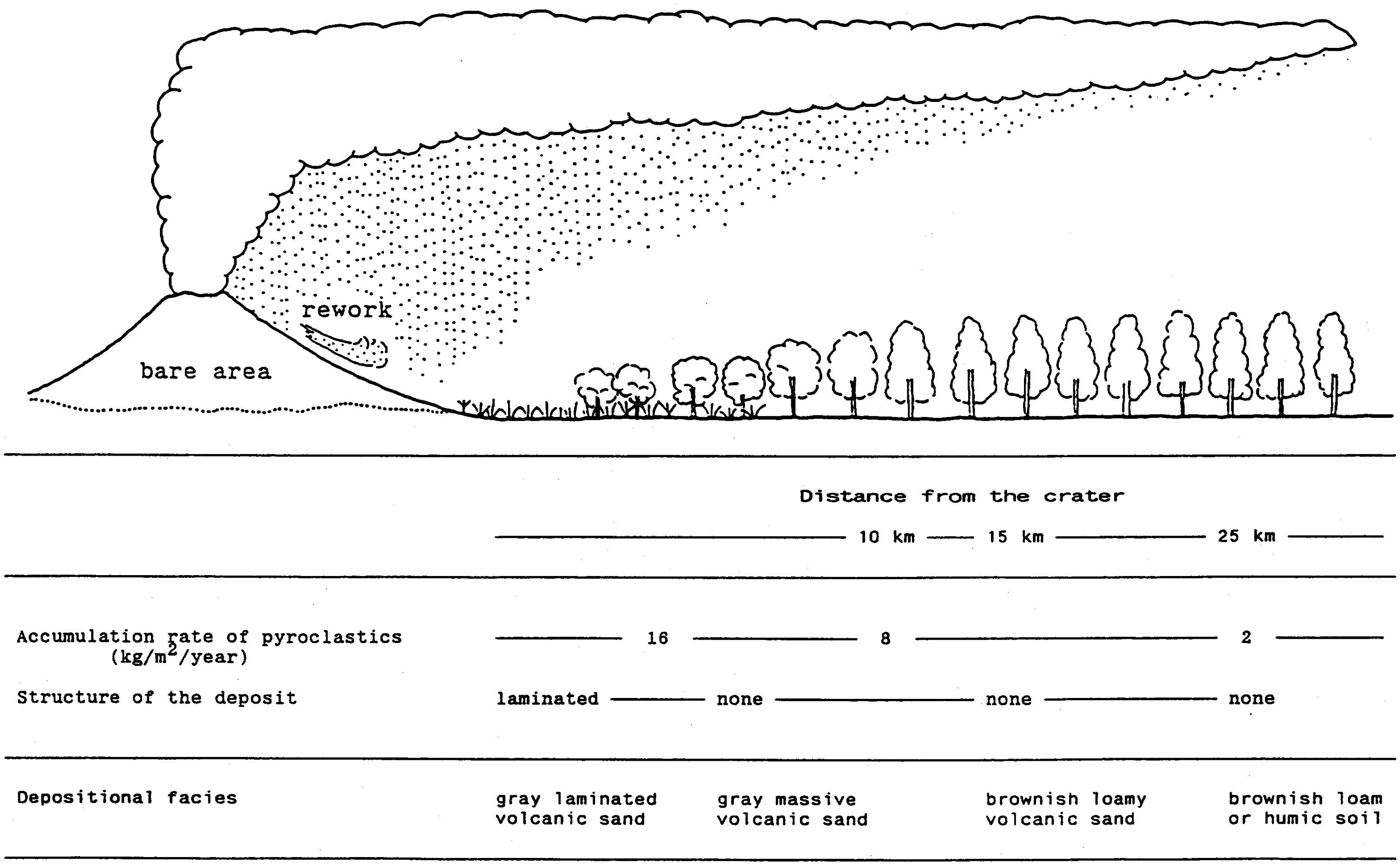

Fig. 15 Relationship between depositional facies and distance from the crater for present-day activity of Sakurajima volcano

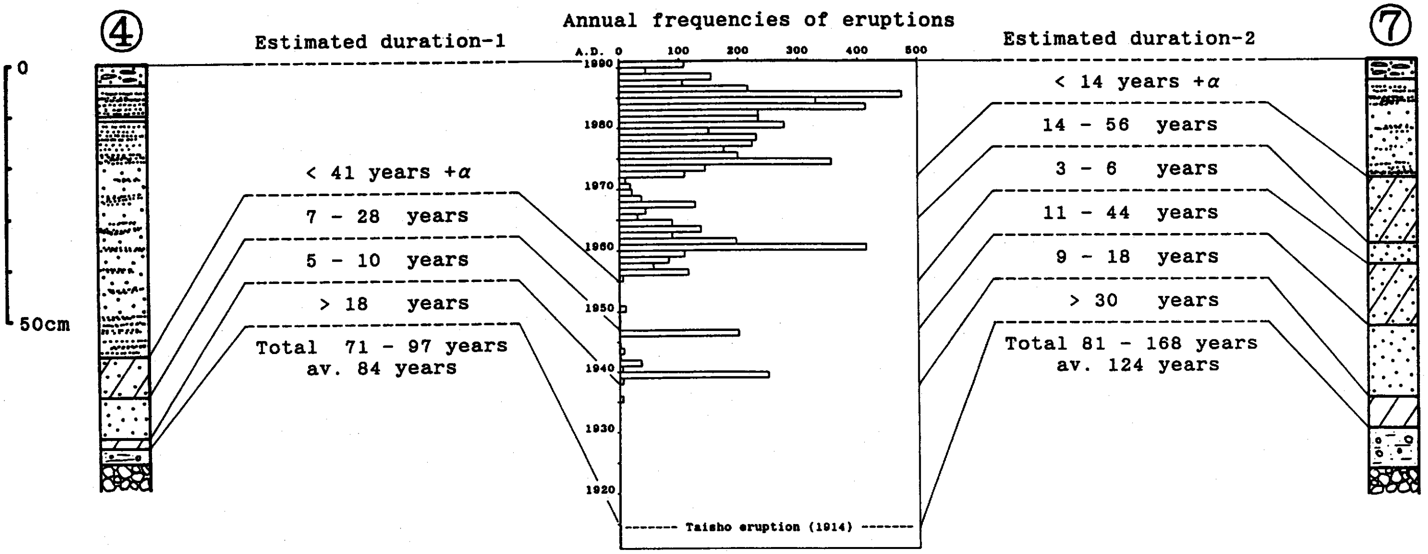

Fig. 16 Comparison of estimated durations of deposition with the observed eruptive activities of Sakurajima volcano since 1914
Estimated durations 1 and 2 are deduced from the sections 4 and 7, respectively.

Confirmation of the method proposed

For confirmation of the method proposed, this facies analysis feeds back to the estimate of duration of recorded eruptions of both Sakurajima and Suwanosejima volcanoes in recent years.

On Sakurajima volcano, the durations of eruptive activities since the 1914 eruption were reconstructed on the basis of analysis applied to the deposits at sections 4 and 7 in Fig. 4, using equation (1). Figure 16 shows the correlation between the estimated duration and observed activity of Sakurajima volcano. Total estimated durations of deposition since 1914 have wide range of 71-97 years (deduced from section 4) and 81-168 years (deduced from section 7). The true duration (75 years) is nearly in those ranges. Closer examination indicates that the estimated duration deduced from lami-

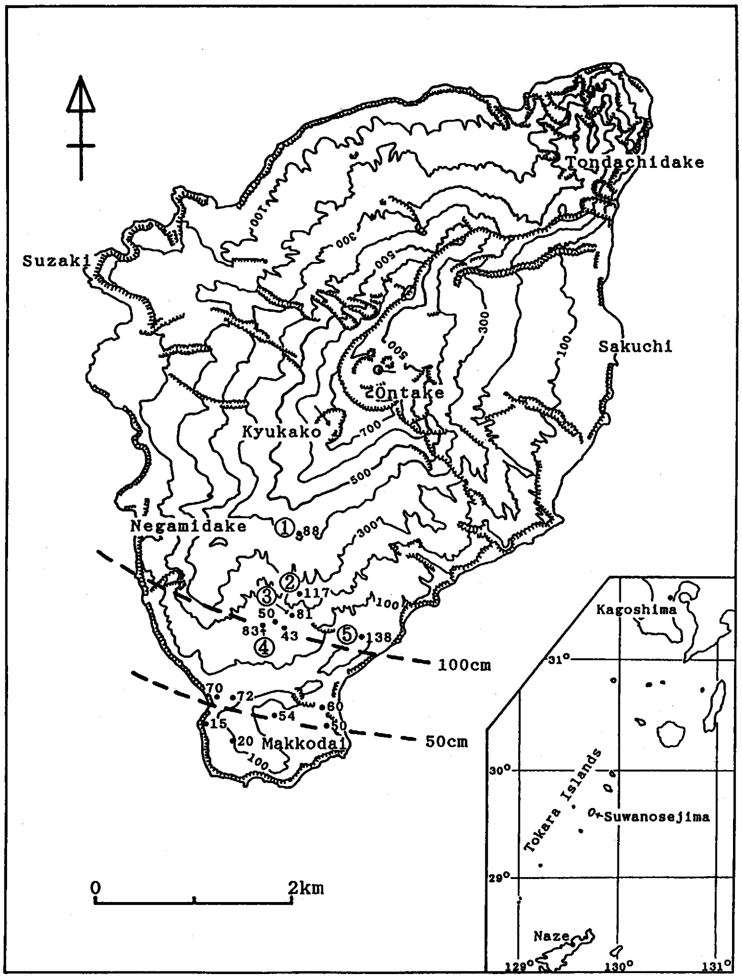

Fig. 17 Thickness (in cm) of the deposit above the Bunka scoria (1813-1814) in Suwanosejima volcano
Number with circle indicates the locality of columnar sections of Figs. 18, 19 and 20. Contour interval is 100 m (after Imura, 1991).

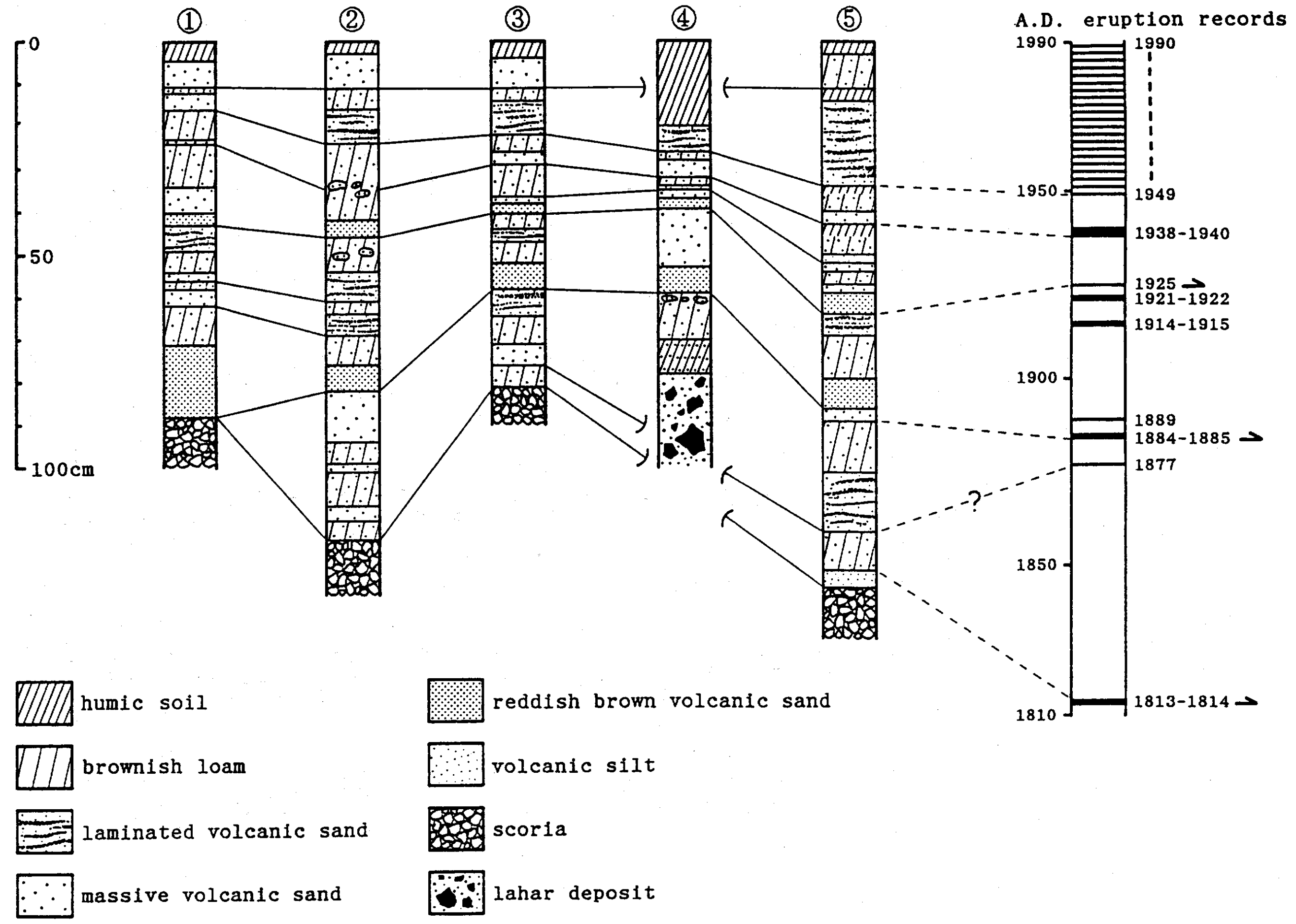

Fig. 18 Representative columnar sections of the deposit above the Bunka scoria and correlation with eruption records (right column) of Suwanosejima volcano
Arrows indicate the emission of lava flows (after Imura, 1991).

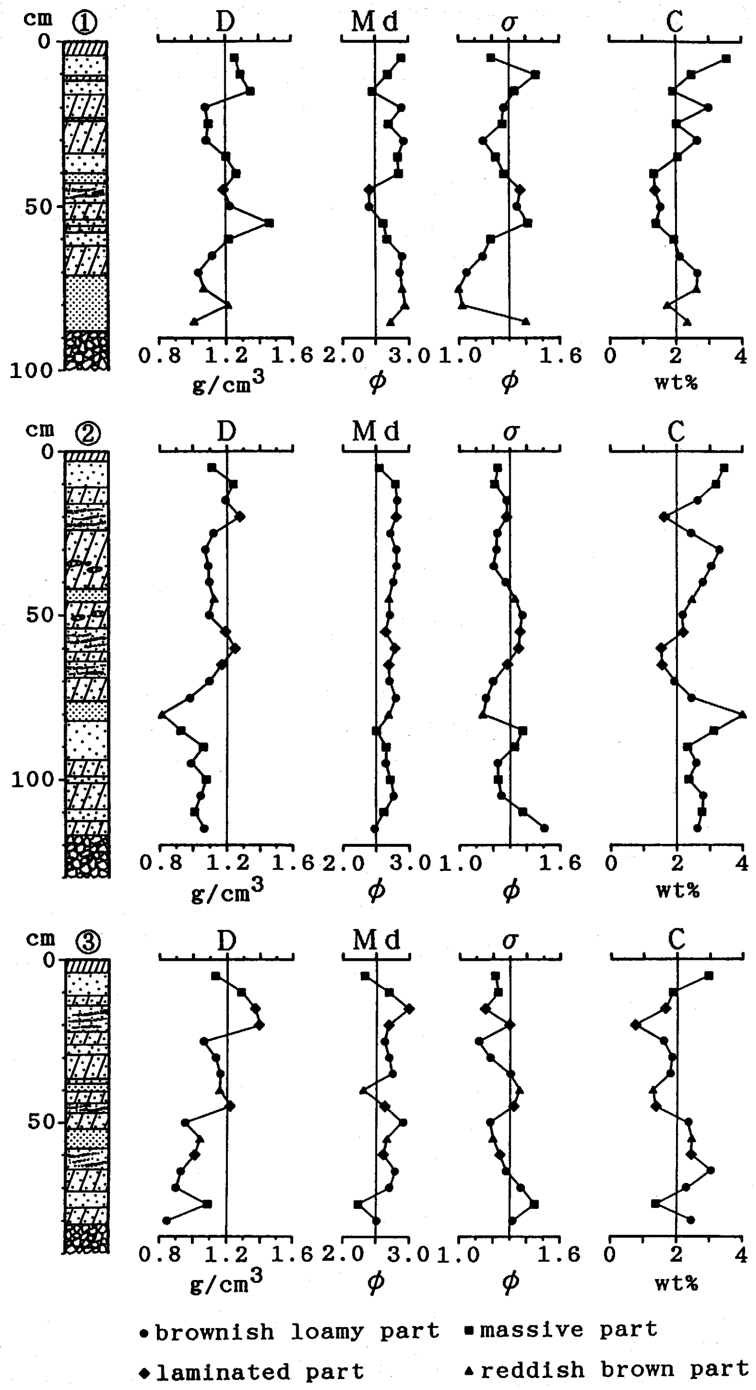

Fig. 19 Deposit density (D), median diameter (Mdϕ), sorting ($\sigma\phi$) and carbon content (C) of the deposits of Suwanosejima volcano (after Imura, 1991)

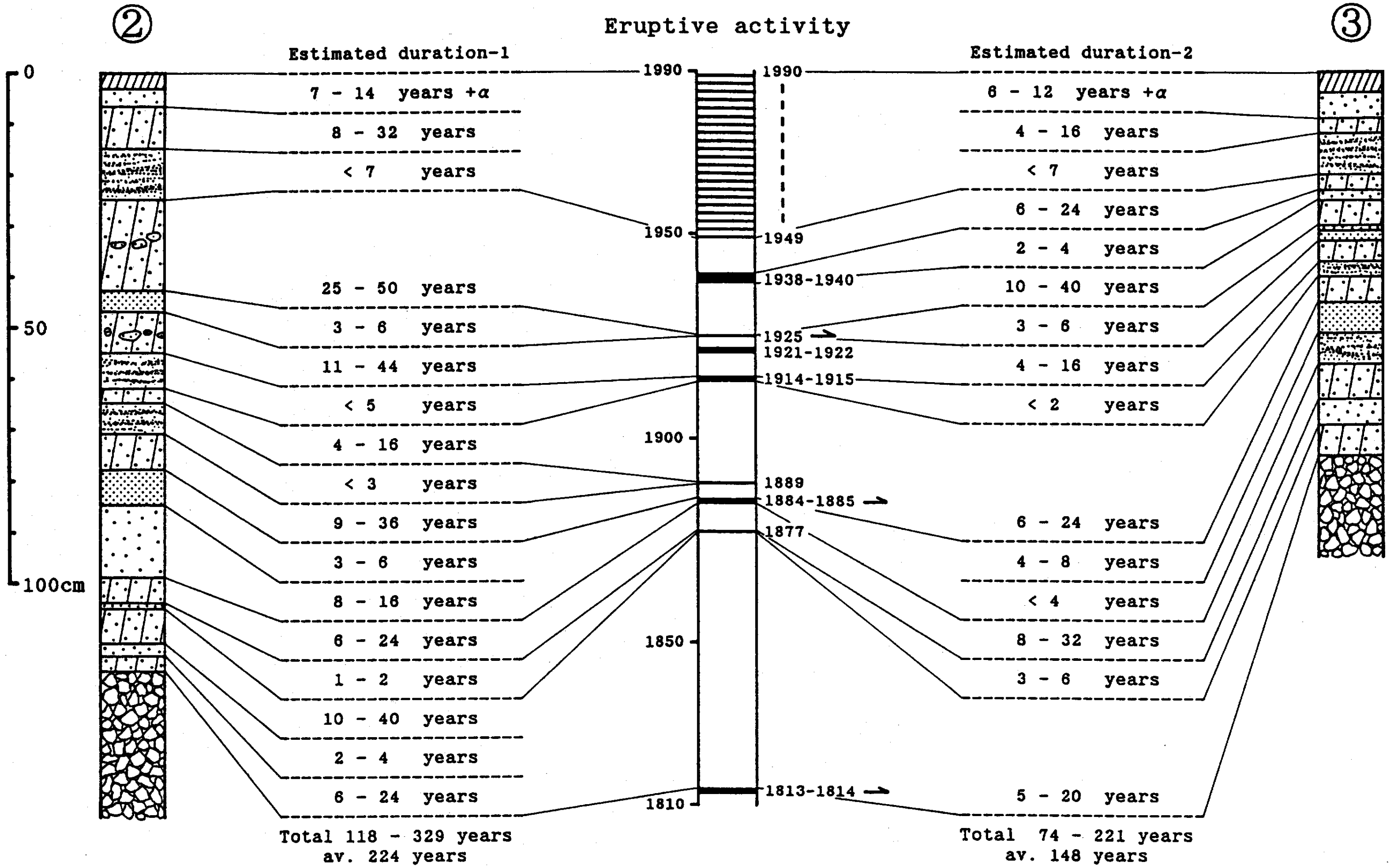

Fig. 20 Comparison of estimated durations of deposition with the observed eruptive activities of Suwanosejima volcano since the 1813-1814 eruption
Estimated durations 1 and 2 are deduced from the sections 2 and 3, respectively.

nated or massive volcanic sand layers seem to approximately coincide with observed activities. In contrast to this, the estimated durations based on the brownish loamy layers include noticeable error.

Suwanosejima volcano is the active volcano situated about 200 km southwest of Kagoshima City (Fig. 17). Suwanosejima volcano has continued its activity since 1949 (Simkin *et al.*, 1981). A large-scale eruption occurred in 1813-1814 when it erupted huge amount of scoria (Bunka scoria) and lava flows (Hirasawa and Matsumoto, 1983). Since then, only small-scale eruptions have taken place (Imura, 1991). The mode of eruption is generally strombolian but sometimes violent vulcanian type. According to Imura (1991), the deposits younger than the 1813-1814 fallout scoria are composed of alternations of gray volcanic sand layers and brownish loamy ash layers (Fig. 18). The depositional facies, deposit density, grain-size characteristics and carbon content are very similar to those of the post-1914 deposits of Sakurajima volcano (Fig. 19). The durations of sedimentation and eruptive activities of Suwanosejima volcano after 1813-1814 eruption were estimated from two localities (sections 2 and 3 of Fig. 18). Data on facies, thickness and density of the deposit were given by Imura (1991).

Estimated durations of accumulation and observed eruptive activities are shown in Fig. 20. Total duration of deposition has wide range of 118-329 years (deduced from section 2) and 74-221 years (deduced from section 3). Although several active periods are included in these deposits, the true duration (176 years) is in the range of estimated ones. Closer examination shows that the estimated duration deduced from specifically laminated or massive volcanic sand layers approximately coincides with the observed activities. On the contrary, the estimated duration using brownish loamy layers include noticeable error.

On both Sakurajima and Suwanosejima volcanoes, the estimated durations using brownish loamy layers include noticeable error. However, estimated durations deduced from laminated or massive volcanic sand layers approximately correspond to the observed eruptive activities. Thus, presented facies analysis should be useful for reconstruction of small-scale eruptive activity.

An application of the proposed method for reconstruction of eruptive activity of Old-Takachiho volcano

We may say that the method is also useful for estimating the duration of non-recorded small-scale eruptive activity of much older age. Many tephra layers similar to those described above are also found on the flank of many volcanoes. Ushi-no-sune ash (UsA) is one of the notable such tephra layers of Kirishima volcanoes, southern Kyushu. In this section, a reconstruction of the pre-historic UsA eruptive activity is discussed using the proposed method.

The UsA was erupted from Old-Takachiho volcano (Inoue, 1988). This tephra layer is divided into upper (UsA-U) and lower (UsA-L) parts by the interbedded Kikai-Akahoya ash (*ca.* 6,300 years ago; Machida and Arai, 1978) which was erupted from Kikai caldera (Fig. 1). Kobayashi (1986a) and Inoue (1988) demonstrated that the UsA was ejected by intermittent vulcanian eruptions. Kobayashi (1986a) inferred that the UsA had accumulated within a period shorter than one thousand years. The UsA-L

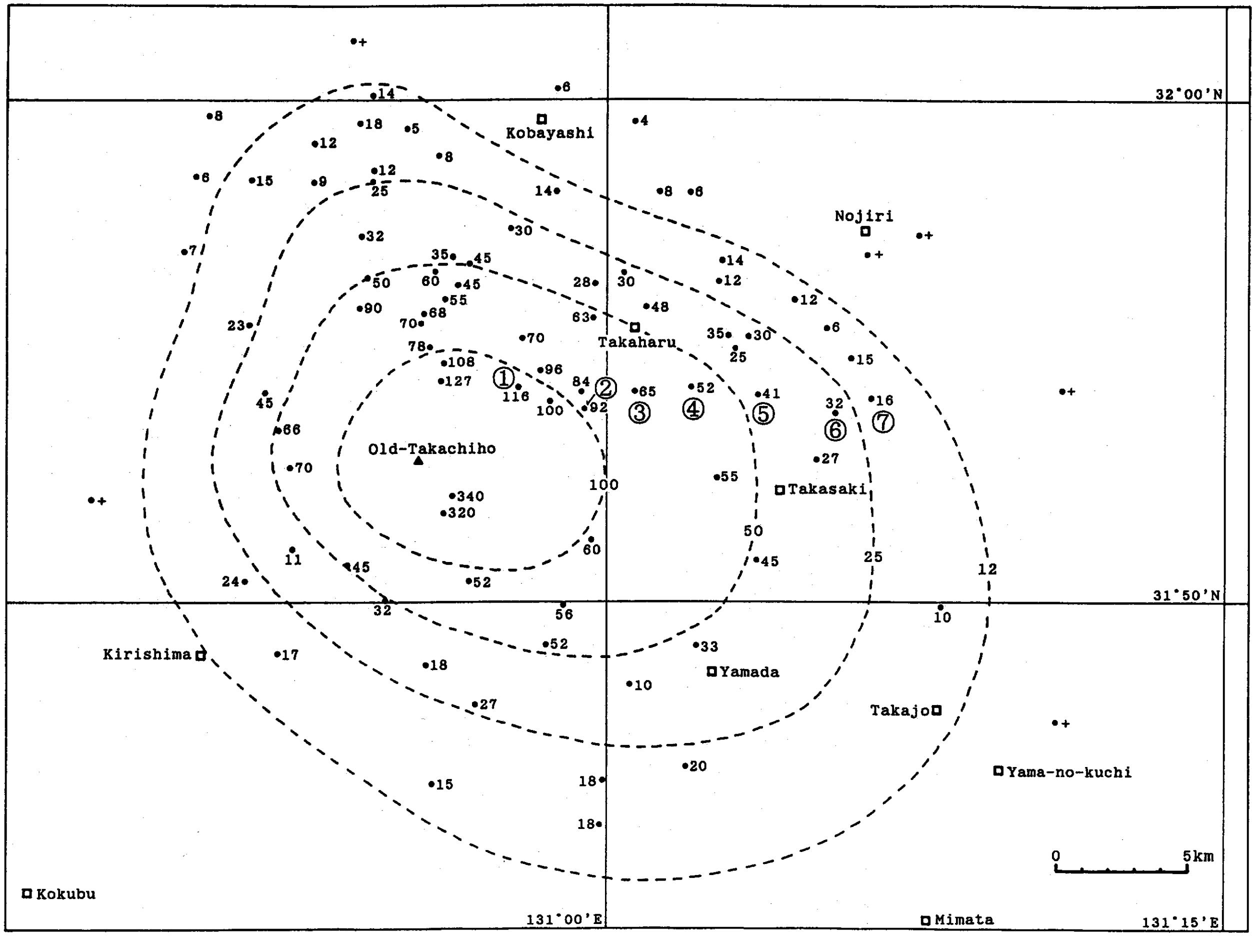

Fig. 21 Isopach map of the lower Ushi-no-sune ash (in cm) in and around the Kirishima volcano
Number with circle indicates the locality of columnar sections of Figs. 22, 23 and 24. Open squares indicate the cities and/or towns.

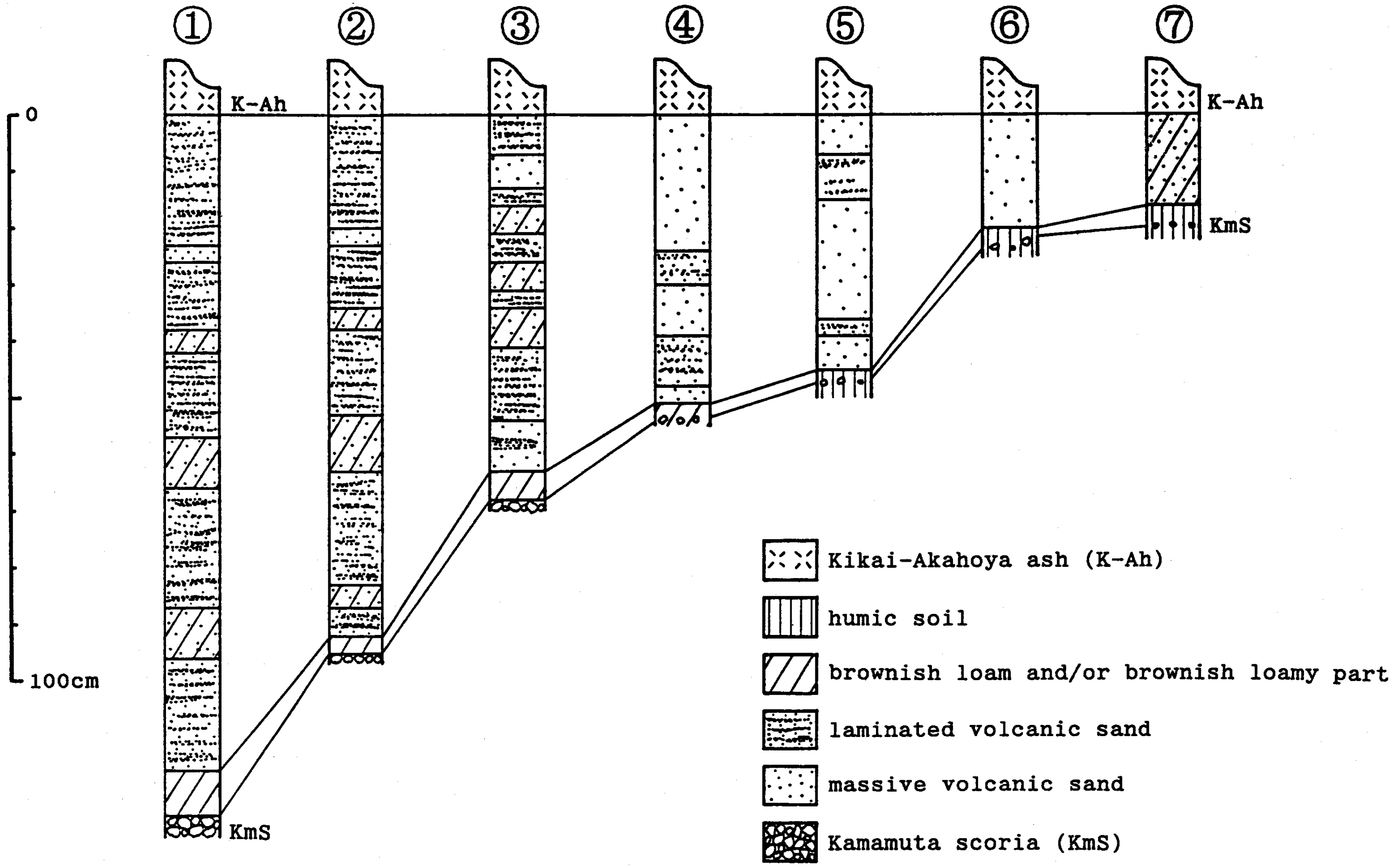

Fig. 22 Representative columnar sections of the lower Ushi-no-sune ash in and around the Kirishima volcano
KmS; Kamamuta scoria (Imura, 1992)

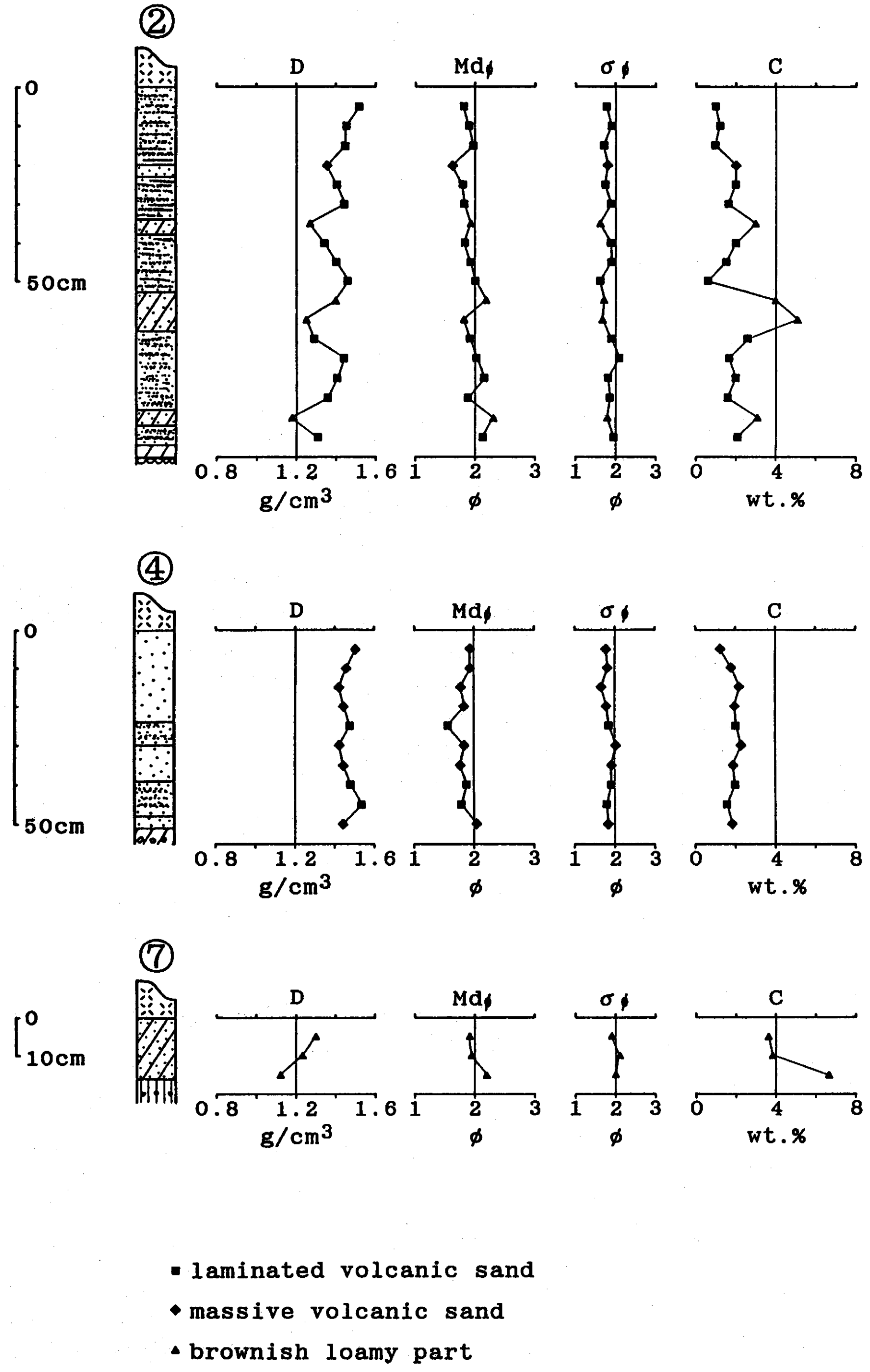

Fig. 23 Deposit density (D), median diameter (Mdϕ), sorting ($\sigma\phi$) and carbon content (C) of the lower Ushi-no-sune ash

remained intact because it was soon after covered by Kikai-Akahoya ash. Thus, the UsA-L is reliable sample deposit for studying the small-scale eruptive activity.

The distribution map, representative columnar sections and their bulk density, grain-size and carbon content data of the UsA-L are presented in Figs. 21, 22 and 23, respectively. As shown in Fig. 21, the UsA-L occurs in a nearly concentrically circular area. This feature suggests that the UsA-L is a product of relatively long-term small-scale eruptions.

The UsA-L is composed of alternations of gray laminated volcanic sand layers, gray massive volcanic sand ones and brownish loamy ash ones (Fig. 22). The gray laminated and massive volcanic sand layers have high deposit density (1.3-1.5 g/cm^3) and low carbon content (1-2 wt.%). In contrast to this, the loamy layers are of relatively low deposit density (1.1-1.3 g/cm^3) and high carbon content (3-7 wt.%). The depositional facies and the feature of UsA-L are very similar to those of the described deposits of Sakurajima and Suwanosejima volcanoes, except for somewhat higher deposit density. This higher density of deposit should be the effect of compaction due to the depth of the deposits.

The duration of eruptive activity of UsA-L was estimated on the basis of two geological successions at the localities 1 and 2 shown in Fig. 21 (5 km and 7 km from the Old-Takachiho volcano, respectively), using equation (1). The estimated durations of eruptive activity calculated from these localities are 91-175 years and 120-195 years,

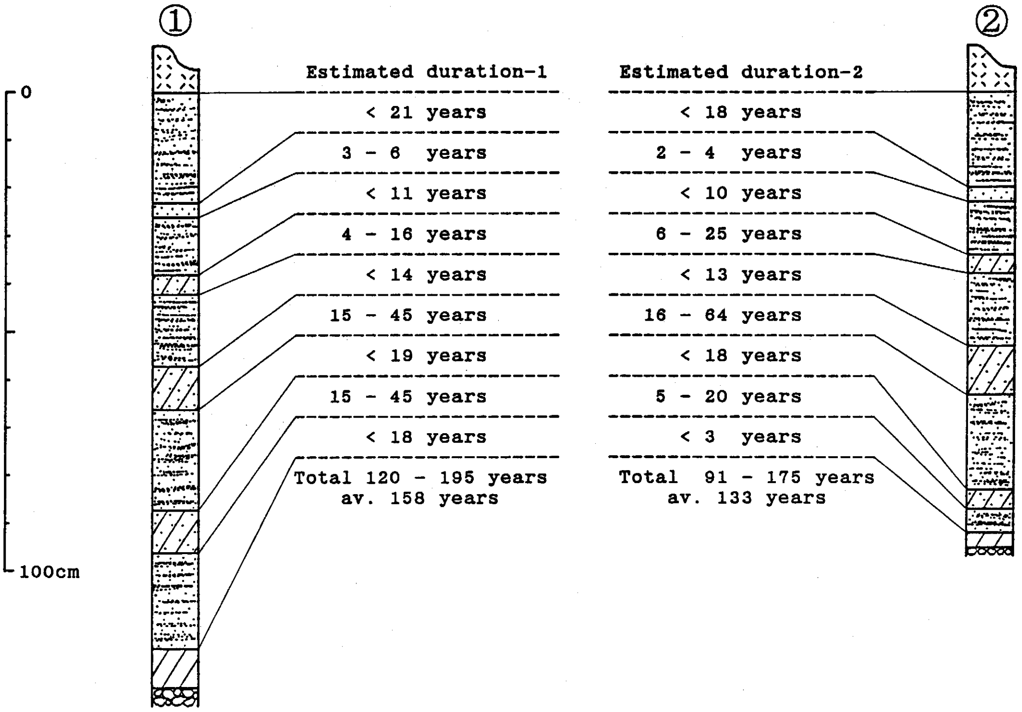

Fig. 24 Estimated durations of the eruptive activity of the lower Ushi-no-sune ash
Estimated durations 1 and 2 are deduced from the sections 1 and 2, respectively.

respectively (Fig. 24).

The bulk volume of UsA-L was estimated as 0.959 km^3 (Inoue, 1988). Assuming that the average deposit density of UsA-L is 1.4 g/cm^3, the discharge rate of ejecta attains 6.9 x 10^9-1.5 x 10^{10} kg/year. This rate is nearly equal to that of present-day activity of Sakurajima volcano (1 x 10^{10} kg/year; Eto, 1988). It is therefore concluded that the eruptive activity of UsA-L is very similar to that of present-day activity of Sakurajima volcano. The activity should have lasted for 91-195 years.

4. Concluding Remarks

Sedimentological and stratigraphical study of the recent deposit of Sakurajima volcano enabled the author to reconstruct the small-scale explosive eruptions. Fallout deposits of such long-term eruptions occur in any nearly concentric circular area around the source. Vegetation plays an important role in the accumulation of volcanic ashes from such eruptions because those fine-grained materials could effectively be trapped by bush. Depositional facies, bulk density and carbon content of the pyroclastic deposits are reflections of the accumulation rate. The sequence of small-scale eruptive activity manifests as the difference of depositional facies in proximal area: laminated and/or massive volcanic sand layer should indicate a period of highly active volcanism; brownish loamy volcanic sand layer that of less active one and brownish loam and/or humic soil that of dormant or inactive one. The duration of those periods of volcanic activity could be estimated from the recent fallout ash data.

The small-scale eruption mainly discussed in this article is generally called "vulcanian eruption". Such eruption is the most common eruptive style shown by andesitic volcanoes clustered along subducting plate margins. Quantitative documentation of small-scale eruptive activity using the method proposed in this study would give more knowledge about generation, rise, storage and discharge rate of magma at island arcs during the intervals of large-scale eruptions.

The present work would contribute to the estimation of magnitude, duration, periodicity and sequence of past small-scale eruptive activities based on specific features of pyroclastic deposits which are commonly observed in volcanic area. It provides a basis for the reconstruction of eruptive history of the volcano and hence for prediction of future volcanic activity. This study may also give a basis for reducing volcanic hazards, which are increasing in intensity with increasing land development in volcanic areas.

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