ERUPTIVE HISTORY OF THE KIRISHIMA VOLCANO DURING THE PAST 22,000 YEARS

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Abstract Eruptive history of the Kirishima volcano during the past 22,000 years is discussed with special reference to volcano-stratigraphic study. Many tephra layers are widely distributed over the eastern foot of Kirishima testifying to the intensity of the pyroclastic eruptions ranging from powerful plinian to milder strombolian activities. Eighteen volcanoes are formed, some of which are polygenetic and others monogenetic, since 22,000 years ago (22 ka). Total mass of erupted material from the Kirishima volcano during the past 22,000 years is estimated to be 23×10^{12} kg (tephra; 6.6×10^{12} kg, lava; 16.4×10^{12} kg). The activity of the Kirishima volcano for the past 22,000 years can be divided into three periods in terms of average magma discharge rate (*i.e.*, 22-15 ka; 7.8×10^{8} m^3/ky, 15-7 ka; 0.4×10^{8} m^3/ky and 7 ka to the present; 4.9×10^{8} m^3/ky) and eruptive style have changed with time from relatively effusive to more explosive type.

Key words: Kirishima volcano, eruptive history, volcano-stratigraphy, magma discharge rate

1. Introduction

Kirishima is an active volcano situated in the southern Kyushu, Japan (Fig. 1). Kirishima is the name of a group of Quaternary small volcanoes collectively called to represent one composite volcano. It occupies an area of about 20×30 km elongated in the northwest to southeast direction and contains more than 20 eruptive centers which have been repeatedly active from Pleistocene to recent.

The first geological report of the Kirishima volcano was published by Oda (1921). Since then, many geological studies on the volcano have been appeared. Sawamura and Matsui (1957) published the comprehensive report and the 1:50,000 geological map of the Kirishima volcano. Over the past few decades, a considerable number of papers have been made on the tephro-stratigraphic study of the Kirishima volcano (*e.g.*, Miyachi, 1965; Naruse, 1966; Endo and Kobayashi Loam Research Group, 1969; Nagaoka, 1984). However, few studies have been attempted to reveal the relationship between growth history of the Kirishima volcano and tephra layers.

The purpose of this paper is to clarify the eruptive history of the Kirishima volcano from a viewpoint of volcano-stratigraphy. In this paper, geologic outline of the Kirishima

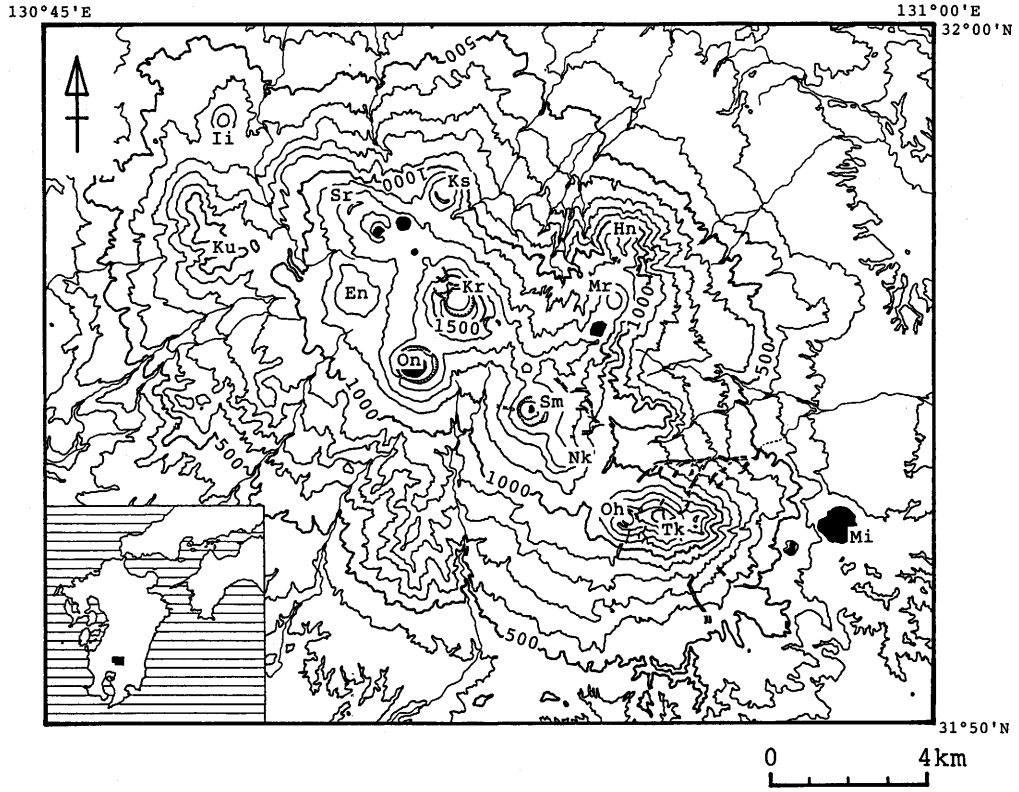

Fig. 1 Topographic map of the Kirishima volcano
Contour interval is 100 meters.
Kr: Karakunidake, Sm: Shinmoedake, On: Ōnamiike, Oh: Ohachi, Tk: Takachiho-no-mine, Mi: Miike, Hn: Hinamoridake, Mr: Maruokayama, Ks: Koshikidake, Sr: Shiratoriyama, En: Ebinodake, Nk: Nakadake, Ii: Iimoriyama, Ku: Kurinodake.

volcano is described first, followed by a description of pyroclastic deposits which gives the base of the chronology. Then, the eruptive history of the Kirishima volcano is discussed. The history older than 22 ka is hard to compile because older tephra layers are extensively covered by thick Ito ignimbrite from the nearby Aira caldera (22 ka; Machida and Arai, 1976).

2. Geologic Outline of the Kirishima Volcano

A new geological map (Fig. 2) is prepared from discrimination of volcanic topography using the aerial photographs. This map has provided much additional information for volcanic activities compared with some of the previous maps. Volcanic stratigraphy (Table 1) of the Kirishima volcano is provided by tephrochronological studies (see chapter 4).

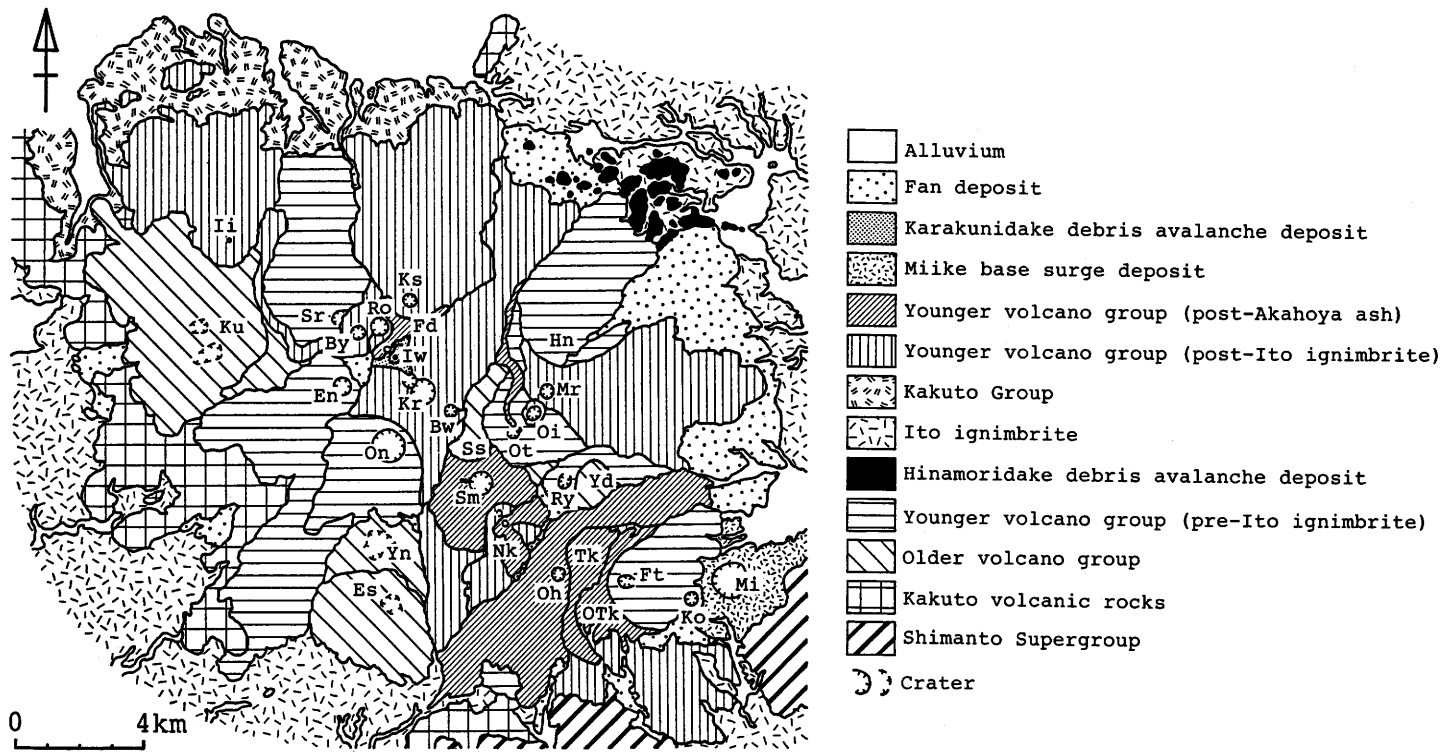

Fig. 2 Geological map of the Kirishima volcano
Abbreviations are shown in Table 1.

Table 1 Volcanic stratigraphy of the Kirishima volcano

Kirishima Volcano	Iw: Iwoyama		
	Fd: Fudoike	Ot: Ōhatayama	Oh: Ohachi Ko: Koike Mi: Miike Tk: Takachiho-no-mine
	Akahoya ash (6.3ka)		
			OTk: Old-Takachiho
	Bw: Biwaike		Oi: Ōhataike
	Kr: Karakunidake	Nk: Nakadake Sm: Shinmoedake	
	Ks: Koshikidake		
	By: Byakushiike		
	Ii: Iimoriyama		
	Ro: Rokkannonmiike		Mr: Maruokayama
	Ito ignimbrite (22ka)		
		Ot: Ōhatayama Hn: Hinamoridake	
	On: Ōnamiike		
	En: Ebinodake	Ry: Ryuodake	Ft: Futagoishi
	Sr: Shiratoriyama	Yd: Yadake	
	Ku: Kurinodake	Yn: Yunotanidake Es: Eboshidake Ss: Shishikodake	
	Kakuto ignimbrite (310-280ka)		
Basement rocks	Kakuto volcanic rocks		
	Shimanto Supergroup		

Basement rocks

The basement rocks of the Kirishima volcano are highly deformed Cretaceous to Paleogene Shimanto supergroup and early to middle Pleistocene volcanic rocks (Kakuto volcanic rocks; Yamamoto, 1960), which are exposed on the northwest to southern flanks of the Kirishima volcano. During middle Pleistocene, at least three voluminous ignimbrites erupted from the Kobayashi and Kakuto calderas (Tajima and Aramaki, 1980) situated at the north of the Kirishima volcano. They are respectively named the Kobayashi (Tajima and Aramaki, 1980), Shimokado (Oki and Hayasaka, 1970) and Kakuto (Aramaki, 1969) ignimbrites although they are not exposed in Kirishima volcano.

The Kirishima volcano

Volcanic edifices younger than Kakuto ignimbrite (0.28 ± 0.13, 0.31 ± 0.12 Ma; Miyachi, 1983) are collectively called the Kirishima volcano in this paper.

The activity of the Kirishima volcano started at the southern part of the Kakuto and Kobayashi calderas in the later stage of middle Pleistocene. Stratovolcanoes with poorly preserved volcanic topography such as Kurinodake, Yunotanidake, Eboshidake and Shishikodake (Older volcano group) were formed in the early stage of activity. These older activities produced the main frame of the present-day Kirishima volcano.

After a few tens of thousands years of relatively dormant period, volcanic activity resumed at 70-60 ka (Inoue, 1988) and continued up to the present Younger volcano group. Many small stratovolcanoes, polygenetic pyroclastic cones and monogenetic maars and lava flows were formed by the activity. At about 35 ka, an important activity occurred at the Hinamoridake, situated at the northeastern end of the Kirishima, collapsed and forming the debris avalanche, which covered an area of the western part of the present-day Kobayashi City.

During the past 22,000 years, the activity of Kirishima volcano occurred in a zone running in the northwest to southeast. Then, the last 10,000 years, most of major eruption occurred in the Takachiho composite volcano (Inoue, 1988) that is an area of the southeastern part of the Kirishima. The growth history of Takachiho composite volcano is well described by Inoue (1988).

More than 50 eruptions have been documented since A.D. 742. They occurred mainly at Ohachi and Shinmoedake but one exception is Iwoyama which issued a small lava flow in 1768.

Most of the rocks of the Kirishima volcano are composed of augite hypersthene andesite, with or without phenocrysts of olivine, with SiO_2 ranging from 53 to 60 wt% (Sawamura and Matsui, 1957; Shinno, 1966). However, olivine basalts (SiO_2=49-52 wt%; Sawamura and Matsui, 1957; Shinno, 1966) are found in some lava flows of Hinamoridake, Ohachi and Takachiho-no-mine lava flows, and hornblende phenocrysts can be found in the Miike pumice.

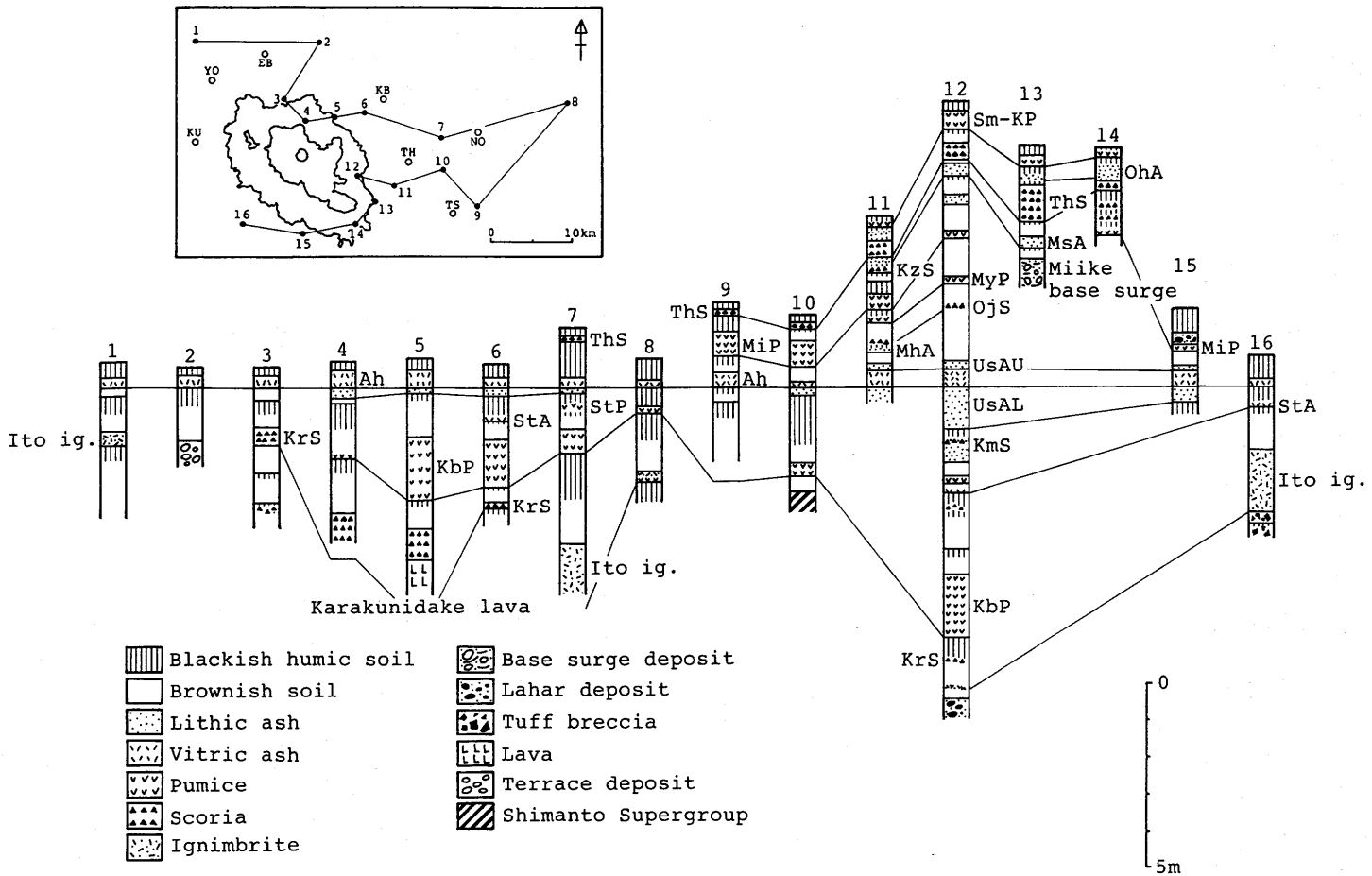

Fig. 3 Representative columnar sections for the tephra layers around the Kirishima volcano Abbreviations are shown in Table 2. Open circles are cities and/or towns, KU: Kurino, YO: Yoshimatsu, EB: Ebino, KB: Kobayashi, NO: Nojiri, TH: Takaharu, TS: Takasaki.

3. Pyroclastic Deposits

Many units of fallout pumice, scoria and ash layers are widely distributed in and around the Kirishima volcano (Fig. 3). Fig. 4 shows the idealized columnar section for the tephra layers younger than Ito ignimbrite. Table 2 shows a correlation of tephra layers between previous works and this paper. Each named tephra layer is the product of a single eruptive episode except for the Ohachi ash. Ohachi ash is composed of at least five dark coarse volcanic sand members with intercalated thin volcanic loess which are the products from multiple eruptive episodes. Table 3 shows source vent, age, distribution and mineral composition, etc. of these tephra layers. In this chapter, ten important tephra layers are described from older to younger.

Karakunidake scoria (KrS; *ca.* 18 ka)

This tephra layer is assigned to the Iimoriyama scoria which was studied by Endo and Kobayashi Loam Research Group (1969) and Nakamura (1987), who described that the tephra layer erupted from the Iimoriyama cone. The isopach and isograde maps of this deposit indicate, however, that the eruptive center of this tephra layer is not

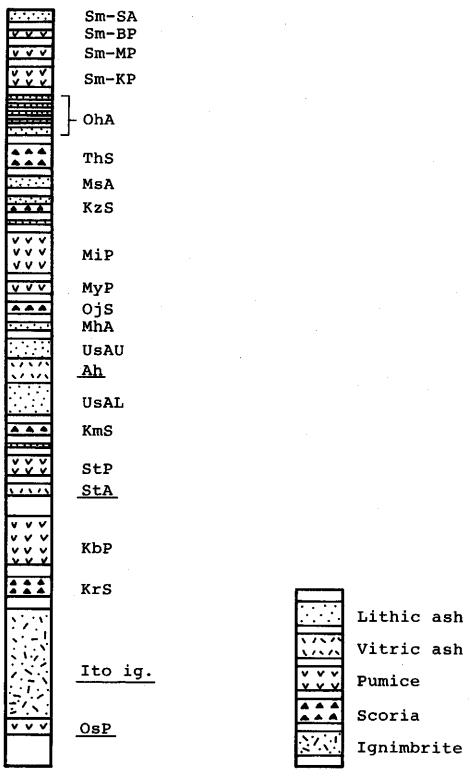

Fig. 4 Idealized columnar section for the tephra layers younger than Ito ignimbrite in and around the Kirishima volcano (not to scale)
Those underlined did not originate from Kirishima volcano. Abbreviations are shown in Table 2.

Table 2 Correlation of tephra layers around the Kirishima volcano

Endo & K.L.R.G. (1969)	Nakamura (1987)	Inoue (1988)	This paper
			Shinmoedake-Showa afa (Sm-SA)
			Shinmoedake-Bunka pfa (Sm-BP)
			Shinmoedake-Meiwa pfa (Sm-MP)
	Shinmoedake lapilli	Shinmoedake pfa	Shinmoedake-Kyoho pfa (Sm-KP)
		Ohachi afa	Ohachi afa (OhA)
Takaharu sfa	Takaharu sfa	Takaharu sfa	Takaharu sfa (ThS)
		Miyasugi afa	Miyasugi afa (MsA)
		Katazoe sfa	Katazoe sfa (KzS)
Miike pfa	Miike pfa	Miike pfa	Miike pfa (MiP)
		Maeyama pfa	Maeyama pfa (MyP)
		Oji sfa	Oji sfa (OjS)
		Mochiharu afa	Mochiharu afa (MhA)
Gi-Ushi loam	Ushinosune afa	Ushinosune afa (Upper)	Ushinosune afa (Upper) (UsAU)
Daiichi orange	Akahoya afa	Akahoya afa	Akahoya afa (Ah)
Ushinosune loam		Ushinosune afa (Lower)	Ushinosune afa (Lower) (UsAL)
		Uramuta sfa	Kamamuta sfa (KmS)
Gi-Kobayashi pfa		Setao pfa	Setao pfa (StP)
1/2 orange		Satsuma afa	Satsuma afa (StA)
Kobayasi pfa	Kobayashi pfa	Kobayashi pfa	Kobayashi pfa (KbP)
Iimoriyama sfa	Iimoriyama sfa		Karakunidake sfa (KrS)
Shinki Shirasu	Ito pfl	Ito pfl	Ito pfl (Ito ig.)
			Osumi pfa (OsP)

K.L.R.G. : Kobayashi Loam Research Group, pfa : pumice fall deposit, sfa : scoria fall deposit, afa : ash fall deposit, pfl : pyroclastic flow deposit.

Table 3 List of tephra layers from the Kirishima volcano during the past 22,000 years

Tephra	Source volcano	Correlations	Age (ka) and (Dating method)	Distribution	Mineral composition	Bulk Volume (km^3)	Type of eruption	V. E. I. *1	Remarks
Shinmoedake-Showa afa (Sm-SA) *2	Shinmoedake		A. D. 1959 (H) *2	NE	nonjuvenile	0.003*2	ph	2	
Shinmoedake-Bunka pfa (Sm-BP) *2	Shinmoedake		A. D. 1822 (H) *2	E	opx, cpx	0.005*2	ph→sp	2	Associated with pfl and bsg near the vent
Shinmoedake-Meiwa pfa (Sm-MP) *2	Shinmoedake		A. D. 1771-1772 (H) *2	E	opx, cpx	0.006*2	ph→sp	2	
Shinmoedake-Kyoho pfa (Sm-KP) *2	Shinmoedake	Shinmoedake lapilli*3 Shinmo edake pumice*4	A. D. 1716-1717 (H) *2	SE, >8km	opx, cpx	0.21*2	ph→sp	4	
Ohachi afa (OhA) *4	Ohachi		A. D. 837-1706 (H)	E		0.022*4	v	2	
Takaharu sfa (ThS) *5	Ohachi		A. D. 788 (H) *4	E, NE, >10km	opx, cpx, (ol)	0.28*4	sp	4	Associated with pfl
Miyasugi afa (MsA) *4	Ohachi		A. D. 742? (C) *6	NNE, SE		0.051*4	v	3	
Katazoe sfa (KzS) *4	Ohachi		2 (S)	E	opx, cpx	0.037*4	sp and v	3	
Miike pfa (MiP) *7	Miike		3 (A) *8	ES, >30km	opx, cpx, ho	3.1	p or pp	5	Associated with bsg near the vent
Maeyama pfa (MyP) *4	Shinmoedake		4 (S) *2	E	opx, cpx	0.046*2	p or sp	3	
Oji sfa (OjS) *4	Takachiho-no-mine		4.5 (S)	ENE, SE	opx, cpx	0.027*4	sp or s	3	
Mochiharu afa (MhA) *4	Takachiho-no-mine		5 (S)	E, S		0.020*4	v	3	
Ushinosune afa (UsA) *4	Old-Takachiho*4	Gi-Ushi loam*5 Ushinosune loam*5*7	6-6.5 (S)	conc.		1.2*4	v	3	Divided into upper and lower by Akahoya afa
Kamamuta sfa (KmS)	Old-Takachiho	Uramuta sfa*4	7 (S)	E	opx, cpx	0.012*4	sp	3	Newly named
Setao pfa (StP) *4	Shinmoedake	Gi-Kobayashi pfa*5	9 (C) *6	NE	opx, cpx	0.067*2	p and v	3	
Kobayashi pfa (KbP) *9	Karakunidake	Ks-h*10	15 (S)	ENE, >60km	opx, cpx	2.1	p and v	5	Associated with pfl near the vent
Karakunidake sfa (KrS) *11	Karakunidake	Iimoriyama sfa*3*5	18 (S) *3	NE, NWN	opx, cpx	0.47	sp and v	4	

Abbreviations are used as follows; pfa : pumice fall deposit, sfa : scoria fall deposit, afa : ash fall deposit, pfl : pyroclastic flow deposit, bsg : base surge deposit, (H) : historical record, (A) : archeology, (C) : radiocarbon, (S) : stratigraphic relation, opx : orthopyroxene, cpx : clinopyroxene, ho : hornblende, ol : olivine, ph : phreatic eruption, sp : sub-plinian eruption, v:vulcanian eruption, p : plinian eruption, pp : phreatoplinian eruption, s : strombolian eruption. The method to calculate the volume is discribed by Hayakawa (1985). References are *1 : Simkin *et al.* (1981), *2 : Imura and Kobayashi (1991), *3 : Nakamura (1987), *4 : Inoue (1988), *5 : Endo and Kobayashi Loam Research Group (1969), *6 : Imura and Koga (1992), *7 : Sawamura and Matsui (1957), *8 : Kuwano *et al.* (1959), *9 : Ida *et al.* (1956), *10 : Miyachi (1965), *11 : Imura and Kobayashi (1987).

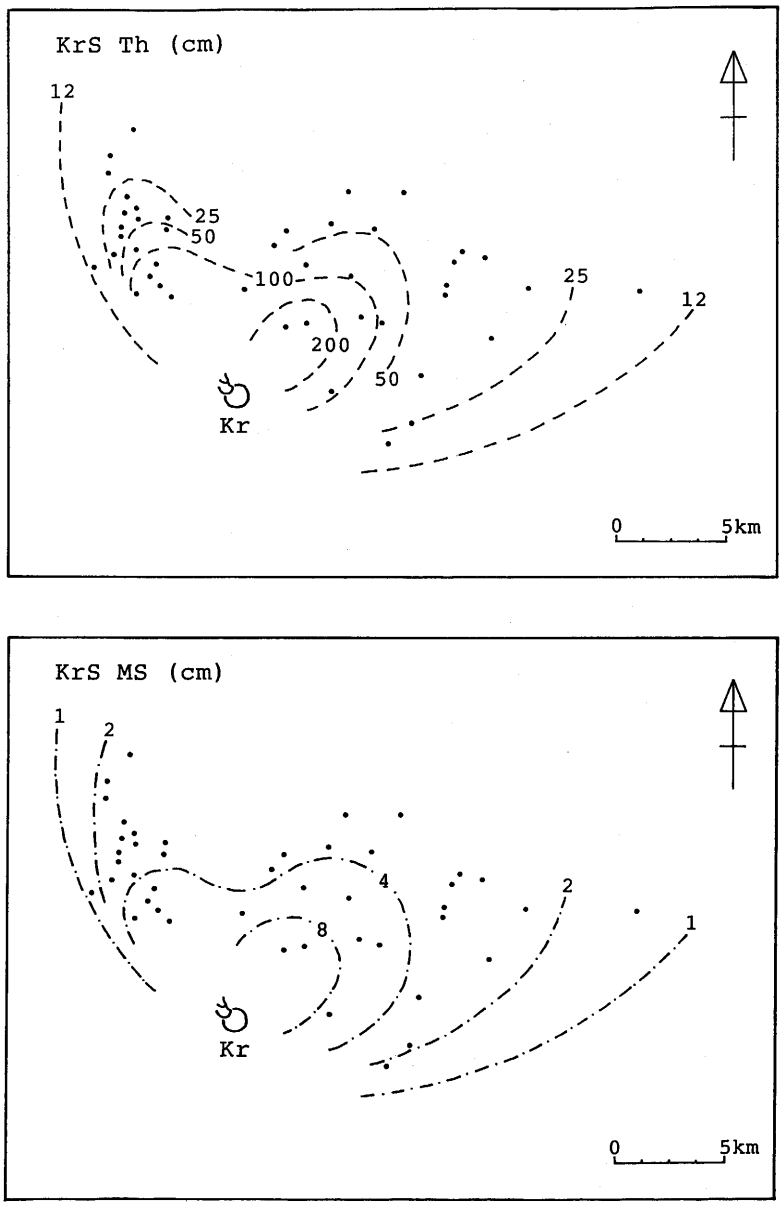

Fig. 5 Dispersal maps of the Karakunidake scoria
Th : thickness (in cm), MS : maximum scoria size (in cm), Kr : Karakunidake.

Iimoriyama but nearby Karakunidake (Fig. 5). Hence, Imura and Kobayashi (1987) renamed the tephra layer Karakunidake scoria (KrS). The KrS is made up from alternations of reddish scoria fall and grayish volcanic sand beds including abundant remains of plants. The feature described above suggests that the eruptive episode of KrS might have been the repetition of sub-plinian and vulcanian eruptions. KrS is intercalated with lava

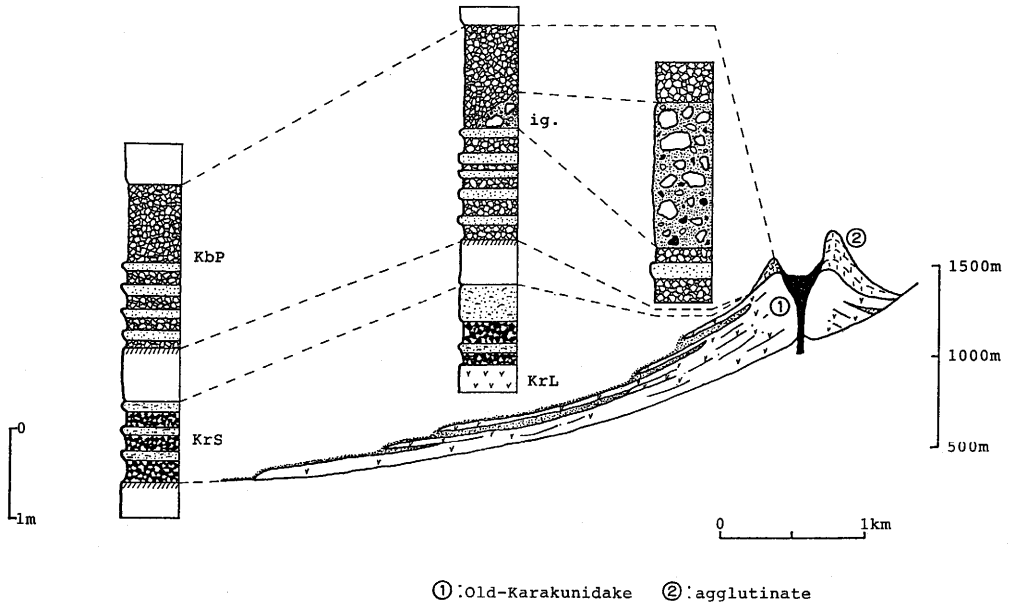

Fig. 6 Schematic cross section of the Karakunidake
KrS: Karakunidake scoria, KbP: Kobayashi pumice, KrL: Karakunidake lava, ig.: ignimbrite.

flows on northern slope of Karakunidake (Fig. 6). This field evidence shows that the eruptive episode of KrS constructed a small stratovolcano of old stage of Karakunidake (Imura and Kobayashi, 1987).

Kobayashi pumice (KbP; *ca.* 15 ka)

The KbP was first described by Ida *et al.* (1956). The KbP widely occurs from the east-northeastern foot of the Kirishima volcano to Miyazaki Plain. The KbP is composed of an alternation of some yellowish pumice and grayish lithic volcanic sand beds. The pumice clast is well-vesiculated with large amount of phenocrysts. The eruptive episode of KbP was interpreted to have been repetition of plinian and vulcanian or strombolian eruptions. Small-scale pyroclastic flow deposits intercalated with KbP are well exposed on the northern and southern flanks of Karakunidake (Fig. 6). A pink thermal coloration produced by oxidation of iron occurs inside the large pumice fragments in the pyroclastic flow deposits.

Setao pumice (StP; *ca.* 9 ka)

The StP (Inoue, 1988) was erupted from the Shinmoedake at 9ka (Imura and Koga, 1992) and the dispersal fan is extended to the northeast. The StP is composed of an alternation of several units of yellowish pumice and grayish lithic volcanic sand, and is similar to that of KbP in facies. The feature described above suggests that the StP activity might have been resembling type to that of KbP.

Kamamuta scoria (KmS; *ca.* 7 ka)

This deposit is composed of reddish brown scoria which was previously called as the Uramuta scoria by Inoue (1988). However, Uramuta should be replaced by Kamamuta because there is no place so-called Uramuta. The KmS erupted from Old-Takachiho (Inoue, 1988) at 7 ka when it was the initial stage of the cone.

Ushinosune ash (UsA; *ca.* 6.5-6 ka)

The UsA is divided into upper and lower parts by the interbedded Akahoya ash (6.3 ka; Machida and Arai, 1978). However, stratigraphic relationship between those tephras are essentially conformable. Inoue (1988) suggests that the UsA was accumulated by the intermittent vulcanian eruptions of Old-Takachiho. The UsA consists predominantly of sandsized lithic fragments with abundant remains of plants. The UsA occurs concentrically with nearly circular isopach (Inoue, 1988). This feature of this tephra suggests that it is a product of relatively long-term weak eruptions during the period of 6.5-6 ka on the basis of stratigraphy. Inoue (1988) revealed that the UsA is a product of the build up stage of Old-Takachiho.

Miike pumice (MiP; *ca.* 3 ka)

The MiP (Sawamura and Matsui, 1957) is one of the largest tephra layers (3.1 km^3 in bulk volume) of the Kirishima volcano and widely occurs over the southeast of the Kirishima volcano. The MiP consists predominantly of poorly vesiculated yellowish pumice clasts and small amount of gray pumice clasts, dense lithic fragments and accretionary lapilli. In addition, base surge deposits are interbedded with the fallout pumice near the vent. The feature described above suggests that the MiP may have been a product of plinian and/or phreatomagmatic eruptions.

Takaharu scoria (ThS; A.D. 788)

The ThS is the largest tephra layers (0.28 km^3 in bulk volume) of the Kirishima volcano in historical age, erupted from Ohachi crater, and has wide distribution over the eastern foot of the Kirishima volcano (Inoue, 1988). ThS is composed of at least three fall units which consist of black scoria with minor light color scoria. ThS was produced by repeating sub-plinian eruptions, accompanied by pyroclastic flows which are well exposed on the northern and southern flanks of Ohachi.

Ohachi ash (OhA; *ca.* 1-0.4 ka)

The OhA (Inoue, 1988) is composed of at least five members of dark coarse volcanic sand beds. These layers are products of the vulcanian eruptions from Ohachi in historical age, however, the exact age of this tephra has not yet been determined.

Shinmoedake-Kyoho pumice (Sm-KP; A.D. 1716-1717)

The Sm-KP is a product of the eruptions of Shinmoedake from 11 March, 1716 to 19 September, 1717 (Imura and Kobayashi, 1991). The Sm-KP is composed of an alternation of poorly vesiculated pumice layers and gray silty to sandy ash beds. Most of the pumice clasts in Sm-KP have chilled margin. The dispersal fan of this deposits extends

to the southeast. The stratigraphy of Sm-KP with historical records shows that the eruption progressed with time from phreatic to magmatic activity (Imura and Kobayashi, 1991) and frequently accompanied with pyroclastic flows and mudflows.

Shinmoedake-Showa ash (Sm-SA; A.D. 1959)

The Sm-SA is a product of the last eruption of the Kirishima volcano and the eruptive sequence was well-documented (*e.g.*, Fukuoka Meteorological Observatory *et al.*, 1959; Minakami *et al.*, 1968). The Sm-SA consists of gray silty to sandy nonjuvenile lithic fragments indicating that only phreatic eruption occurred. The Sm-SA is found in a scattered area of the eastern foot of Shinmoedake, however, according to Fukuoka Meteorological Observatory *et al.* (1959), the fallout area of this tephra was far larger than those observed today.

4. Eruptive History of the Kirishima Volcano During the Past 22,000 Years

Stratigraphic relationship between the volcanic edifices and the tephra layers is shown in Fig. 7. In this chapter, the eruptive history of Kirishima volcano is described. Then, the characteristics of those eruptive activities are discussed. Table 4 shows the mass of volcanic edifices formed since 22 ka.

The eruptive activity of Kirishima volcano of the period between 22 ka and 18 ka is represented by Iimoriyama and Maruokayama stratocones and small volcanoes such as Byakushiike lava flows and Rokkannonmiike maar. These two small volcanoes are formed by short life monogenetic activities.

About 18,000 years ago, three stratocones, such as Old-Karakunidake (Imura and Kobayashi, 1987), Koshikidake and Shinmoedake, were formed by accumulation of lava flows and minor pyroclastics. The KrS tephra is accompanied with the growth of Old-Karakunidake (Fig. 6). Koshikidake seems to be formed partly contemporaneous with and partly postdated the eruptive episode of KrS.

About 15 ka, the powerful eruption occurred at Karakunidake and ejected KbP. During the eruptive episode of KbP, present-day Karakunidake cone was built by alternative ejections of heavy pyroclastic fall and/or flow deposits overlying the older stratocone (Fig. 6). Those deposits were densely and partially welded, forming the cone. Thereafter, the activity of Nakadake started upon the southeast flank of Shinmoedake and made up the main volcanic edifice which consists of lava flows. At 9 ka, Shinmoedake erupted the StP tephra, which represent the second stage of activity of this cone.

About 7,000 years ago, the activity of Old-Takachiho started upon the southeastern area of the Kirishima volcano (Inoue, 1988). Small volcanoes such as Ōhataike and Biwaike maars might be also formed by single-eruptive episode.

At the time of the Akahoya ash eruption (6.3 ka), Old-Takachiho erupted the UsA tephra and made up the volcanic edifice. After a thousand years of relatively dormant period, the activity of Takachiho-no-mine started upon the western slope of Old-Takachiho. Takachiho-no-mine is a stratovolcano with an exogenous lava dome that

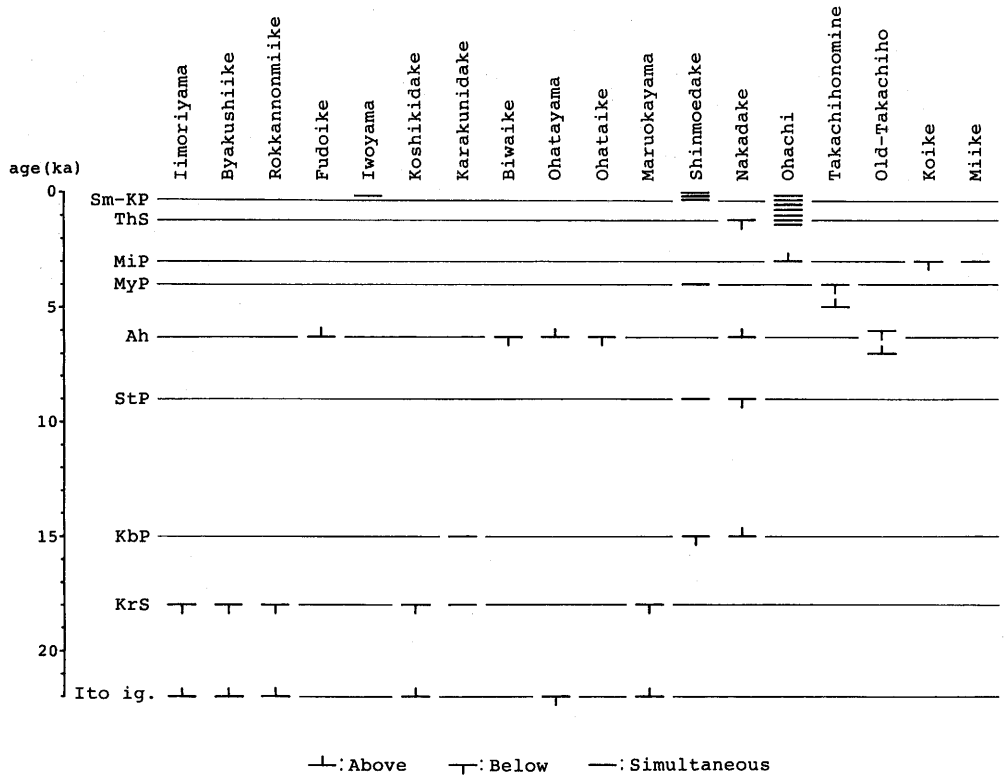

Fig. 7 Relationship between the volcanic edifices and the tephra layers during the past 22,000 years
Abbreviations are shown in Table 2.

filled the summit crater. Fudoike and Ōhatayama effused small lava flows, and Shinmoedake erupted the MyP tephra (4 ka).

About 3,000 years ago, Miike maar was formed by a powerful eruption with a great volume of fall-out pumice. This eruption accompanied base surge near the vent. Afterward, at 2.5 ka, Ohachi was born on the western slope of Takachiho-no-mine, and has been active since then. Lava flows of Ohachi are basic with low viscosity, accordingly, most of the lava flows through a distance away from the vent, therefore, the main edifice is made up of densely or partially welded pyroclastic materials.

The eruptions of Kirishima volcano in the historical age, have mainly occurred from Ohachi and Shinmoedake volcanoes. Most of the activities were characterized as weak eruptions, however, activities in 788 (Ohachi) and 1716-1717 (Shinmoedake) were powerful eruptions which ejected the ThS (0.28 km^3) and Sm-KP (0.21 km^3). In 1768, a small lava flow issued from Iwoyama. The last eruption of the Kirishima volcano occurred from the Shinmoedake in 1959. This activity was phreatic eruption formed the 500m long fissure on the western slope of the Shinmoedake. Thereafter, only fumarolic activity was seen in the Kirishima volcano, but a minor phreatic activity occurred at the Shinmoedake from November, 1991 to March, 1992 (Imura, 1992).

Table 4 Mass of volcanic edifices in the Kirishima volcano during the past 22,000 years

Volcano	Type	Area (km^2)	Thickness (m) *	Volume (km^3) **	Density (kg/m^3)	Mass ($10^{11}kg$)	D. R. E (10^6m^3)
Iwoyama	lava flow	0.15	20	0.003	2000	0.06	2.4
Ohachi	stratocone	19.32	–	1.23	2000	20.6	824.0
Takachiho-no-mine	stratocone	3.36	–	0.089	2000	1.78	71.2
Fudoike	lava flow	1.21	20	0.024	2000	0.48	19.2
Ōhatayama	lava flow	1.08	20	0.022	2000	0.44	17.6
Old-Takachiho	stratocone	13.64	–	0.73	2000	14.6	584.0
Nakadake	stratocone	4.79	–	0.15	2000	3.0	120.0
Shinmoedake	stratocone	10.56	–	0.50	2000	10.0	400.0
Karakunidake	stratocone	20.11	–	1.31	2000	26.2	1048.0
Koshikidake	stratocone	24.13	–	1.72	2000	34.4	1376.0
Maruokayama	stratocone	19.25	–	1.22	2000	24.4	976.0
Byakushiike	lava flow	4.48	20	0.090	2000	1.80	72.0
Iimoriyama	stratocone	19.44	–	1.24	2000	24.8	992.0

* The thickness values are inferred from the topography.

** The method to calculate the volume of stratocones are described by Sugimura *et al.* (1962).

Characteristics of eruptive activities for the past 22,000 years

On the basis of the above description, it can be stated that the Kirishima volcano has erupted more or less in succession since the 22 ka. During the past 22,000 years, the total magma erupted amounts to 23×10^{12} kg. This corresponds to the magma discharge rate

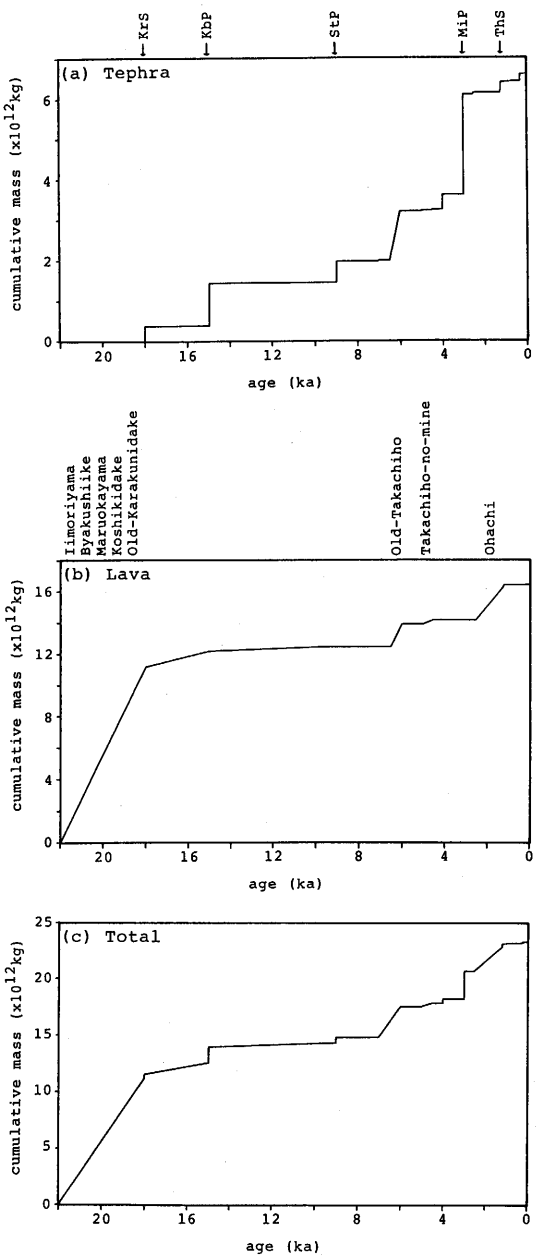

Fig. 8 Cumulated mass plotted against time for erupted materials from the Kirishima volcano during the past 22,000 years
Abbreviations are shown in Table 2.

Table 5 Eruptive mass and magma discharge rate of the Kirishima volcano during the past 22,000 years

Period	Eruptive mass ($\times 10^{12}$kg)			Magma discharge rate (D.R.E., $\times 10^{6}$m^3/ky)		
	tephra	lava	total	tephra	lava	total
0-7ka	4.60	4.00	8.60	2.63	2.29	4.92
7-15ka	0.55	0.30	0.85	0.28	0.15	0.43
15-22ka	1.44	12.16	13.60	0.82	6.95	7.77
0-22ka total	6.59	16.46	23.05	1.20	2.99	4.19

of 4.2×10^8 m^3 per thousand years of dense rock equivalent and this value is on the average of those of the Quaternary volcanoes in Japan (Ono, 1990).

However, mass of erupted material plotted against time (Fig. 8) shows that the activity of the Kirishima volcano has not been constant. Take Fig. 8-a for example, the erupted tephra seems to be increasing since 10 ka. In contrast to this, seventy four percent of lava has been erupted in the period between 15 ka and 22 ka (Fig. 8-b). Then, Fig. 8-c shows that the activity of the Kirishima volcano during the past 22,000 years can be subdivided into three periods by the magma discharge rate, *i.e.*, the periods as 22-15 ka, 15-7 ka and 7-0 ka. Table 5 shows the eruptive mass and the magma discharge rate for each periods. This table tells us that the magma discharge rate in the period between 15 ka and 7 ka is less than the other two periods by one figure. It seems reasonable to conclude that the period between 15 ka and 7 ka was a comparatively tranquil period. To put it another way, the activity of the Kirishima volcano for the past 22,000 years consists of the two major active periods and intercalates a tranquil period. On the other hand, the erupted mass ratio of tephra and lava changes with time. During the period between 22 ka and 15 ka, they are in the ratio of about one to nine. In contrast to this, the mass of erupted tephra since 15 ka is as same as or more than that of lava. The feature suggests that the eruptive style changes with time. That is to say, the eruptive style of the Kirishima volcano since the 22 ka changed with time from comparatively effusive activity to more explosive activity.

5. Conclusions

Volcano-stratigraphic study of the Kirishima volcano has been carried out to construct the eruptive history of the volcano for the past 22,000 years. Main results are summarized as follows:

1) In the period from 22 ka to 15 ka, five stratocones and two small volcanoes were formed. The eruptive activity of this period is characterized by predominant effusion of lava with smaller amount of pyroclastics.

2) The activity in the period 15-7 ka was comparatively tranquil. The erupted magma in this period was less than the other periods by one figure.

3) In the period 7 ka to the present, most of the major eruptions occurred in the southeastern part of the Kirishima volcano. On the other hand, only monogenetic activities occurred at the central part of the Kirishima volcano except the eruptions of

Shinmoedake. The eruptive activity of this period is characterized by the explosive eruption.

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(*: in Japanese, **: in Japanese with English abstract)