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Lithofacies and Petrographic Properties of the 1.6 Ma Fukuda Volcanic Ash Bed and its Correlatives in the Kinki and Tokai Districts, Central Japan

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(with 7 Figures and 2 Tables)

Abstract

The Fukuda volcanic ash bed and its correlatives, which occur on the Pliocene-Pleistocene boundary, are intercalated in fluvio-lacustrine deposits throughout the Kinki and Tokai districts. These ash beds are the most useful marker beds of Pliocene-Pleistocene deposits in this area, due to their characteristic stratification and petrographic properties. The ash beds generally consist of three units: a yellowish grey to light-grey unit A, consisting chiefly of glass (mainly H- and C-type shards with refractive indices from 1.499 to 1.503) with trace amounts of plagioclase, orthopyroxene (γ=1.707–1.760) and opaque minerals; a reddish brown to light-brown unit B, which consists of glass (mainly C- and H-type shards with refractive indices from 1.499 to 1.557) with minor amounts of plagioclase, amphibole, orthopyroxene (γ=1.705–1.732) and opaque minerals; and a yellowish grey to light-grey unit C, consisting chiefly of glass (mainly H- and C-type shards with refractive indices from 1.498 to 1.503) with trace amounts of plagioclase, opaque minerals, orthopyroxene, amphibole, biotite and epiclastic fragments, in ascending order. Based on the lithofacies and petrographic properties, units A and B are interpreted as water-settled, pyroclastic fall deposits, and unit C is interpreted as a resedimented volcaniclastic deposit. According to the lateral change of the thickness and maximum grain size of units A and B, the source volcano of the Fukuda volcanic ash bed and its correlatives is considered to be located in the Chubu district of central Japan.

Key Words: Fukuda volcanic ash bed, Kinki and Tokai districts, Pliocene-Pleistocene, lithofacies, petrographic properties

1. Introduction

The Pliocene-Pleistocene deposits in the Kinki and Tokai districts are composed mainly of unconsolidated gravel, sand and mud of fluvio-lacustrine origin. These deposits, which are widely distributed in several sedimentary basins, are known as the Osaka Group (Osaka Group Research Group, 1951; ITIHARA, 1960; ITIHARA *et al.*, 1975; ITIHARA *et al.*, 1984) in the Harima, Osaka, Nara and Kyoto basins; the Shobudani Formation (SANGAWA, 1977; MIZUNO and MOMOHARA, 1993) in the Kinokawa River drainage basin; the Kobiwako Group (IKEBE, 1933; TAKAYA, 1963 ; KAWABE, 1989) in the Iga and Omi basins; and the Tokai Group (TAKEHARA *et al.*, 1963; TAKEMURA, 1984; YOSHIDA, 1990) in the Tokai basin.

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At least 100 volcanic ash beds are intercalated in these deposits. These volcanic ash beds are valuable markers for regional stratigraphy and they play an important role in interbasinal correlation. YOSHIKAWA (1976, 1984), YOSHIKAWA *et al.* (1988, 1991), and MIZUNO (1993) described the lithologic and petrographic properties of these ash beds, and discovered some widespread ash beds that are continuously distributed in the Kinki and Tokai districts. The Fukuda volcanic ash bed, which occurs on the Pliocene-Pleistocene boundary of the Osaka Group, is widely distributed in the Kinki and Tokai districts. It is one of the most useful widespread marker-beds in these districts, not only because of its continuity but also for its characteristic stratification and remarkable petrographic properties (YOSHIKAWA, 1983; SOMEKAWA and YOSHIKAWA, 1983; YOSHIKAWA, 1984; YOSHIKAWA *et al.*, 1991; FUJIMOTO *et al.*, 1989; MIZUNO, 1993).

This paper describes the lithofacies and petrographic properties of the Fukuda volcanic ash bed and its correlatives in the Kinki and Tokai districts, and discusses the depositional environments and eruptive processes of these ash beds.

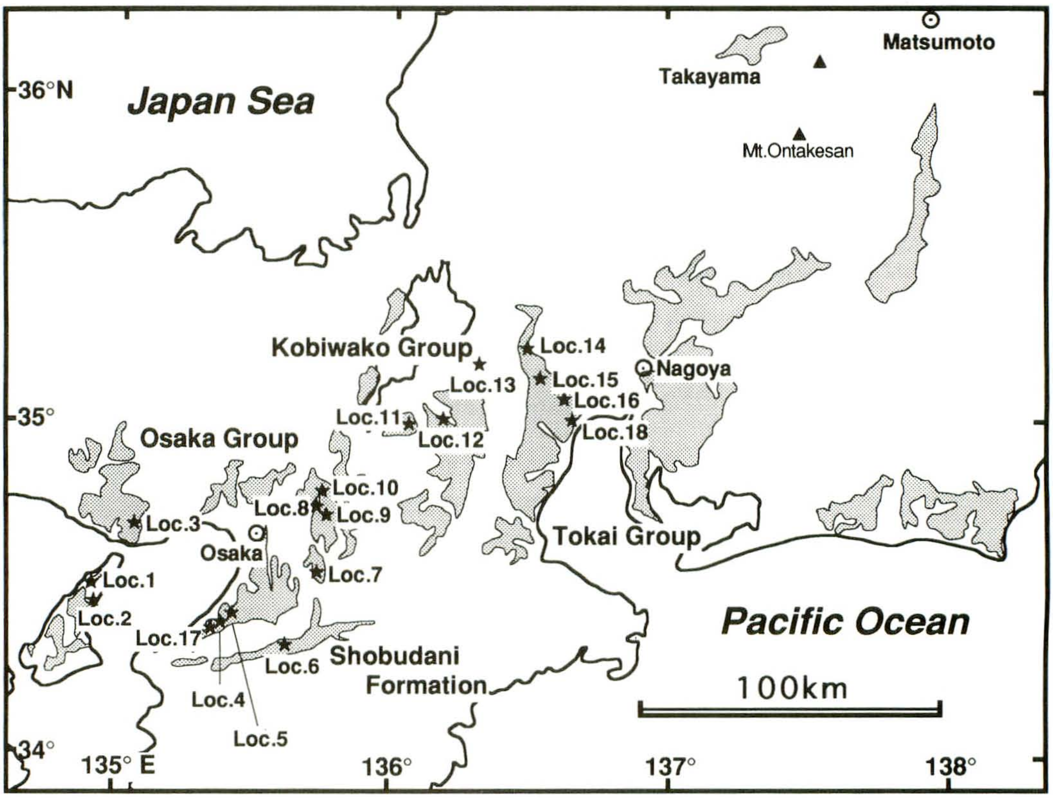


Fig. 1. Distribution of the Pliocene-Pleistocene deposits in the Kinki and Tokai districts, and localities of the Fukuda volcanic ash bed and its correlatives. Dotted area shows the Pliocene-Pleistocene deposits.

2. Stratigraphic position and the age of the Fukuda volcanic ash bed and its correlatives

Pliocene-Pleistocene deposits in the Kinki and Tokai districts, which include the Fukuda volcanic ash bed and its correlatives, have been studied in detail from the litho-, bio-, tephro- and magneto-stratigraphic, and radiometric veiwpoints by many researchers. They are regarded as the standard Pliocene-Pleistocene fluvio-lacustrine sequences in Japan (ITIHARA *et al.*, 1984;ITIHARA *et al.*, 1988). Biostratigraphically, the Fukuda volcanic ash bed and its correlatives are intercalated in deposits immediately below the horizon which marks the age of the beginning of the *Metasequoia* flora extinction. This is inferred as the Pliocene-Pleistocene boundary by ITIHARA (1960). Magneto-stratigraphically, these ash beds occur in deposits just above the Olduvai normal porality subchron (ISHIDA *et al.*, 1969; TORII *et al.*, 1974; Kobiwako Research group, 1977, 1981; NAKAYAMA and YOSHIKAWA, 1990). Eight fission-track ages of the Fukuda ash bed and its correlatives have been published. They are 2.2 Ma (IIDA, 1980), 1.9 Ma (HUZITA and MAEDA, 1984), 1.59 Ma, 1.60 Ma, 1.67 Ma, 1.99 Ma, 2.07 Ma (SUZUKI, 1988) and 2.5 Ma (MIZUNO *et al.*, 1990).

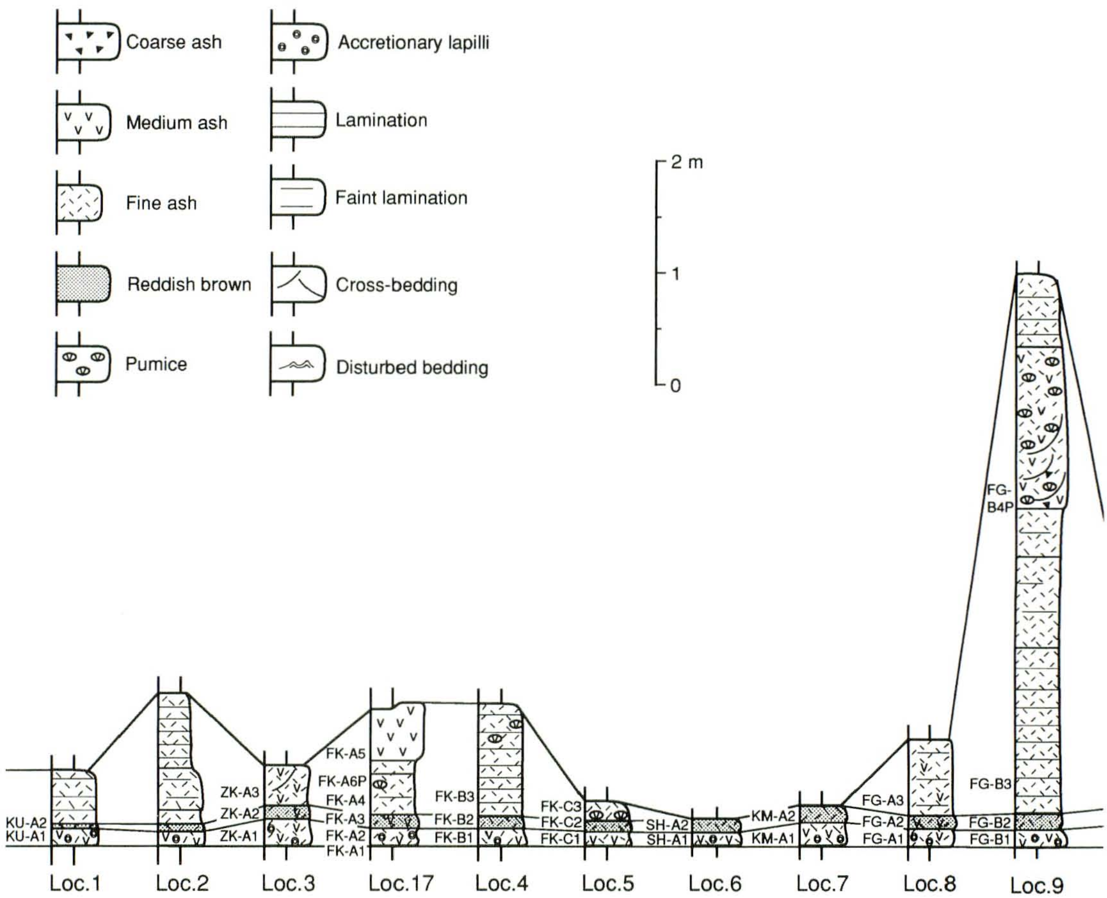
These stratigraphic and radiometric data indicate that the Fukuda volcanic ash bed and its correlatives exist at the Pliocene-Pleistocene boundary and are about 1.6 Ma old.

3. Lithofacies and Petrographic Properties

The lithofacies and petrographic properties of the Fukuda volcanic ash bed and its correlatives were studied at eighteen representative outcrops in the Kinki and Tokai districts (Table 1). Detailed lithofacies log-sections of these outcrops are shown in Figure 2. A list of the petrographic properties of the Fukuda volcanic ash bed and its correlatives reported in this paper is shown in Table 2. Characterization of the lithologic and petrographic properties of the ash follows YOSHIKAWA (1976, 1984).

Table 1. Localities of the Fukuda volcanic ash bed and its correlatives in the Kinki and Tokai districts.

Locality number	Latitude	Longitude	Locality
Loc.1	34°32'01"N,	134°55'21"E	Asano, Tsuna-gun, Hyogo
Loc.2	34°31'28"N,	134°59'25"E	Kuruma, Tsuna-gun, Hyogo
Loc.3	34°42'14"N,	135°03'23"E	Zenkai, Kobe City, Hyogo
Loc.4	34°24'18"N,	135°22'51"E	Mitsumatsu,Kaizuka City, Osaka
Loc.5	34°25'52"N,	135°25'09"E	Fukuda, Kishiwada City,Osaka
Loc.6	34°20'03"N,	135°36'33"E	Miyukitsuji, Hashimoto City, Wakayama
Loc.7	34°34'48"N,	135°43'07"E	Kammaki, Kitakatsuragi-gun, Nara
Loc.8	34°45'54"N,	135°43'29"E	Sebado, Ikoma City, Nara
Loc.9	34°44'52"N,	135°45'01"E	Higashibata, Souraku-gun, Kyoto
Loc.10	34°47'58"N,	135°44'10"E	Sonnenji, Hirakata City, Osaka
Loc.11	35°00'52"N,	136°02'32"E	Gokenjaya, Koka-gun, Shiga
Loc.12	35°01'41"N,	136°10'21"E	Gamodo, Gamo-gun, Shiga
Loc.13	35°12'52"N,	136°18'44"E	Taga, Inukami-gun,Shiga
Loc.14	35°14'54"N,	136°28'27"E	Shimoyama, Yoro-gun, Gifu
Loc.15	35°09'54"N,	136°31'39"E	Nishikaino, Inabe-gun, Mie
Loc.16	35°06'15"N,	136°37'21"E	Tado, Kuwana-gun, Mie
Loc.17	34°23'33"N,	135°21'10"E	Gomon, Kaizuka City, Osaka
Loc.18	35°01'56"N,	136°39'20"E	Asahi, Yokkaichi City, Mie



3.1 Lithofacies

As shown in Figure 2, the Fukuda volcanic ash bed and its correlatives, are generally about 100–1000 cm thick and are composed of coarse to fine ash with pumice lapilli. Based on the lithofacies, the Fukuda volcanic ash bed and its correlatives can be divided into three parts; a yellowish grey to light-grey lower part (unit A); a reddish brown to light-brown middle part (unit B); and a yellowish grey to light-grey upper part with pumice lapilli (unit C). Unlike units A and C, unit B is a characteristic reddish brown ash with relatively abundant crystals. Therefore, unit B is a useful marker horizon and can be clearly traced througout the study area. The lateral and vertical relationships of these units are shown in Figure 2.

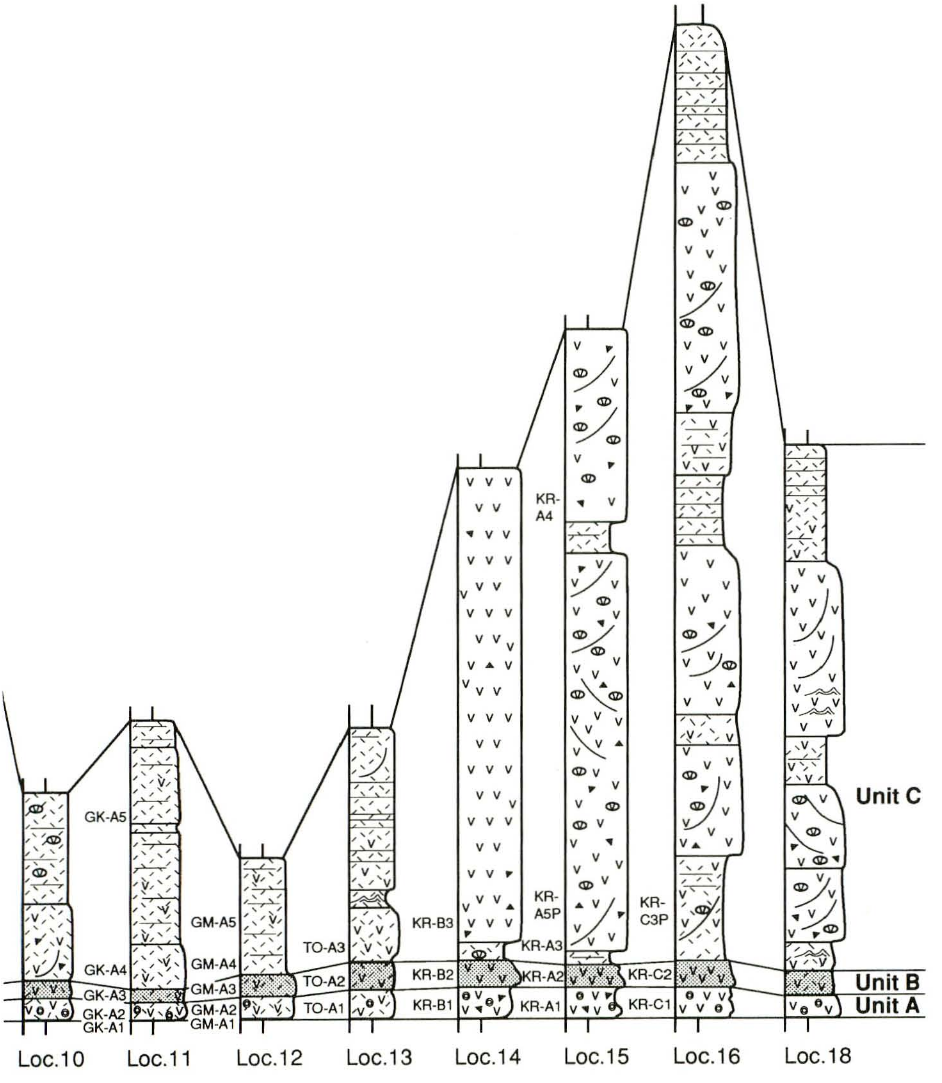


Fig. 2. Stratigraphic columnar sections of the Fukuda volcanic ash bed and its correlatives. Localities are shown in Fig. 1 and Table 1. KU-A1, KU-A2, ZK-A1, … and KR-C3P indicate the sample numbers.

We describe the detailed lithofacies of units A, B and C, in ascending order, as follows.

Unit A Unit A, is about 10–30 cm thick and is laterally continuous. The lower contact with fluvio-lacustrine mud is sharp and non-erosive. This unit is a moderately to well-sorted, yellowish grey to light-grey, coarse to fine ash, which commonly encloses accretionary lapilli (Fig.2). Unit A, as a whole, shows multiple normal grading (Fig.3).

The lower part of this unit, which is several centimeters thick, consists primarily of normally graded, coarse to fine ash, with localized small-scale cross laminae indicative

Table 2. Petrographic properties of the Fukuda volcanic ash bed and its correlatives in the Kinki and Tokai districts.

Volcanic ash name (Locality)	Sampling horizon	Sample No.	Mineral composition (%)				Glass							Heavy mineral composition (%)						
							Shape (%)						Refractive index (mode)							
			Gl.	Fl.	Qz.	Hm.	Ha	Hb	Ca	Cb	Ta	Tb		Bi.	Am.	Op.	Cp.	Zr.	Ap.	Oq.
Kuruma volcanic ash																				
(Loc.1)	Unit B	KU-A2	95	4	0	0.9	4	53	25	13	5	0	1.499-1.553(1.501-1.502)	1	76	10	1	1	0	11
	Unit A	KU-A1	98	2	0	0.2	6	71	12	9	2	0	1.500-1.502	6	8	5	2	8	0	71
Zenkai volcanic ash																				
(Loc.3)	Unit C	ZK-A3*	97	3	0	0.1	8	37	19	30	1	4	1.499-1.502	20	38	2	0	10	0	30
	Unit B	ZK-A2*	92	7	0	0.8	1	56	25	13	5	0	1.501-1.555(1.5015-1.5025)	1	63	5	1	2	0	28
	Unit A	ZK-A1*	96	4	0	0.1	6	44	33	15	1	1	1.498-1.502	17	12	11	1	5	0	54
Fukuda volcanic ash																				
(Loc.17)	Unit C	FK-A6P*	100	0	0	0.0							1.500-1.502	1	3	13	0	1	0	82
	Unit C	FK-A5*	80	15	3	1.7	5	57	12	26	1	0	1.500-1.503	1	33	27	2	4	0	33
	Unit C	FK-A4*	97	3	0	0.1	8	34	20	32	1	4	1.500-1.502	1	31	19	0	4	0	45
	Unit B	FK-A3*	87	10	2	1.1	2	43	17	31	1	5	1.500-1.557(1.5010-1.5025)	2	53	23	1	3	0	18
	Unit A	FK-A2*	98	2	0	0.1	8	49	15	19	5	4	1.500-1.503(1.5015-1.5025)	13	10	8	1	15	0	53
	Unit A	FK-A1*	98	1	1	0.1	7	42	16	28	2	4	1.500-1.503(1.5010-1.5020)	6	4	5	2	13	0	70
(Loc.4)	Unit C	FK-B3	98	2	0	0.1	4	49	18	24	3	2	1.499-1.503							
	Unit B	FK-B2	94	5	0	1.2	6	54	20	13	6	1	1.501-1.556(1.5010-1.5025)	1	79	2	0	2	0	16
	Unit A	FK-B1	97	3	0	0.1	5	56	25	10	3	1	1.498-1.503	7	11	5	0	13	0	64
(Loc.5)	Unit C	FK-C3	98	2	0	0.1	4	49	20	26	1	0	1.500-1.503	2	28	21	0	3	0	46
	Unit B	FK-C2	91	8	0	1.0	3	57	26	8	5	1	1.500-1.554(1.5015-1.5025)	0	68	4	0	2	0	26
	Unit A	FK-C1	97	3	0	0.1	5	53	27	11	3	1	1.499-1.503	3	16	7	0	14	0	60
Shoubudani-1 volcanic ash																				
(Loc.6)	Unit B	SH-A2	89	10	0	1.1	0	40	32	14	13	1	1.500-1.555(1.5010-1.5025)	1	59	25	5	0	0	10
	Unit A	SH-A1	95	5	0	0.3	1	62	24	9	3	1	1.500-1.503	3	9	62	8	2	0	16
Kammaki volcanic ash																				
(Loc.7)	Unit B	KM-A2	92	7	0	0.8	1	39	29	14	16	1	1.499-1.555(1.5010-1.5025)	1	63	10	0	1	0	26
	Unit A	KM-A1	97	3	0	0.1	5	55	22	17	1	0	1.500-1.503	2	6	1	3	9	1	60
Fugenji volcanic ash																				
(Loc.8)	Unit C	FG-A3*	99	1	0	0.1	4	51	21	23	1	0	1.499-1.503	0	21	2	0	9	0	68
	Unit B	FG-A2*	89	9	0	1.7	3	21	50	12	13	1	1.501-1.552(1.5010-1.5025)	0	60	18	1	3	0	22
	Unit A	FG-A1*	97	3	0	0.1	7	28	35	29	1	0	1.499-1.503(1.5015-1.5020)	1	15	8	1	12	0	63
(Loc.9)	Unit C	FG-B4P	100	0	0	0.0							1.500-1.502	1	1	12	1	15	0	69
	Unit C	FG-B3	89	9	1	0.1	5	48	18	28	1	0	1.500-1.503	0	19	1	0	7	0	73
	Unit B	FG-B2	77	17	2	3.2	1	43	36	14	6	0	1.500-1.552(1.5010-1.5025)	0	68	17	3	3	2	6
	Unit A	FG-B1	98	2	0	0.1	8	64	17	10	1	0	1.500-1.503	8	15	7	1	15	0	54
Gokenjaya volcanic ash																				
(Loc.11)	Unit C	GK-A5*	100	0	0	0.0	7	27	26	36	0	4	1.499-1.502	67	18	1	0	4	0	10
	Unit C	GK-A4*	99	1	0	0.1	6	36	14	38	2	4	1.500-1.502	19	25	3	0	0	0	53
	Unit B	GK-A3*	93	5	0	1.8	0	39	36	15	7	3	1.500-1.557(1.5015-1.5025)	0	59	21	3	1	0	16
	Unit A	GK-A2*	98	1	1	0.2	3	56	15	25	1	1	1.498-1.503(1.5005-1.5020)	1	6	49	5	1	0	38
	Unit A	GK-A1*	98	2	0	0.1	1	53	15	31	0	1	1.499-1.503(1.5010-1.5020)	1	4	56	5	1	0	33
Gamodo volcanic ash																				
(Loc.12)	Unit C	GM-A5*	100	0	0	0.0	10	32	18	29	1	10	1.499-1.502	25	11	6	0	14	0	44
	Unit C	GM-A4*	99	1	0	0.1	3	33	16	39	3	6	1.500-1.502	11	14	1	0	5	0	69
	Unit B	GM-A3*	94	5	0	0.8	0	34	17	37	4	17	1.500-1.556(1.5010-1.5025)	1	76	0	0	1	0	22
	Unit A	GM-A2*	96	3	1	0.1	3	36	15	36	5	4	1.499-1.503	2	21	1	1	4	0	71
	Unit A	GM-A1*	98	2	0	0.1	3	51	14	28	2	2	1.500-1.502	5	6	1	0	9	0	79
Tomino volcanic ash																				
(Loc.13)	Unit C	TO-A3	99	1	0	0.1	8	39	15	33	2	3	1.499-1.502	10	10	1	0	9	0	70
	Unit B	TO-A2	92	7	0	1.0	2	48	30	19	1	0	1.501-1.555(1.5010-1.5025)	0	89	2	1	4	0	3
	Unit A	TO-A1	97	3	0	0.1	4	52	31	12	1	1	1.499-1.503(1.5010-1.5020)	1	14	38	2	1	0	44
Karegawa volcanic ash																				
(Loc.14)	Unit C	KR-B3	99	1	0	0.1	7	49	18	25	1	0	1.500-1.503	2	13	1	0	8	0	76
	Unit B	KR-B2*	84	13	0	2.9	2	46	29	17	6	0	1.501-1.503	1	63	16	4	0	0	16
	Unit A	KR-B1*	99	1	0	0.3	3	47	32	10	6	2	1.499-1.503	0	2	37	2	1	0	58
(Loc.15)	Unit C	KR-A5P*	99	1	0	0.1							1.499-1.502	1	9	38	1	1	0	50
	Unit C	KR-A4*	82	16	1	0.6	6	40	33	20	1	0	1.498-1.503	0	49	15	2	2	0	32
	Unit C	KR-A3*	100	0	0	0.0	8	48	23	20	0	1	1.500-1.502	0	13	3	1	1	0	82
	Unit B	KR-A2*	93	5	0	1.9	3	35	36	20	6	0	1.501-1.552(1.5015-1.5025)	1	80	8	1	1	0	9
	Unit A	KR-A1*	98	2	0	0.1	7	34	34	21	3	1	1.498-1.502(1.5000-1.5020)	5	15	27	1	4	0	48
(Loc.16)	Unit C	KR-C3P	100	0	0	0.0							1.499-1.502	8	15	39	1	5	0	32
	Unit B	KR-C2	93	5	0	1.8	1	38	37	18	5	1	1.500-1.553(1.5015-1.5025)	1	77	1	0	1	0	20
	Unit A	KR-C1	97	3	0	0.1	2	60	25	11	1	1	1.499-1.502	1	10	1	0	2	0	86

Mineral composition — Gl.: Glass Fl.: Feldspar Qz.: Quartz Hm.: Heavy minerals
Heavy mineral composition — Bi.: Biotite Am.: Amphibole Op.: Orthopyroxene Cp.: Clinopyroxene Zr.: Zircon Ap.: Apatite Oq.: Opaque minerals
Shape of glass shard — after Yoshikawa(1984)
* : Yoshikawa et al.(1994)

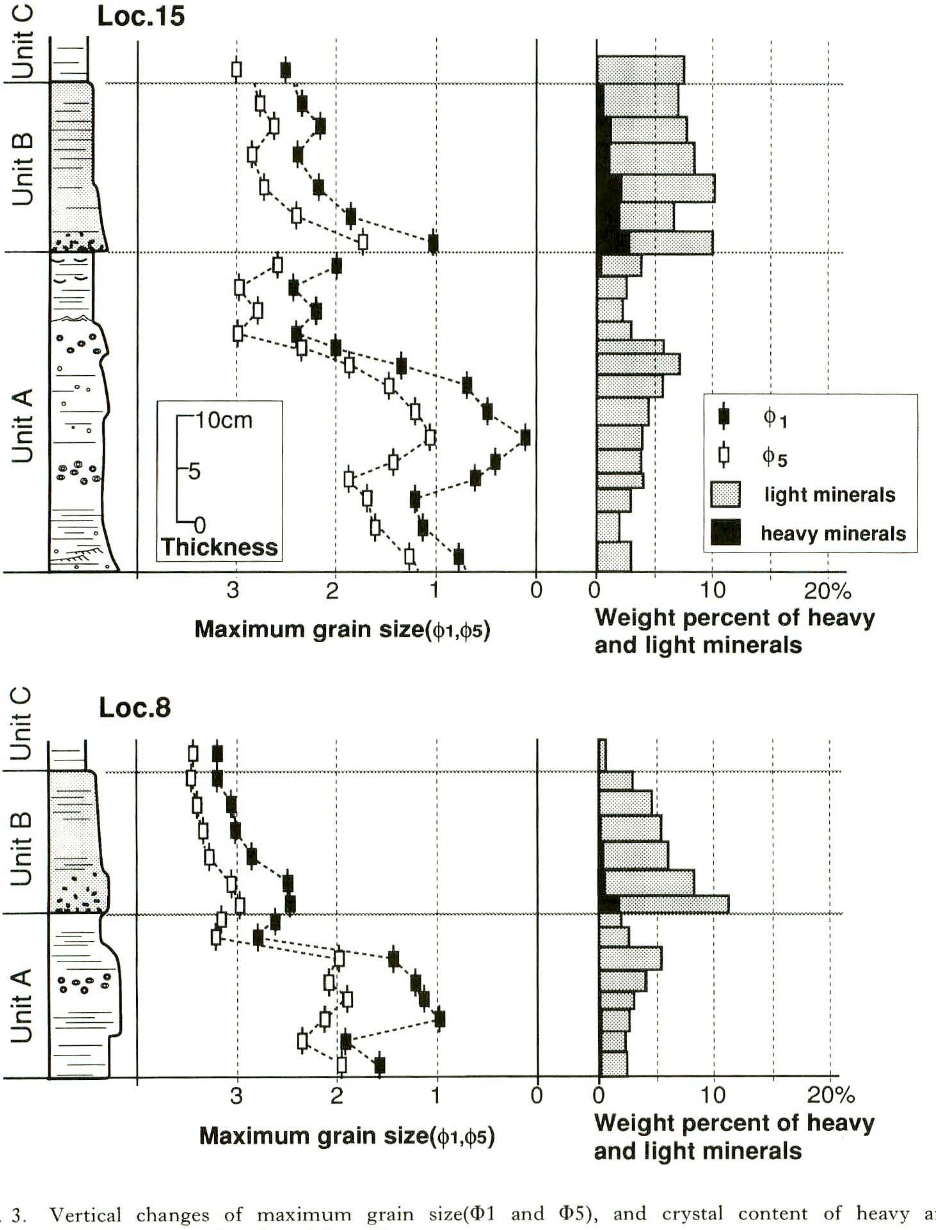


Fig. 3. Vertical changes of maximum grain size(Φ1 and Φ5), and crystal content of heavy and light minerals at Loc.8 and Loc.15.

of minor reworking. The middle part, which is the coarsest and thickest part of unit A, consists of slightly normally graded, coarse to medium ash, with accretionary lapilli. The accretionary lapilli are composed of a medium-grained core surrounded by a fine-grained rim, and are 1.5–5 mm in diameter. They occur in two distinct stratigraphic horizons of the middle part at most localities, and decrease slightly in amount from northeast to southwest. The upper part, which is several centimeters thick, is the finest

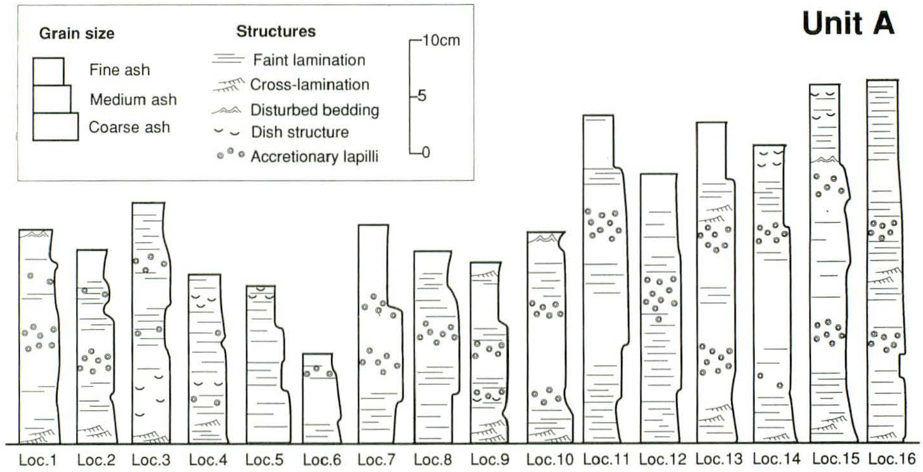


Fig. 4. Stratigraphic columnar sections of unit A of the Fukuda volcanic ash bed and its correlatives.

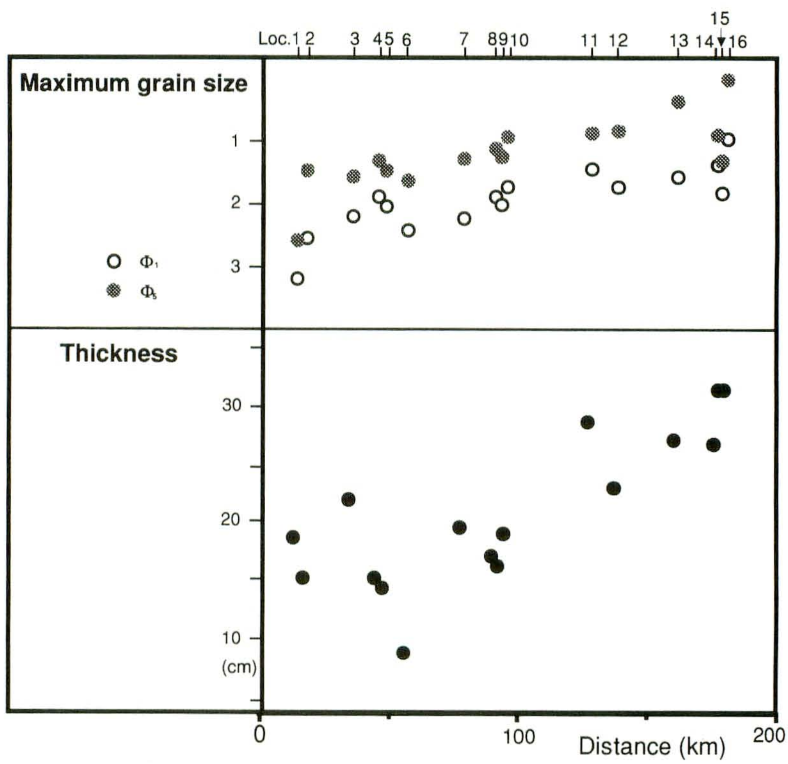


Fig. 5. Lateral changes of thickness and maximum grain size (Φ1 and Φ5) of unit A.

part in unit A, and consists mainly of mostly ungraded, weakly horizontally laminated fine to very fine ash. Disturbed bedding and dish structures due to dewatering occur

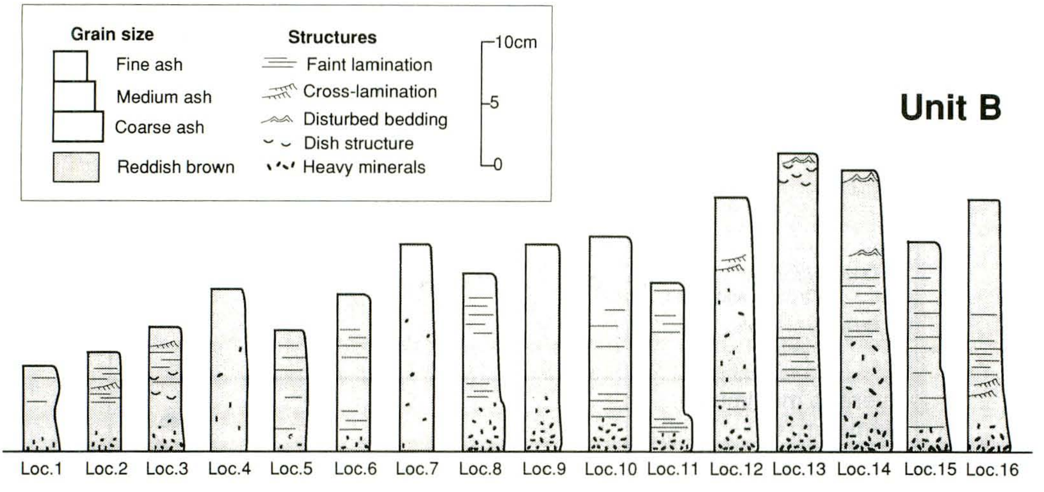


Fig. 6. Stratigraphic columnar sections of unit B of the Fukuda volcanic ash bed and its correlatives.

in the upper and middle parts, but rarely in the lower part.

Figure 5 shows the lateral changes of thickness and maximum grain size (Φ1 and Φ5) of unit A. The thickness of unit A generally increases northeastward from about 15 cm in the southwest to about 30 cm in the northeast of the study area. The maximum grain size of the middle part of this unit also increases to the northeast.

Unit B Unit B is 7–20 cm thick and is laterally continuous. Its lower contact with unit A is sharp and non-erosive. This unit is a well-sorted, normally graded, reddish brown to light-brown, medium to fine ash with heavy and light mineral crystals (Fig.6). Figure 3 clearly shows that the maximum grain size and crystal content of unit B decreases upward from the base to the top.

The lower part of unit B is massive, reddish brown, medium to fine ash which contains abundant crystals. These crystals are concentrated near the base of this unit, and gradually decrease upward in size and amount. The upper part of unit B consists of massive to crudely laminated, light-brown, fine to medium, glass-rich ash. In the upper part, small-scale cross laminae are locally developed, and disturbed bedding and dish structures occur at a few localities.

The thickness of unit B increases systematically northeastward, from 7 cm in the southwest to about 20 cm in the northeast of the study area (Figs.6 and 7). The grain size of unit B, as a whole, increases northeastward. As shown in Figure 7, the maximum grain size at the base of this unit coarsens from southwest to northeast in the study area.

Unit C Unit C varies in thickness from about 10 to 1000 cm and is absent at some localities. This unit is laterally discontinuos and shows marked lateral facies variations. The base of this unit is sharp at most localities, but is locally gradational. The upper contact with fluvio-lacustrine deposits is commonly gradational. In some areas, where unit C is absent, unit B is directly overlain by fluvio-lacustrine deposits, with a

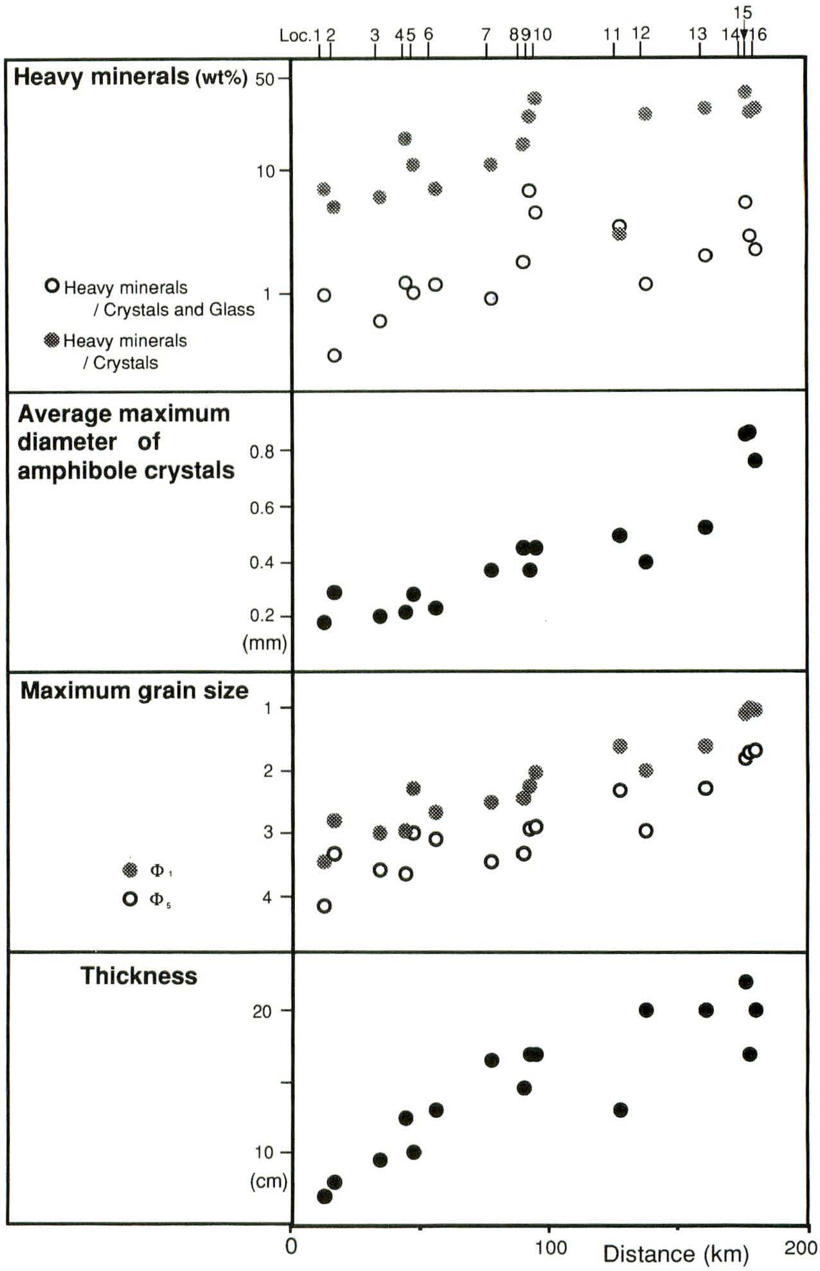


Fig. 7. Lateral changes of thickness, maximum grain size(Φ1 and Φ5), average muximum diameter of amphibole crystals and heavy mineral content of unit B.

sharp contact.

Generally this unit consists of moderately sorted, yellowish grey to light-grey, coarse to fine ash with localized pumice fragments. Three main interbedded lithofacies occur in this unit: cross-bedded, coarse to medium ash with pumice fragments, massive medium to coarse ash, and weakly horizontally laminated fine to medium ash. The cross-bedded coarse to medium ash, 50–500 cm thick, is laterally discontinuous, and has a markedly erosional surface with scours up to 1 m deep at the base. Pumice fragments are well rounded, vesiculated lapilli, 1–30 cm in diameter. The pumice lapilli commonly occur together with sand-size glass in some cross-bedded units. Rounding of the pumice lapilli and lithofacies of this ash indicate tractional transport and reworking. The massive, medium to coarse ash is 50–500 cm thick, and is laterally discontinuous. Small pumice fragments, less than 1 cm in diameter, locally occur in this ash. The weakly horizontally laminated fine to medium ash is 10–100 cm thick, and has occasional intercalations of tuffaceous mud.

The thickness of unit C, as a whole, gradually increases northeastward from about 10 cm in the southwest to about 1000 cm in the northeast of the study area. The maximum grain size of this unit also increases northeastward (Fig. 2).

3.1 Petrographic Properties

Mineralogically, the ash of the Fukuda volcanic ash bed and its correlatives is rhyolite to dacite in composition, and is largely made up of glass shards. Accessory minerals include plagioclase, amphibole, orthopyroxene, opaque minerals, quartz, clinopyroxene, biotite and zircon. The detailed petrographic properties of units A, B and C are as follows.

Unit A The mineralogic composition of all ash samples from unit A is homogeneous over the study area. Generally, the ash of this unit is largely (90–95%) made up of glass particles, which consist mainly of colorless H- and C-type shards. The refractive index of the glass shards ranges from 1.498 to 1.503 (modal range:1.5010–1.5020). Accessory minerals include plagioclase, opaque minerals, orthopyroxene, amphibole, with subordinate amounts of biotite, clinopyroxene and zircon. Quartz is found in trace amounts in some samples. As shown in Figure 3, the content of plagioclase is relatively abundant in the middle part of unit A. The refractive index of orthopyroxene (γ) ranges from 1.707 to 1.760.

Unit B The ash of unit B consists chiefly of glass particles, with minor amounts of plagioclase and heavy minerals. The plagioclase and heavy mineral content gradually decreases from the base to the top. The ash of unit B is different in mineral composition from that of units A and C, as the glass has a distinctly higher refractive index, and amphibole is more abundant.

Most glass particles are colorless C- and H-type shards with refractive indices from 1.499–1.503 (1.5010–1.5030), but some are pale brown T- and C-type shards with indices from 1.548–1.555. Pale brown T- and C-type shards are crowded with microlites of plagioclase. In the heavy minerals, amphibole is abundant, opaque minerals and orthopyroxene are common, and clinopyroxene, zircon and biotite are rare. The refractive index of orthopyroxene (γ) ranges from 1.705 to 1.732.

As shown in Figure 7, the average maximum diameter of amphibole crystals at the base of this unit coarsens from southwest to northeast in the study area. The crystal content at the base of this unit generally increases northeastward.

Unit C The ash in unit C consists mainly of glass particles with trace amounts of plagioclase, heavy minerals and epiclastic fragments. Epiclastic lithic and crystal fragments, indicating sedimentary contamination, commonly occur in the ash. The epiclastic crystal fragments are subrounded and stained quartz, plagioclase, amphibole and zircon.

Glass particles are dominantly colorless C- and H-type shards, with refractive indices from 1.499–1.503 (1.5010–1.5030). In the heavy minerals, amphibole is abundant, opaque minerals and orthopyroxene are common, and clinopyroxene, zircon and biotite are rare. The refractive index of orthopyroxene (γ) is 1.705–1.732.

The pumice fragments in unit C comprise abundant colorless glass, together with minor plagioclase and heavy minerals. The refractive index of glass ranges from 1.498–1.503 (1.5010–1.5020). Heavy minerals include opaque minerals, orthopyroxene ($\gamma=1.707$–1.760), amphibole, with subordinate amounts of biotite, clinopyroxene and zircon. Quartz is also found in trace amounts in some samples.

4. Discussion and Conclusion

Depositional environments and eruptive processes of the Fukuda volcanic ash bed and its correlatives can be discussed in terms of the lithofacies and petrographic properties of each unit.

The Fukuda volcanic ash bed and its equivalents are intercalated in fluvio-lacustrine deposits (ITIHARA *et al.*, 1988; KAWABE, 1989; YOSHIDA, 1992).

Unit A is interpreted as a pyroclastic air-fall deposit formed in a fluvio-lacustrine environment. In unit A, the moderately to well sorted nature and the multiple, normally graded lithofacies, the lateral continuity, the systematic changes of thickness and grain size, and the sharp and non-erosive bases suggest a pyroclastic air-fall (WALKER, 1973; FISHER and SCHMINCKE, 1984). Multiple normal grading and two accretionary lapilli-bearing horizons reflect changes in eruption-column height, fragmentation processes or dispersal directions during the eruption. Unit B is also interpreted as pyroclastic air-fall deposits formed in a fluvio-lacustrine environment, because of its well-sorted and normally graded lithofacies, lateral continuity, systematic changes of thickness and grain size, and sharp and non-erosive bases. Small-scale cross laminae in units A and B suggest the effects of minor reworking. Units A and B are formed by deposition from weak water currents following fallout of ash onto a small lake or swamp. Abrupt changes in the petrographic properties between units A and B could be caused by compositional changes in the source magma of the eruption.

Unit C is interpreted as resedimented volcaniclastic deposits (MCPHIE *et al.*, 1993) formed in a fluvio-lacustrine environment such as a river, swamp or small lake. This is consistent with the presence of epiclastic fragments, intercalations of tuffaceous mud, and marked lateral and vertical facies variations.

On the basis of these interpretations, the Fukuda volcanic ash bed and its correlatives generally comprise two water-settled pyroclastic fall deposits and resedimented volcaniclastic deposits.

The source volcano of the Fukuda volcanic ash bed and its correlatives is considered to be located in the Chubu district, 100 to 200 km to the northeast of the study area. The thickness of units A and B increases northeastward. The maximum grain size of units A and B, and average maximum grain size of amphibole crystals at the base of unit B also increase northeastward. The thickness and grain size data are consistent with a source volcano in the Chubu district. Recently, the Fukuda volcanic ash bed has been correlated with the Ebisutoge pyroclastic deposits of the Takayama basin in the Chubu district (NAGAHASHI, 1993, 1995), and with the Tsujimatagawa volcanic ash bed of the Niigata district (YOSHIKAWA *et al.* 1994). These data also support a source volcano in the Chubu district of central Japan.

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