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Tuffs from the Lower Sequence of the Kiwada Formation along the Yoro River in the Boso Peninsula, Central Japan

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Abstract Modal proportions of heavy minerals and chemical compositions of orthopyroxene and cummingtonite were measured from 100 tuff layers in the lower sequence of the Kiwada Formation along the Yoro River. The sequence is divided into three zones on the basis of the modal proportion of hornblende. The upper zone, rich in hornblende, includes a biotite-rich tuff, Kd24, and several cummingtonite-bearing tuffs. Tuffs in the middle zone are composed mostly of pyroxenes in heavy fractions. The lower zone is rich in hornblende and is characterized by presence of cummingtonite-rich tuffs, Kd38 and YK14.

Chemical composition of orthopyroxene varies widely in the sequence. Although simple correlation by its composition may not be available, peak position of X_{Mg} in orthopyroxene can be used as a correlation factor referring to modal proportion and lithology. The results of this study demonstrate the potential of the methods for tuff discrimination in distal areas, especially for tuffs in the Boso Peninsula.

Key words : tuff, modal proportion, cummingtonite, Kiwada Formation.

Introduction

In the Boso Peninsula, more than thousand tuff layers are observed in the Tertiary to Quaternary sequence. Although geological map of northern part of the peninsula was proceeded referring many key tuff layers (Mitsunashi *et al.*, 1959, 1979), it is hard to correlate precisely each tuff layer because of so many tuffs in the peninsula. Kd38 tuff, which was first denoted for the tuff along the Yoro River by Mitsunashi *et al.* (1959), occurs near the boundary between Tertiary and Quaternary (Takayama *et al.*, 1995). The Kd38 tuff was described in the other areas of the peninsula (Yoshikawa, 1996; NHMIC, 1990; Watanabe and Danhara, 1996), but modal and chemical compositions of the tuffs from the Kurotaki area are different from that in the Yoro River (Yokoyama *et al.*, 1997). Hence a detailed standard section along the Yoro River is important to compare the tuffs with those in the other areas of the peninsula. In this paper, we analyzed modal proportions and chemical compositions of heavy minerals in 100 tuffs from the lower sequence of the Kiwada Formation along the Yoro River.

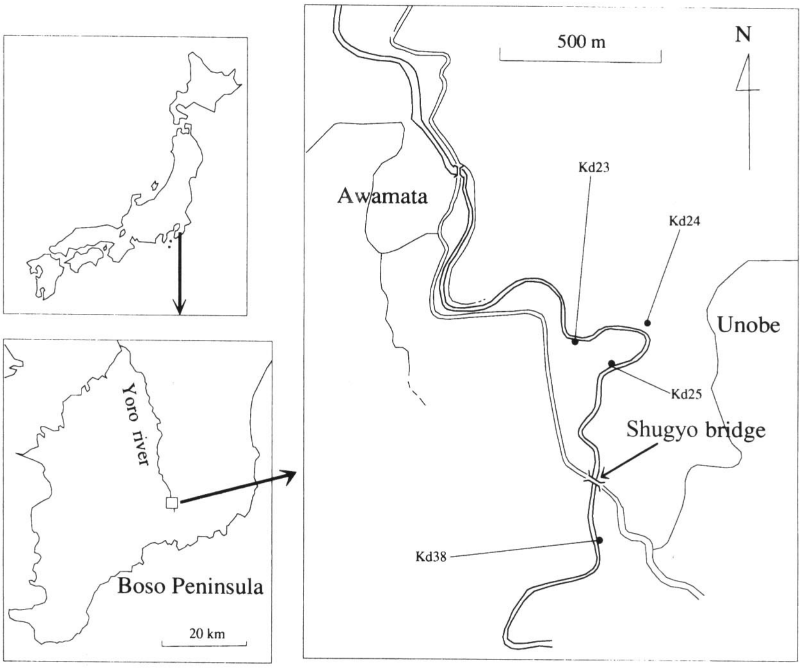

Fig. 1. Locality map for the representative tuffs in the Kiwada Formation along the Yoro River.

Sampling and Analytical Method

About 100 tuff samples were collected in the Kiwada Formation in the Kazusa Group along the Yoro River (Figs. 1, 2 and 3). The tuffs are intercalating mostly with siltstone in the upper sequence, whereas with sandstone in the lower sequence. Although large scale of discontinuity has not been recognized, slumping structure and siltstone with rip-up clast develop in the upper sequence. Whatever a tuff layer is thick or thin, its thickness is mostly constant in the studied area. Only a few tuffs are pinching and swelling out in a outcrop.

Mitsunashi *et al.* (1959) described several tens tuffs in the Kiwada Formation and named each tuff or assemblage of the tuffs with a character of 'Kd' such as Kd8 and Kd25 . Their localities except for several tuffs are not certain now because of abundant tuff layers in the area (*e.g.* NHMIC, 1990). Names of four tuffs or assemblages among them are succeeded in this paper: Kd23, Kd24, Kd25 and Kd38 in Fig. 1. Cross lamina, graded bedding and fine-banded structure are observed in a thick tuff layer. Several samples were collected in such a thick layer to study variation of modal proportion and mineral composition within a layer.

Crystal-rich tuff is the most common in the sequence. It is composed of black and white grains. The former consists of pyroxenes, amphibole and Fe-oxides, where-

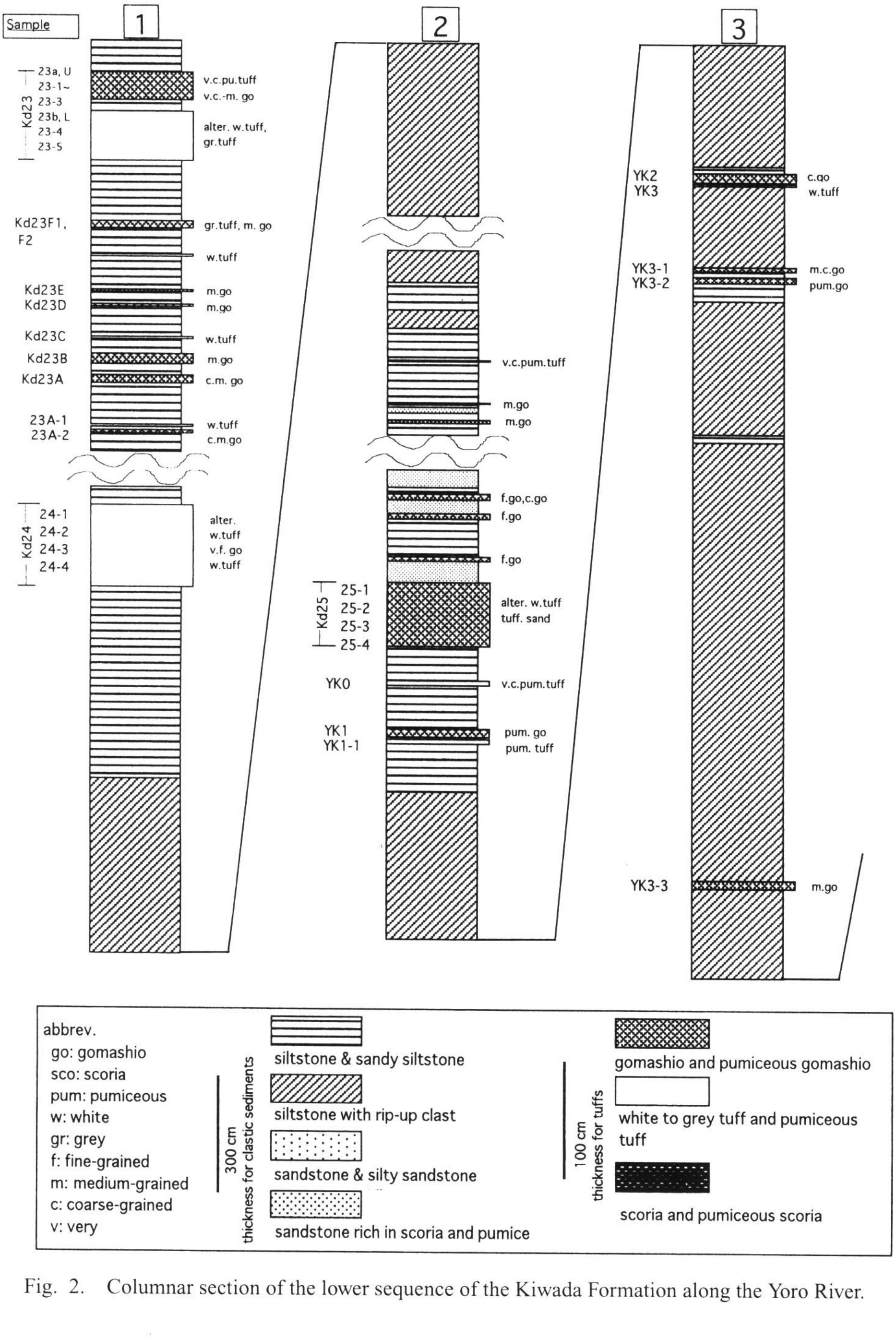

Fig. 2. Columnar section of the lower sequence of the Kiwada Formation along the Yoro River.

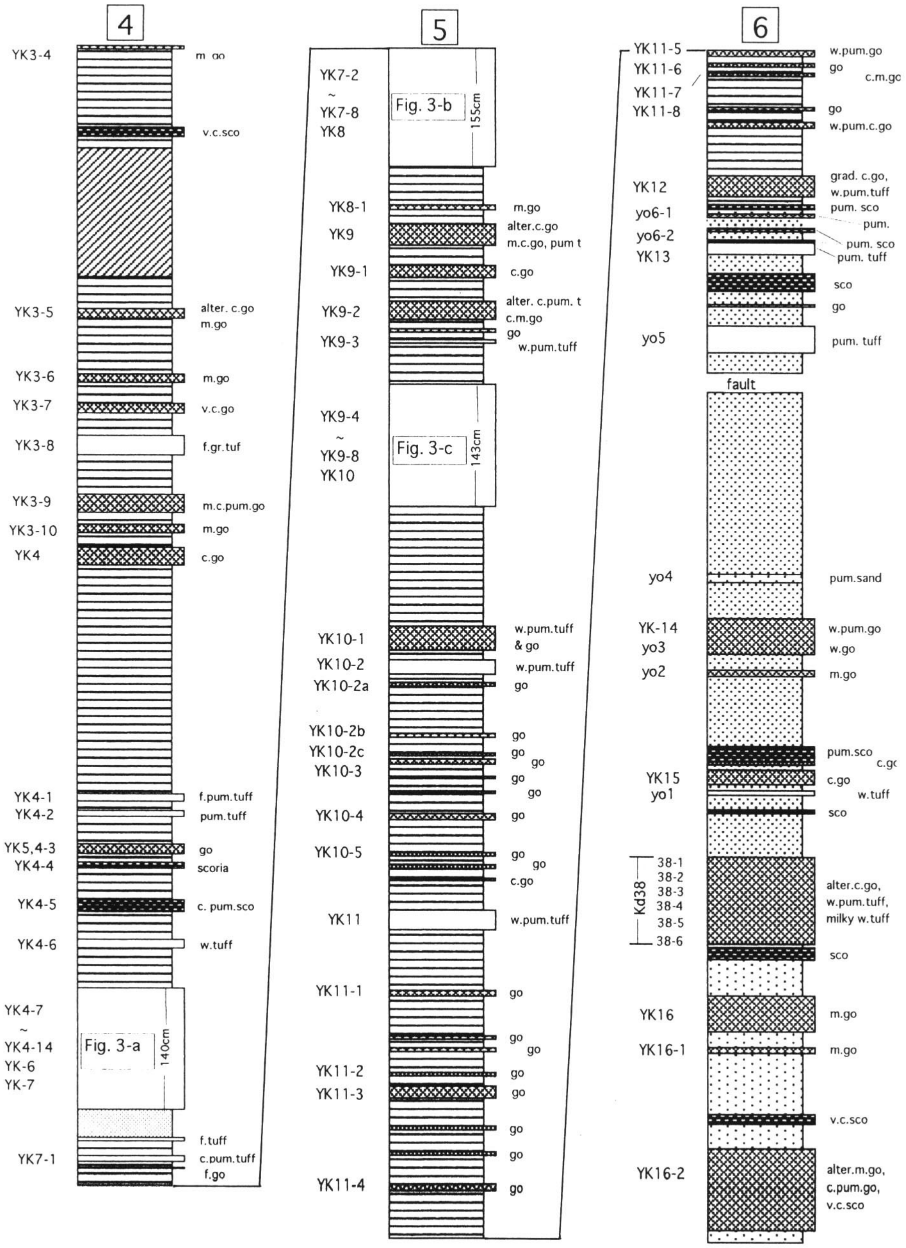

Fig. 2. (Continued)

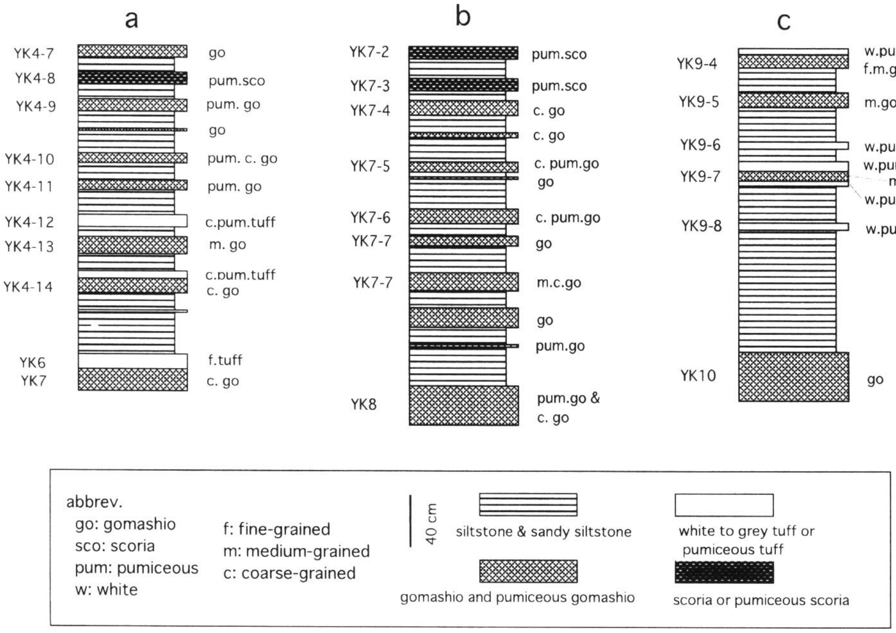

Fig. 3. Columnar sections at the tuff-rich parts in Fig. 2.

as the latter of plagioclase and glass. Such tuff is called "gomashio tuff" named from apparent similarity with seasoning made of sesame seed and salt. White tuff is not common, but is marked in the sequence. Some of the white tuffs are fine-grained and are too poor in crystal to separate heavy minerals.

Detailed analytical method was reported in the foregoing paper (Yokoyama *et al.*, 1997). The procedure was described briefly here. Tuffs were disaggregated by boiling in water with 5% of hydrogen peroxide. They were subsequently dried and sieved into four fractions: A (0.5–0.25 mm), B (0.25–0.125 mm), C (0.125–0.063 mm), D (<0.063 mm). Heavy minerals were separated from the fractions by mixing with methylene iodide with specific gravity around 2.8. Micaceous and carbonate minerals are present in both heavy and light fractions. Hence, these minerals except for biotite were not included in the following mineral count. Pyrite and goethite are common in some tuffs. Most of them are considered to be secondary formed as an authigenic mineral or replacing magnetite. They are not included in the mineral proportion.

Most of the minerals were identified by means of profiles obtained by energy dispersive spectrometer (EDS, LINK Systems). Orthopyroxene and cummingtonite were analyzed by wave-length spectrometer (JXA 8800 of JEOL) using an accelerating voltage of 15 kV, a 20 nA beam current and a 3 μm beam diameter. The most homogeneous pyroxenes in the Kd39 tuff (Yokoyama *et al.*, 1997) were analysed routinely to check for any machine drift.

Heavy Minerals and Modal Proportions

Modal proportions and chemical compositions of heavy minerals in a tuff are more or less different from fraction to fraction divided by grain size, and heavy minerals such as zircon and magnetite are strongly enriched in the fine-grained fraction (Yokoyama *et al.*, 1997). In this paper, we mostly use fraction B (0.25–0.125 mm) for the modal and chemical analyses. Fine-grained fraction C is used occasionally in the fine-grained samples or white tuffs. These selections may affect at the correlation of tuffs, but the modal proportion should be useful if the grain size and heavy minerals with the similar density are selected and applied to the samples in a restricted region such as the Boso Peninsula.

Although, in the heavy fraction, more than 12 minerals were observed from the tuffs (Yokoyama *et al.*, 1997), pyroxene and amphibole in addition to magnetite and ilmenite are dominant in the fraction B (Table 1). Cummingtonite is one of major phases in some tuffs. Satoguchi (1995) reported the modal proportions of heavy minerals in the tuffs from the Kazusa Group, but cummingtonite had not been recognized in any tuff.

Modal proportions of pyroxene and amphiboles are presented in Table 1 and Fig. 4. These minerals have similar density to each other and were expected to behave in a similar way during gravity settling. Biotite is present in the light and heavy fractions. Its modal proportion may not be compared with more heavy pyroxene and amphibole. Biotite occurs only in a few samples which are useful markers in the sequence from the Kiwada Formation. Hence, it was tentatively calculated as well as the pyroxene and amphiboles in Table 1.

Ortho- and clinopyroxenes are mostly major phases and present in almost all the samples (Table 1). As hornbelnde-bearing tuffs is concentrated in the lower and upper parts of the sequence, the studied sequence is divided into three zones on the basis of the mineral assemblage. The upper zone, rich in hornblende-bearing tuff, is defined from YK-3 to the top of the sequence (Table 1). Biotite-rich tuff and cummingtonite-bearing tuff occur locally in the zone. Modal proportion of hornblende exceeds more than 50% in some tuffs and is maximum around 90. The middle zone is composed mainly of pyroxene tuff. Hornblende occurs only in thin white tuff layers. The lower zone, also rich in hornblende-bearing tuff, is defined from the bottom to YK11-4. Modal proportion of hornblende is mostly less than 50%. The zone is characterized by cummingtonite-rich tuffs; Kd38 and YK14.

Cummingtonite was observed only in hornblende-bearing tuff. It is usually small in amount in the upper zone, whereas close to 90% in the lower zone. Biotite is abundant in Kd24 tuff and is rarely observed in the other tuff. It is not found in the middle and lower zones.

Although modal proportions of the heavy minerals are sometimes variable within a thick tuff layer (Yokoyama *et al.*, 1997; Table 1 in this paper), all samples from

Table 1. Modal proportions of mafic minerals and chemical compositions of orthopyroxenes in the tuffs from the Kiwada Formation.

		Modal proportion					Chemical compositon of opx, 100xMg/(Mg+Fe)																						
sample	size	opx	cum	cpx	hb	bi	80	78	76	74	72	70	68	66	64	62	60	58	56	54	52	50	48	46	44	42	40	38	
Kd23-a	B	61		39						2	1		1	15	21	4													upper zone
Kd 23-1U	B	52		48							3	1	2	9	14	6		1											
Kd23-1	B	63		37							1	1	2	14	20	1	1												
Kd23-2	B	47		52	0.5				1		2	7	6	3	4		2	1	1			3	3	2		3			
Kd23-3	B	63		38									2	17	19	2													
Kd 23-1L	B	56		44						1	3	1	2	11	12	4	1	3											
Kd23-b	B+C	52		30	18							3	1	10	31	14	3	1											
Kd23-4	B	62		38								1	7	21	7														
Kd23-5	B+C	33	0.6	12	54				1	2	1	8	4	9	4	5	1												
Kd23-F1	B	36		64				1		2	4	2	5	5	2	1	1				1			1	3	4	3	1	
Kd23-F2	B	31		69						1	5	14	10	2	1	3	1						1						
Kd23-E	B	31			69						1	19	18		1	1													
Kd23-D	B	11		1.7	87								5	30	2	1													
Kd23-C	B+C	60	7.4	18	14	0.7				1			3	10	6	5	5		1						1				
Kd23-B	B	60		40									6	22	11														
Kd23-A	B	60		40									3	15	19	3													
Kd23-A1	B	66		33	0.7	0.7						1	7	16	8	4	3												
Kd23-A2	B	73		27											12	26													
Kd24-1	B	21	1.5	24	2.3	51				1	2	3	13	13	2	1	1												
Kd24-2	B	3.8	0.4	0.8	4.6	90				2	1	5	7	7	4														
Kd24-3	BC	30		16	1.6	53						1	17	10	2														
Kd24-4	B	2.4		3.8	2.1	92				1	1	1	7	6	1														
Kd25-4	B	51		25	24					1	3		2	7	7	3	3	2	2		1		1		1				
Kd25-4	C	37		14	49					1		2	6	7	7	8	5	2	1				1						
Kd25-4	D			14	86																								
YK-1	B	57		43						2	1	1	2	8	19	6	1												
YK1-1	B	53		45	2.1					1	3	3	4	9	5	6	2	3	1	2	3								
YK-2	B	41		59						2	5	3	4	5				1	2	1	8	5	3						
YK-3	C	18	1.2	23	58					2	2	3	3	16	9	1	1				1								
YK3-1	B	16		84						10	20	8	4	2		1													middle zone
YK3-2	B	46		54							2	3	2	12	16	8		2											
YK3-3	B	28		72						3	5	3	2	9	19	3													
YK3-4	B	32		68						1	2	5	6	5	20	3	1												
YK3-5	B	48		52						1	2	6	8	6	11	9													
YK3-6	B	45		55						6	17	9	6	5	1														
YK3-7	B	40		60								1	1	5	11	20	5		1										
YK3-8	B	25		75																									
YK3-9	B	65		35									1		1	1			4	25	9	1							
YK3-10	B	48		52						2			2	1		2		5	8	13	9	1							
YK-4	B	32		68								3	3	24	8	1					1								
YK4-1	B	54		42	3.8				1	1				5	30	4	1			1									
YK4-2	B	63		35	1.9				1					4	12	7	1	1					15						
YK-5	B	60		40									1	7	27	4	1												
YK4-3	B	49		51									3	11	28	2	1												
YK4-4	B	46		54						3	29	5	2	2	2			1											
YK4-5	B	30		70						4	25	8	1	1		1													
YK4-6	B	7		16	78					7	8	5	8	5	6								1						
YK4-7	B	32		68							12	14	7	6	3	2	1												
YK4-8	B	33		67							12	18	3	1	3	1													
YK4-9	B	29		71							12	14	2	7	1	2													
YK4-10	B	50		50						1	2	5	10	13	7	2													
YK4-11	B	61		39					2	14	4	2	4	4	3	1		1			2	1							
YK4-12	B	70		30					3	12	5	1	1	2	3	2	1		2	3	2	1	1						
YK4-13	B	54		46					1	7	9	4	2			1	1	3	1	3	1	5	1						
YK4-14	B	49		51								3	2	7	30	2													
YK-6	B	56		44							1	1	2	23	13														
YK-7	B	53		47									4	21	13	2													
YK7-1	B	15		85						5	26	9	4	2	2														
YK7-2	B	44		56							5	16	5	3	4	2	1		1	1									
YK7-3	B	30		70							13	20	3		2														
YK7-4	B	32		68							13	10	6	7	3														

Table 1. (Continued)

		Modal proportion					Chemical compositon of opx, 100xMg/(Mg+Fe)																						
sample	size	opx	cum	cpx	hb	bi	80	78	76	74	72	70	68	66	64	62	60	58	56	54	52	50	48	46	44	42	40	38	
YK7-5	B	54		46						1	2	7	5	14	9	1			1										middle zone
YK7-6	B	72		28						10	10	1	1	2	2		2		2	3	2	2	2						
YK7-7	B	58		42					1	14	7	6			1	1	1	1	5	2									
YK7-8	B	56		44									1	8	25	1		1											
YK-8	B	47		53								2	7	23	7	1													
YK-9	B	51		49							2	3	4	3	2	25	1												
YK9-1	B	19		81						1	19	5	3	8	8	1													
YK9-2	B	32		68							11	9	14	4	1	2	1	1				1							
YK9-3	B+C	65		35						2	2	6	6	6	10	8	2												
YK9-4	B	37		63						1	2	14	4	3	3	20	6	5	4										
YK9-5	B	39		61						2	4	12	15	2	3	1	1	2	1					1					
YK9-6	B	22		78							9	4	3	3	2	6													
YK9-7U	B	41		59							10	8	3	8	10	3	1	1											
YK9-7L	B	31		69							13	16	4	3	9														
YK9-8	B	42		58								3	18	16	7		1												
YK-10	B	61		39											1	10	14	14	1										
YK10-1	B	70		30								2	7	17	16	1													
YK10-2U	B	74		26									1	20	22														
YK10-2L	B	65		35										23	17	3	1												
YK10-2a	B	65		35										25	16	2													
YK10-2b	B	49		51											9	34													
YK10-3	B	39		61							1	3	10	12	15	4													
YK10-4	B	49		51								1		3	25	14													
YK10-5	B	61		39								2	1	4	27	6	1	1											
YK-11	B	70		30						2			1		2	6	15	13	1										
YK11-1	B	30		70							4	11	9	9	2	7	1	1											
YK11-2	B	45		55								1	1	1	25	13													
YK11-3	B	58		42										2	39	3													
YK11-4	B	69		15	16							1	1	24	18	1													lower zone
YK11-5	B	81		19								1	1			2	5	21	13	1	1								
YK11-6	B	54		46	0.5								3	13	27			1											
YK11-7	B	71		29							1	2	2	3	5	2	1	6	17	4									
YK11-8	B	72		27	1.4							3	10	19	8	1	1			1									
YK-12	B	69		31									1		6	23	9			1									
Yo6/1	B	51		46	2.6						2	2	3	8	17	4	4												
YK-13	B	45		52	3.1				1		5	6	10	7	5	2	1	2	1										
Yo5	B	68		31	1.4					1	3	3	3	18	14	2				1									
Yo4	B	32		18	51					1		2	2	8	6	24	2												
YK-14	B	20	55	18	6.8						1		5	4	1														
Yo3	B	57	4.3	36	1.9					1		1	5	18	13	3			1										
Yo2	B	54	12	26	8.6						1	4	5	16	9	1		1											
YK-15	B	53		9.5	38								2	1	2	7	28												
Yo1	B	67		33					1			3	16	19	2	1													
Kd38-1	A	53	13	15	19					1		1		13	9	7				1									
Kd38-1	B	49	18	17	16					1	1	2		13	11		1												
Kd38-1	C	58	8.5	26	7.1					1	1			27	6														
Kd38-4	A	51	22	6.2	21					1		1		8	17	1													
Kd38-4	B	41	33	6.5	20						1		2	4	11	1	1				1								
Kd38-4	C	26	44	12	18						1			10	3		1												
Kd38-6	A	12	58	22	7.4					4	3																		
Kd38-6	B	2.6	85	4.3	7.8				1																				
Kd38-6	C	2.9	86	1.4	10							1																	
YK-16	B	19		9.4	72							2	2	17	19														
YK16-1	B	63		24	13							4	6	16	16	2	1												
YK16-2	B	67		33	0.7							4	19	16	4	1			1										

Abbrev. opx: orthopyroxene, cpx: clinopyroxene, cum: cummingtonite, hb: calcic amphibole, bi: biotite. Grain size A: 0.5–0.25 mm, B: 0.25–0.125. C: 0.125–0.063, D: <0.063.

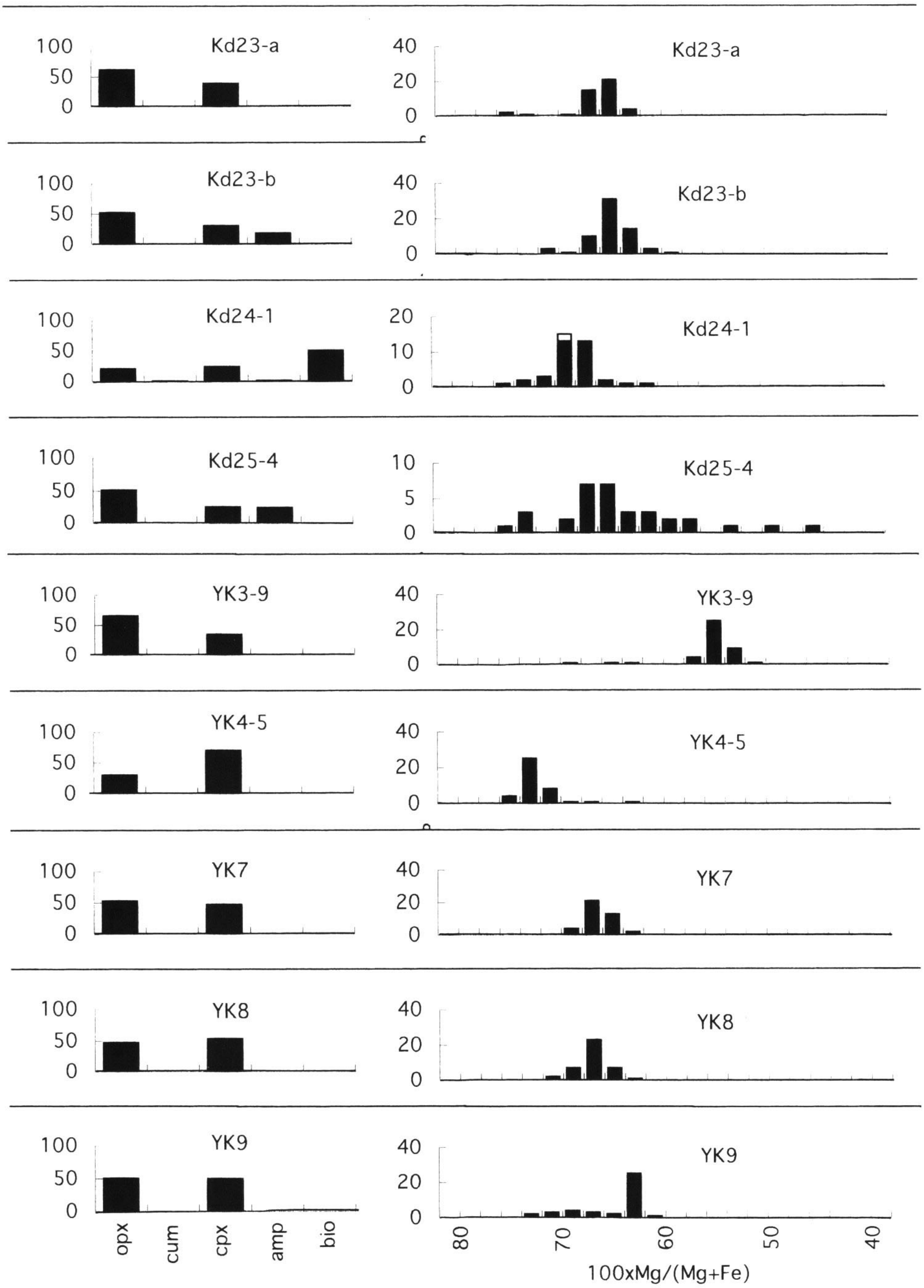

Fig. 4. Histograms of modal proportions of mafic minerals and chemical compositions of orthopyroxene (solid) and cummingtonite (open) in thick tuff layers. Abbreviation of minerals are in the Table 1.

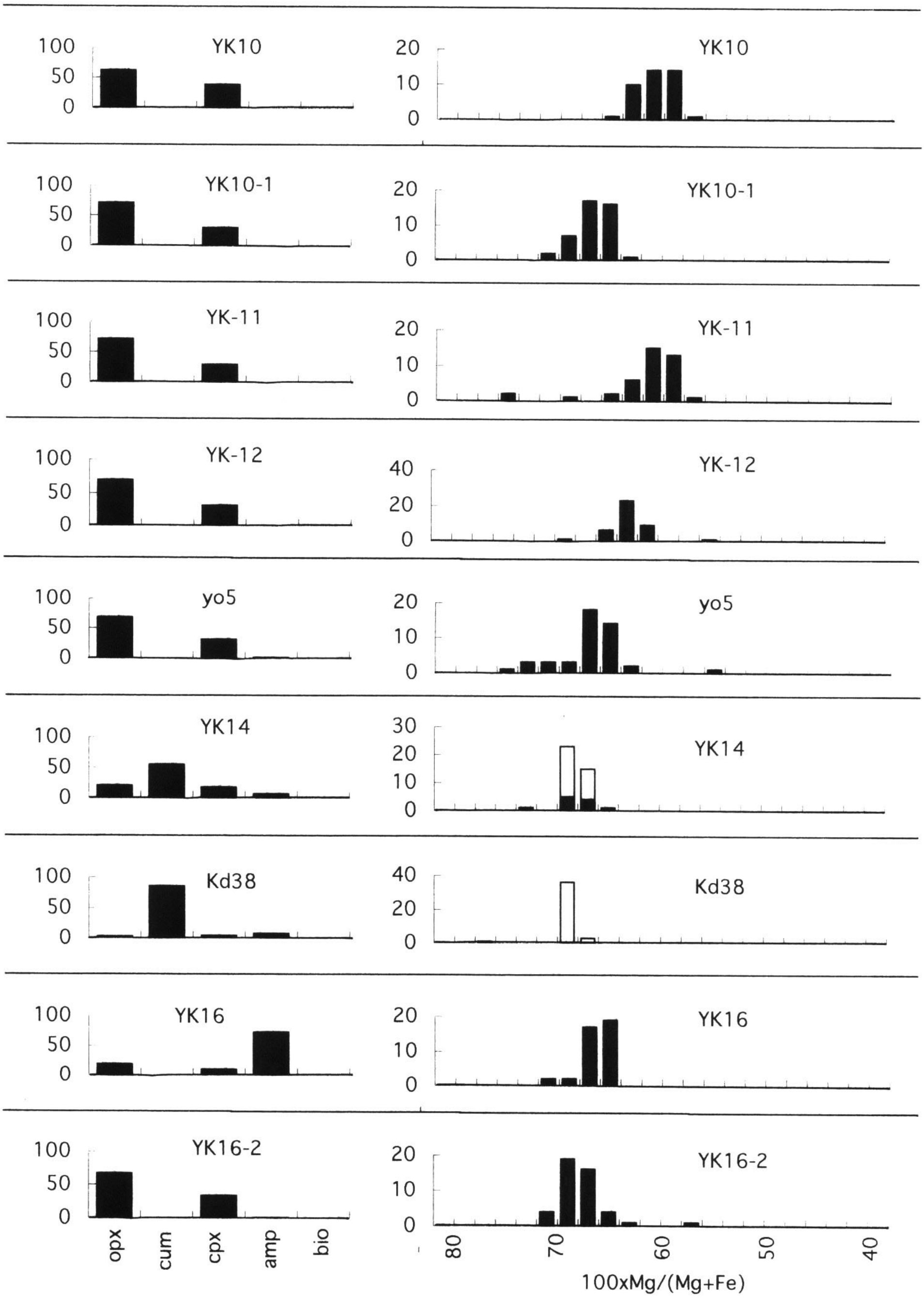

Fig. 4. (Continued)

the Kd24 tuff contain biotite abundantly. Furthermore, many samples from Kd38 tuff and also their fractions separated by grain size always include cummingtonite. As such specific minerals are not common, they can be used as a correlation in the series of the tuffs from the Kiwada Formation. In such a thick layer, one representative sample was selected from the many studied samples and is shown in Fig. 4.

Compositional Variation of Orthopyroxene

Orthopyroxene is almost always present in the tuffs from the sequence in the Kiwada Formation (Table 1). It is present mostly as an euhedral grain and is less weathered material than glass. Plagioclase and clinopyroxene are also major phases among the minerals in the tuffs. The former displays usually strong oscillatory zoning and the latter has more complex chemistry than orthopyroxene. Hence, they were not targeted in this study. The difference of X_{Mg}, $100\times Mg/(Mg+Fe)$, in orthopyroxene between core and rim is studied in detail (Yokoyama *et al.*, 1997). As the difference is mostly less than 2 mole% in X_{Mg}, we analyze a central part of the randomly cut grain.

X_{Mg} ratio of orthopyroxene in the tuff varies from 38 to 78 in the tuffs studied (Table 1). It is more or less variable even in each tuff and bimodal distribution is common. These characteristics are mainly due to mixing of essential, accessary and accidental fragments at the eruption. Even though such variations are recognized, there is commonly a peak of X_{Mg} ratio in each tuff (Table 1 and Fig. 4). The orthopyroxenes with the peak X_{Mg} ratio were probably derived as essential materials. The peak composition or bimodal nature may be used as a correlation factor of tuff. As shown in Fig. 4 where data of only thick tuff layers are plotted, each tuff has specific peak or compositional variation. The peak position varies from 55 to 72. Hence, the factor is useful as far as the thick tuff layers are concerned and the tuffs from a restricted areas are compared. More characteristic features is observed in a thin tuff, YK4-2, which is clearly bimodal with peak compositions of 64 and 48. The most Fe-rich orthopyroxene with peak positions of 26 is observed at the other area in the Boso Peninsula (Yokoyama *et al.*,1997).

Cummingtonite is rather narrow compositional variation compared with orthopyroxene. Its X_{Mg} ratio in the Kd38 and YK14 tuffs from the lower zone is from 66 to 70. Whereas it is 52 in the cummingtonite-rich tuff, Kd23-C, from the upper zone. The difference is also available in a detailed correlation of the tuffs.

Summary

Tuff has been used as a key bed in a sequence of the Boso Peninsula where numerous tuff layers are intercalated. Modal proportion of heavy mineral is one of the indicators for the correlations of the tuff layers. However, its variation within a tuff layer is often significant. It will be due to mixing of essential, accidental and accessary fragment at the eruption in addition to sedimentary processes such as graded bedding, cross lamina and reworking. Furthermore, the mixing and processes induced complex variation in mineral composition within a tuff (Yokoyama *et al.*, 1997).

Although relative proportions among the minerals with similar density were analysed in this paper, mineral assemblage is rather available for comparison of tuffs. The studied sequence, lower part of the Kiwada Formation, is divided into three zones based on the assemblage. The upper zone is rich in hornblende-bearing tuff. Biotite-rich tuff and cummingtonite-bearing tuff occur locally in the zone. The middle zone is composed mainly of pyroxnene tuff. Hornblende occurs only in thin white tuff layers. The lower zone is also rich in hornblende-bearing tuff. The zone is characterized by cummingtonite-rich tuffs; Kd38 and YK14. The division will be available as a first step for comparison of tuffs in the Boso Peninsula referring the lithological work.

As a subsequent factor for the comparison, X_{Mg} value of orthopyroxene is useful. Compositional range of X_{Mg} in each tuff is mostly too wide to use as a correlation factor. Peak position of X_{Mg} ratio, however, varies from 55 to 72 in thick tuff layers, and some tuffs have characteristic peak positions. Bimodal distribution of the X_{Mg} value in some tuffs will also support the comparison of the tuffs. The Plio-Pleistocene boundary is around Kd38 (Takayama *et al.*, 1995) which is the most characteristic tuff in the lower zone of the studied sequence. Hence, the methods of identification of tuffs around the Kd38 have become increasingly sophisticated. Although some tuffs have similar modal proportions of heavy minerals and peak X_{Mg} ratios of orthopyroxenes, accurate and reliable correlations of the tuffs around the boundary in the Boso Peninsula should be made by comparisons of the assemblage of heavy minerals, chemical composition of orthopyroxene and lithological work.

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