IDENTIFICATION OF THREE EARLY PLEISTOCENE TEPHRAS IN AND AROUND THE WEST PART OF THE MUSASHINO UPLAND, TOKYO, NORTHEAST JAPAN

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Abstract In and around the west part of the Musashino Upland, southwest of the Kanto Tectonic Basin, Ob4b-4 (1.62 Ma), Ob4b-1 (1.63 Ma), and Ob3 (1.71–1.78 Ma) tephras in the Kazusa Group, early Quaternary strata, were identified by using characteristic properties such as chemical composition of volcanic glass shards and titanomagnetite, and refractive indices of glass shards, hornblende, cummingtonite, and orthopyroxene. Changes in altitudes of Ob4b-1 identified in four cores and at three outcrops together with those by previous studies indicate geological structure of the Kazusa Group, revealing a gentle northeastward sloping with a gradient of 15/1000 and a prominent discontinuity of the strata along the Tachikawa Fault Zone.

Key words: Kanto Tectonic Basin, Tokyo, Early Pleistocene, tephra, Tachikawa Fault Zone

1. Introduction

The Kanto Tectonic Basin (KTB) (Fig. 1), the largest plain in the Japanese Islands, is originated from a paleo-forearc basin formed mainly by the subduction of the Philippine Sea Plate beneath the North American Plate (Kaizuka 1987). The Kazusa Group composed of early Quaternary marine and fluvial strata fills this paleo-forearc basin. In order to establish the chronology of the development of KTB, combination of chronological framework and reconstruction of changes in depositional environment of the Kazusa Group should be clarified. Recently, Lower and Middle Pleistocene tephrostratigraphical studies in KTB had advanced resulting in providing precise datum planes within the Kazusa Group (e.g. Fujioka and Kameo 2004; Suzuki and Murata 2011; Suzuki *et al*. 2011). Tephrochronological studies also play a significant role to establish the history of local tectonic movement such as active faulting. The Tachikawa Fault Zone (TFZ) crossing the southwest part of KTB (Fig. 1) had been recognized as an active reverse fault with a NW-SE trend and uplift of the northeast side (Yamazaki 1978). Tephrochronological examination on the Quaternary sediments along TFZ had revealed its activity throughout Quaternary, suggesting no cumulative deformation of the strata between the depositions of the Sayama Glassy Ash (SYG; 1.71–1.76 Ma) (Shoda *et al*. 2005; Suzuki *et al*. 2011) and the Hakonegasaki Tephra Group (ca. 2.0 Ma) (Suzuki *et al*. 2008, 2011). This indicates that TFZ was not active during the period from 2.0 to 1.7 Ma.

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Recently, in the survey of *Integrated Research Project for the Tachikawa Fault Zone* (2012-2014) supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT), we conducted two all-core boring surveys (TC-12-1 and TC-13-1) at Enoki, Musashi-murayama, in 2012 and 2013 (Fig. 1). As reported by MEXT and Earthquake Research Institute, the University of Tokyo (ERI) (2015), three Early Pleistocene tephras (1.62 Ma to 1.71-1.78 Ma) were found. This paper describes these tephras together with their correlative tephras in and around the west part of the Musashino Upland, southwest of KTB.

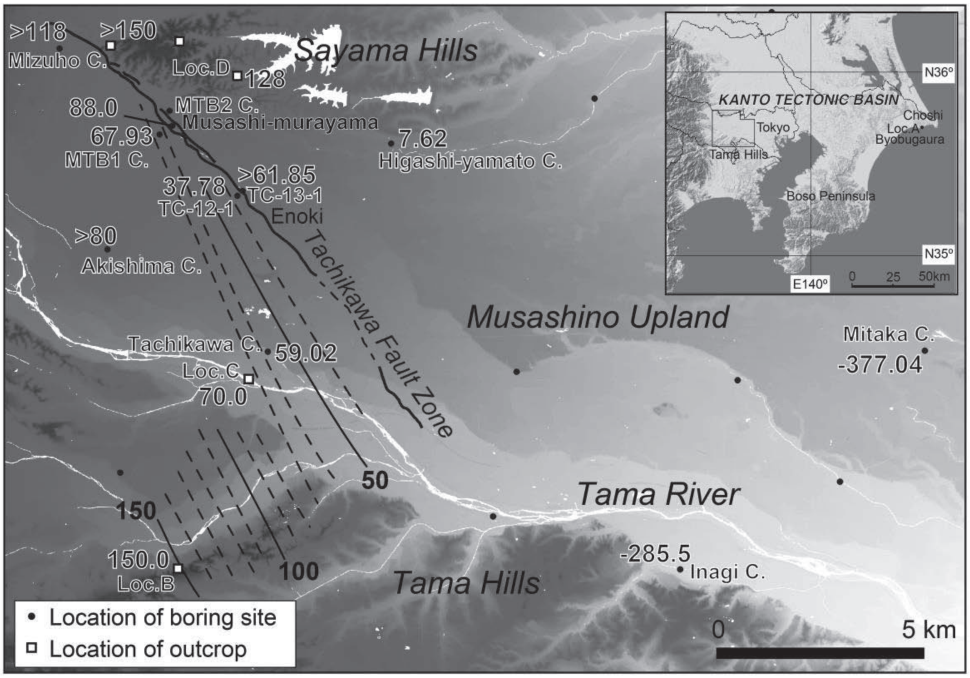

Fig. 1 Map showing boring sites, outcrops and altitude of Ob4b-1.

2. Description and Correlation of Tephras in TC-12-1 and TC-13-1 Cores

TC-12-1 Core

An all-core boring of TC-12-1 (N35°44'14.3", E139°23'15.4"; 100.67 m a.s.l.) with a length of 95 m in the downward side of TFZ was carried out on the southwestern bottom of the Enoki trench excaved for the fault survey. Sediments with a depth 0 to 28.70 m are composed of cobbles, equivalent to the fluvial terrace deposits of the Tachikawa 2 Formation and middle Pleistocene buried fluvial deposits of the Ome Formation (Ueki and Sakai 2007) (Fig. 2). Sediments with a depth 28.70 to 95.00 m are composed of an alternation of gravel, sand, and silt, and are correlative to the Kazusa Group. In silt and sand sediments with a depth of 58.12-64.61 m, tephric layers repeatedly occurred. Most of these layers contain rounded pumice clasts, indicating their sedimentations as reworked tephra. On the other hands, two pumice layers positioned at the depths of 61.82–61.85 m (TC-12-6185) and 62.42–62.89 m (TC-12-6289) are recognized as primary fall-out tephra layers.

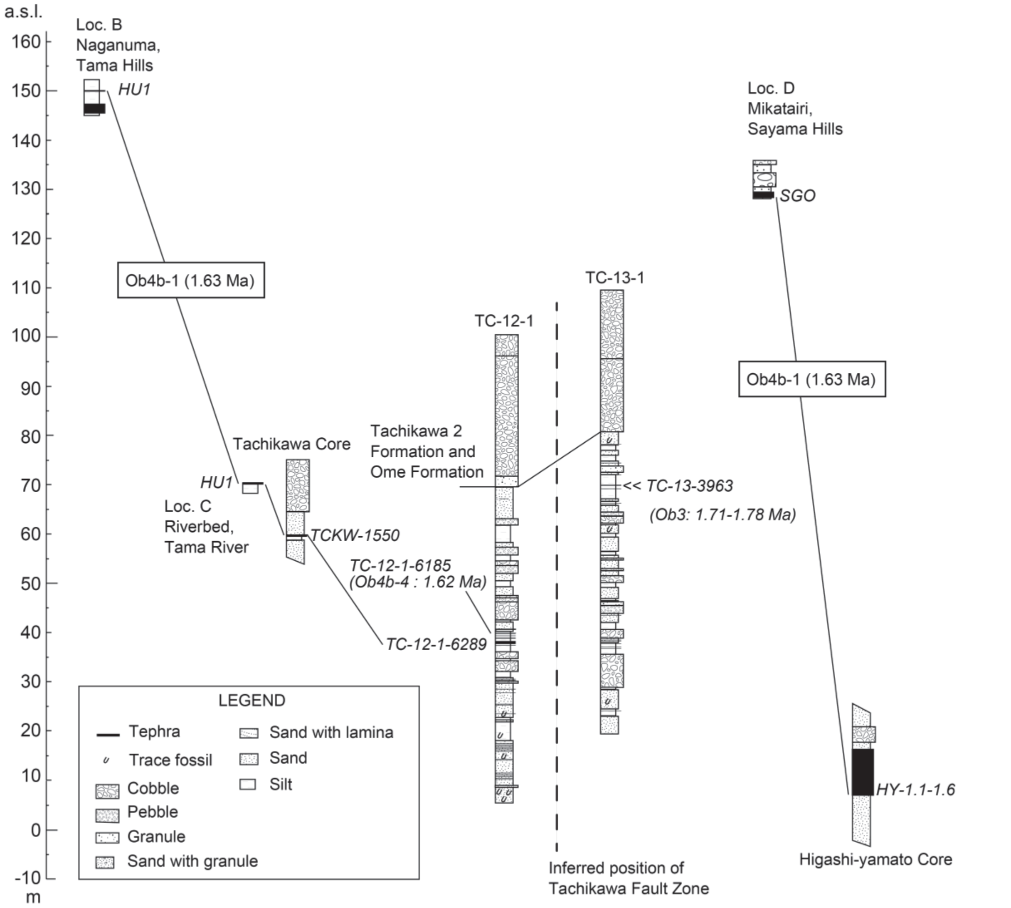

Fig. 2 Lithological columnar sections of the Kazusa Group at the boring sites and outcrops where Ob4b-4, Ob4b-1, and Ob3 are found.

TC-12-6185 is a white pumice fall deposit (3 cm in thickness) composed of fine pumice clasts with diameters less than 3 mm. It contains abundant hornblende with refractive indices (n_2) of 1.667-1.685 and volcanic glass shards of sponge type (Table 1). The properties of volcanic glass shards such as refractive indices (n) and chemical compositions of major elements (mean weight %) are 1.509–1.511 and SiO_2: 74.6 wt.%, Al_2O_3: 14.5 wt.%, FeO: 1.7 wt.%, CaO: 2.4 wt.%, and K_2O: 2.1 wt.%, respectively.

TC-12-6289, ca. 60 cm below TC-12-6185, is a pumice fall deposit (47 cm in thickness) composed of weathered white pumice clasts with maximum grain diameter of 8 mm. This tephra is characterized by abundant mafic mineral such as hornblende, titanomagnetite, orthopyroxene, and cummingtonite. Refractive indices of hornblende (n_2), cummingtonite (n_2), and orthopyroxene (γ) are 1.668–1.676, 1.658–1.661, and 1.703–1.708, respectively.

Table 1 Petrographic properties of tephra layers

(1) Tephra Alititude (above sea level) of tephra base detected in core is shown in italic: m	(2) Reference	(3) Locality or depth of base in core: m	(4) Thickness: cm	(5) Max. grain size: mm	(6) Composition Shape of glass shards Mineral	(7) Refractive index gl: glass (n) cum: cummingtonite (n_2)	ho: hornblende (n_2) opx: orthopyroxene (γ) N: measured by E. Nakajima
Byobugaura Ob4b-4	a						
Ob4b-4		A	3	2	spg ho>mt,opx	gl:1.509-1.512	ho:1.680-1.689
TC-12-6185 TC-12-1 Core: *38.85-38.82*		- 61.85	3	3	spg ho,mt	gl:1.509-1.511	ho: 1.667-1.685
Byobugaura Ob4b-1	a						
Ob4b-1		A	25	20	spg ho>opx,mt>>cum	gl:1.504-1.507 cum:1.657-1.661 (N)	ho:1.668-1.676 opx:1.702-1.707
Horinouchi 1st (HU1)	b						
Naganuma Park, Hachioji, Tokyo		B	12	70	spg ho,mt>cum	gl:1.505-1.507 cum:1.656-1.661	ho:1.666-1.673 opx:1.702-1.706
River Bed of the Tama River, Hino, Tokyo		C	>35	70	spg, fib ho>mt>cum>opx	gl:1.504-1.509 (N) cum:1.657-1.663 (N)	ho:1.667-1.673 (N) opx:1.701-1.707 (N)
Sayama Gomashio (SGO)	c						
Mikatairi, Tokorozawa, Saitama (Sayama Hills)		D	100	20	gl: weathered ho,mt>cum(bi,qt)	gl: weathered cum:1.654-1.659 (N)	ho:1.666-1.671 (N)
TC-12-6289 TC-12-1 Core: *37.78*		62.89	47	8	gl: weathered ho>mt>cum>opx	gl: weathered cum: 1.658-1.661	ho:1.668-1.676 opx:1.703-1.708
TCKW-1550: Tachikawa Core: *59.02*		15.5	25	15	gl: weathered ho,mt>>cum,opx	gl: weathered cum:1.658-1.660	ho:1.668-1.674 opx:1.703-1.709
HY-1.1-1.6 (HY-1.6) Higashi-yamato Core: *7.62*		89.7	970 rework	15	spg ho≥opx,mt>cum	gl: 1.505-1.507	ho:1.666-1.671 opx: 1.701-1.706
Byobugaura Ob3	d						
Ob-3		A	1	—	bi,opx,cpx,ho	gl:1.506-1.508	opx: 1.724-1.727
TC-13-3963 (39.50-39.63) TC-13-1 Core: *69.87*		39.63	13		spg,fib(str) opx≥cpx>mt	gl:1.506-1.508	opx: 1.724-1.727

(1) Name by previous study in (2) is shown in Italic. (2) Reference, a: Suzuki and Murata (2011), b: Takano (1994), c: Taura *et al.* (2004), d: Sakai (1990) (3) Localities are shown in Fig 1. (6) opx: orthopyroxene, cpx: clinopyroxene, ho: hornblende, cum: cummingtonite, bi: biotite, qt: quartz, type of glass shards, fib: fiber type, str: stripe type, spg: sponge type (7) Determined with RIMS2000.

Combinations of the recognition of SYG (1.71–1.76 Ma) at 24.17 m a.s.l. in the MTB-1 Core (Fig. 1; Suzuki *et al*. 2008) in the downward side of TFZ, and characteristic properties and depth of TC-12-6185 and TC-12-6289 (37.78–38.85 m a.s.l.) in the downward side suggest that TC-12-6185 and TC-12-6289 can be correlated with Ob4b-4 (1.62 Ma) and Ob4b-1 (1.63 Ma) defined by Suzuki and Murata (2011) in the Obama Formation of Inubo Group at Byobugaura, the east end of KTB (Loc. A; Fig. 1).

TC-13-1 Core

An all-core boring of TC-13-1 with a length of 90 m was carried out at 109.50 m a.s.l., ca. 300 m northeast of TFZ in the upward side. Sediments with a depth 0 to 28.65 m are composed of cobbles equivalent to the fluvial terrace deposits of the Tachikawa 2 Formation and the Ome Formation. Sediments with a depth of 28.65 to 90.00 m is composed of an alternation of gravel, sand, and silt, and five cycles of sedimentation composed of upper consolidated silt and lower gravel bed were recognized. At the depth of 39.50–39.63 m (69.87 m a.s.l.), a pink to purple coloured vitric ash tephra layer (TC-13-3963) with normal grading exists. TC-13-3963 contains orthopyroxene, clinopyroxene, titanomagnetite, and volcanic glass shards of sponge and fiber type. Refractive indices of glass shards (n) and orthopyroxene (γ) are 1.506–1.508 and 1.724–1.727, respectively. Chemical compositions of major elements (mean weight %) of volcanic glass shards are SiO_2: 75.3 wt.%, Al_2O_3: 13.3 wt.%, FeO: 1.9 wt.%, CaO: 1.4 wt.%, K_2O: 4.0 wt.%, and Na_2O: 3.4 wt.%. Cumulative displacement of early Pleistocene tephras shown by Suzuki *et al*. (2008) around the area, ca. 3 km northwest of TC-13-1 site, and identifications of Ob4b-4 (1.62 Ma) and Ob4b-1 (1.63 Ma) at the altitude of 37.78–38.85 m a.s.l. in TC-12-1 Core (downward side) suggest that the age of TC-13-3963 is most likely to be 1.6-2.0 Ma. We examined the candidate for correlative tephra of TC-13-3963 in the Inubo Group where tephras in the Kazusa Group have been ideally preserved and exposed, and found a similar tephra ca. 9 m below SYG (1.71–1.76 Ma). This tephra is Ob3 (Sakai 1990) above Ob2 correlated to Eb-Fukuda tephra (1.76–1.78 Ma) (Fujioka and Kameo 2004), suggesting that the age of Ob3 is 1.71–1.78 Ma. Characteristic properties of TC-13-3963 and Ob3 are similar, confirming their correlation (Tables 1 and 2).

Table 2 Chemical compositions of volcanic glass shards

Tephra	Chemical compositions of volcanic glass shards (wt.%)											
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	K_2O	Na_2O	Total		n
Byobugaura Ob4b-4												
Ob4b-4	74.7	0.3	14.5	1.6	0.2	0.6	2.4	2.1	3.7	100.0	92.4	16
	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.0	0.8	
TC-12-6185	74.6	0.3	14.5	1.7	0.1	0.6	2.4	2.1	3.6	100.0	91.7	16
38.85-38.82	0.4	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.0	0.9	
Byobugaura Ob4b-1												
Ob4b-1	76.8	0.3	13.2	1.4	0.1	0.5	1.9	2.4	3.4	100.0	93.3	17
	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.5	
Horinouchi 1st (HU1)												
Naganuma Park,	76.9	0.2	13.2	1.3	0.1	0.5	1.9	2.4	3.4	100.0	92.4	16
Hachioji, Tokyo	0.4	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	1.1	
River Bed of the Tama	76.5	0.3	13.3	1.6	0.1	0.5	2.0	2.3	3.4	100.0	93.2	16
River, Hino, Tokyo	0.4	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	1.3	
HY-1.1-1.6 (HY-1.6)	76.3	0.3	13.5	1.5	0.1	0.5	2.1	2.4	3.3	100.0	92.2	18
Higashi-yamato Core: *7.62*	0.4	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.0	1.5	
Byobugaura Ob3	75.2	0.3	13.3	1.9	0.1	0.3	1.4	4.0	3.4	100.0	92.9	16
Ob-3	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.4	
TC-13-3963 (39.50-39.63)	75.3	0.3	13.3	1.9	0.1	0.3	1.4	4.0	3.4	100.0	93.6	16
TC-13-1 Core: 69.87	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.4	

Recalculated to 100% on a volatile-free basis. All values are presented as a mean and standard deviation of n shard analyses. Determined by JSM-6390 and EDAX-Genesis APEX2 energy dispersive X-ray spectrometry using a 0.6 nA current at 15 kV. Detailed measurement condition is shown in Suzuki *et al.* (2014).

3. Ob4b-1 and its Correlative Tephra in and around the Musashino Upland

Ob4b-1 is correlative to the Horinouchi 1st tephra (HU1; Takano 1994) intercalated in the upper part of the Oyamada Formation, Kazusa Group, in the Tama Hills (Suzuki and Murata 2011), and also is recognized in four boring cores obtained at the Haginaka Park in Ota Ward, Mitaka, Inagi, and South Machida in and around the Musashino Upland (Suzuki *et al*. 2011; Suzuki and Murata 2011). In this study, we recognized Ob4b-1 in TC-12-1 Core, and examined the candidate tephra layers correlative to Ob4b-1 in other boring cores and exposures where the Kazusa Group is cropped out together with additional characteristic properties such as chemical composition of titanomagnetite. Chemical composition of titanomagnetite is useful for confirming correlation (Suzuki 2008), also applicable for not only newly found tephra layers but also for several ones already identified based on refractive indices and glass chemistry (Table 3).

Table 3 Chemical compositions of titanomagnetite in tephras

Tephra	Chemical composition of titanomagnetite (wt.%)											Ulvospinel basis				
	SiO_2	TiO_2	Al_2O_3	V_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	ZnO	Total	Fe_2O_3	FeO	Total	Usp. Mol. %	n
Byobugaura Ob4b-1																
Ob4b-1	0.2	5.6	2.7	0.6	0.3	82.9	0.7	1.5	0.1	0.9	95.4	55.1	33.3	100.9	16.3	12
	0.1	0.3	0.1	0.1	0.1	0.5	0.1	0.1	0.0	0.2	0.6	0.6	0.4	0.6	0.8	
Horinouchi 1st (HU1)																
River Bed of the Tama	0.2	5.4	2.5	0.6	0.4	82.7	0.7	1.5	0.1	0.9	95.0	55.1	33.1	100.5	16.0	14
River, Hino, Tokyo	0.1	0.3	0.1	0.1	0.1	0.6	0.1	0.1	0.0	0.2	0.6	0.7	0.4	0.7	0.9	
Sayama Gomashio (SGO)																
Mikatairi, Tokorozawa,	0.3	5.7	2.6	0.6	0.4	81.8	0.6	1.6	0.1	0.8	94.5	54.0	33.2	100.0	17.1	14
Saitama (Sayama Hills)	0.2	0.3	0.1	0.1	0.2	0.7	0.1	0.1	0.1	0.2	0.8	1.0	0.5	0.8	1.1	
TC-12-6289	0.2	5.7	2.7	0.5	0.2	83.0	0.6	1.7	0.1	0.9	95.7	55.1	33.5	101.2	16.7	7
TC-12-1 Core: *37.78*	0.1	0.2	0.1	0.2	0.2	1.2	0.1	0.1	0.0	0.2	1.0	1.0	0.5	1.1	0.6	
TCKW-1550:	0.3	5.5	2.6	0.7	0.5	82.0	0.6	1.6	0.1	0.9	94.7	54.3	33.2	100.1	16.7	9
Tachikawa Core: *59.02*	0.1	0.5	0.1	0.1	0.2	1.4	0.1	0.1	0.1	0.3	0.9	1.4	0.4	1.0	1.5	
HY-1.1-1.6 (HY-1.6)	0.2	5.8	2.4	0.6	0.2	81.1	0.8	1.5	0.1	1.0	93.7	53.7	32.8	99.1	17.3	10
Higashi-yamato Core: *7.62*	0.0	0.3	0.1	0.1	0.1	0.4	0.1	0.1	0.1	0.2	0.5	0.4	0.4	0.5	0.6	

All values are presented as a mean and standard deviation of n shard analyses. Determined by JSM-6390 and EDAX-Genesis APEX2 energy dispersive X-ray spectrometry using a 0.6 nA current at 15 kV. Detailed measurement condition is shown in Suzuki *et al.* (2014).

We newly identified Ob4b-1 in two cores (Tachikawa and Higashi-yamato Cores) and two locations (Fig. 1; C: Riverbed of the Tama River, D: Mikatairi in the Sayama Hills). At the depth of 15.25–15.50 m of the Tachikawa Core (N35°41'43.6", E139°23'44.9"; 74.52 m a.s.l.; Endo *et al.* 1978) obtained at Fujimi-cho, Tachikawa, a pumice fall deposit named TCKW-1550 with a thickness of 25 cm and a maximum grain size of 15 mm was found. Refractive indices of hornblende (n_2: 1.668–1.674), cummingtonite (n_2: 1.658–1.660), and orthopyroxene (γ: 1.703–1.709), and chemical compositions of titanomagnetite indicate that TCKW-1550 can be correlated to Ob4b-1. HY1.1-HY1.6 in the Higashi-yamato Core (N35°45'4.9", E139°25'44.3"; 97.32 m a.s.l.; Kawashima and Kawai 1977) at Narabashi, Higashi-yamato is a thick tephra layers with a thickness of 970 cm, probably composed of primary pumice fall deposits and reworked pumice clasts. Chemical composition and refractive indices of well-preserved volcanic glass shards in HY1.6 together with refractive indices of hornblende and orthopyroxene and chemical compositions of titanomagnetite indicate that HY1.1-HY1.6 can be correlated to Ob4b-1.

HU1 exposed at the riverbed of the Tama River (Loc. C) was already identified using its mineral assemblage and refractive index of glass shards (Research Group for Fossil Footprints from the Riverbed of Tamagawa 2002). This correlation was confirmed by refractive indices of volcanic glass shards, hornblende, cummingtonite, and orthopyroxene, and by chemical compositions of volcanic glass shards. Sayama Gomashio (SGO) intercalated in the Sayama Formation (Ueki and Sakai 2007) in the Sayama Hills is positioning above SYG (Taura *et al.* 2004). Although this tephra at Loc. D is a conspicuous tephra with a thickness of 100 cm composed of pumice clasts with a maximum grain size of 20 mm, glass shards and orthopyroxene had been disappeared by strong weathering. However, refractive indices of hornblende (n_2: 1.666–1.671) and cummingtonite (n_2: 1.654–1.659) and chemical compositions of titanomagnetite indicate that SGO can be correlated to Ob4b-1. Since SGO had been correlated to MTB1-9-10L tephra (54.38–56.08 m in depth) in the MTB1 Core and MM-8-8.2 tephra (35.75–36.36 m in depth) in the Musashi-murayama Core (Fig. 1; Suzuki *et al.* 2008), MTB1-9-10L and MM-8-8.2 are also correlated to Ob4b-1.

In the Higashi-yamato Core and Sayama Hills, Ob4b-1 are thicker than those of other areas. It is expected that the axis of its distribution stretches in the north part of the Musashino Upland, and that Ob4b-1 had reworked again and again after its primal deposition by the effect of wave action in shallow sea.

4. Discussion

In the west part of KTB where the west Musashino Upland, Sayama and Tama Hills are distributed, Ob4b-1 is recognized at ten locations. Altitudes of Ob4b-1 and possible minimum altitudes estimated by those of SYG older than Ob4b-1 are shown in Fig.1, showing general trend of a datum plane in the upper part of the Oyamada Formation in the Kazusa Group. The upper part of the Oyamada Formation including Ob4b-1is interpreted as a shore surface deposit (Takano 1994). Also, Nishida *et al.* (2014) concluded that the sedimentary facies indicating the sedimentary environments for the Oyamada Formation are fluvial, coastal, and shallow-marine facies. These studies suggest the change of initial altitudes of Ob4b-1 shows mostly flat and gentle tilting. Present changes in altitude of Ob4b-1 show a gentle northeastward sloping with a gradient of 15/1000. This trend is most likely caused by the crustal movement since its deposition. On the other hand, a prominent discontinuity of this general trend is noticeable along TFZ. It can be judged that this discontinuity was originated from the movement of the northeast uplifting of TFZ. Vertical displacement at Enoki is estimated to be at least 30 m because of the difference between Ob3 (69.87 m a.s.l.; upward side) and Ob4b-1 (37.78 m a.s.l.; downward side) in altitude. It is concordant with the previous study reported that the altitudes of SYG show northeast-side-up offset with an accumulated displacement of ca. 126 m, 3 km northwest of Enoki (Suzuki *et al*. 2008).

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