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A marker tephra bed close to the Lower-Middle Pleistocene boundary: Distribution of the Ontake-Byakubi Tephra Bed in central Japan

Yoshihiro Takeshita [a,*], Nobuyuki Matsushima [b], Hiroshi Teradaira [b], Takashi Uchiyama [c], Hisao Kumai [d]

[a] Institute of Education, Shinshu University, 6-ro, Nishinagano, Nagano 380-8544, Japan
[b] Nature Association of Ina Valley, 2-655-7, Ottemachi, Iida, Nagano 395-0034, Japan
[c] Mount Fuji Research Institute, Yamanashi Prefectural Government, 5597-1 Kenmarubi, Kamiyoshida, Fujiyoshida, Yamanashi 403-0005, Japan
[d] Osaka City University, 3-3-138 Sugimoto, Sumiyoshi, Osaka 558-8585, Japan

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ABSTRACT

Tephrochronology is an exceptionally important tool in the precise regional correlation of Early and Middle Pleistocene sedimentary strata in Japan. The present study reveals that the Yukawa tephra 5 (YUT5) derived from the Older Ontake volcano, the Nezumigawa (Nzg) and Mitamitajima (Mtj) tephras of the Ina Bazin, and the Byakubi-E tephra (Byk-E) of the Boso Peninsula are the same tephra on the basis of their lithofacies, bulk grain composition, mafic mineral composition, major element composition of hornblende, and stratigraphic relationships with the dated tephras. We propose to call the series of tephras correlated with Byk-E the Ontake-Byakubi Tephra Bed (On-Byk Tephra) following the naming convention in which the tephra name consists of the names of the source volcano and the type location. The Matuyama-Brunhes Chronozone boundary occurs just above Byk-E in the type section of the Kokumoto Formation in the Kazusa Group, which is a candidate Global Boundary Stratotype Section and Point (GSSP) for the lower boundary of the Middle Pleistocene Subseries. Therefore, On-Byk Tephra becomes a critically important marker tephra bed for the Early-Middle Pleistocene boundary in central Japan. The present study indicates that the major element composition of hornblende can be a useful tool for identification and correlation of strongly weathered tephra layers such as Nzg and Mtj in which all the volcanic glass shards have been altered.

1. Introduction

The Kazusa Group, which is widely distributed in the central part of the Boso Peninsula, is representative of Lower and Middle Pleistocene marine sediments in Japan. Comprehensive studies of the lithostratigraphy, biostratigraphy, magnetostratigraphy, and oxygen-isotope stratigraphy of this group have been carried out (Working Group for Quaternary Stratigraphy of Boso, 2009; Kazaoka et al., 2015). A continuous exposure of the Kokumoto Formation, middle part of the Kazusa Group, along the Yoro River, Chiba Prefecture, is a candidate Global Boundary Stratotype Section and Point (GSSP) for the lower boundary of the Middle Pleistocene Subseries (Head et al., 2008). The Kazusa Group contains numerous tephra layers, and the tephrostratigraphy is well constrained by many marker tephras (Mitsunashi et al., 1959, 1979; Satoguchi, 1995, 1996; Satoguchi and Nagahashi, 2012). Among the tephra layers, the Byakubi-E tephra (Byk-E: Kazaoka et al., 2015) in the middle part of the Kokumoto Formation, is intercalated approximately 1 m below the Matuyama–Brunhes Polarity Chronozone boundary (Kazaoka et al., 2015). Therefore, Byk-E has the potential to be an important regional marker tephra bed for the Lower-Middle Pleistocene boundary if its distributional area and characteristics for identification and correlation are clarified.

Takeshita et al. (2005) showed that Byk-E is correlated with either the Yukawa tephra 4 or 5 (YUT4 or YUT5) at the foot of Ontake volcano in central Japan, and showed that its source was the Older Ontake volcano. Byk-E has not been correlated, however, with tephra layers in any other locality. In this paper, we show that the Minamitajima (Mtj) and Nezumigawa (Nzg) tephras in the Ina basin, which lies between the Boso Peninsula and the Older Ontake volcano, correlate with Byk-E. This correlation confirms that Byk-E was erupted from the Older Ontake volcano. Furthermore, we show

* Corresponding author.
E-mail address: takey@shinshu-u.ac.jp (Y. Takeshita).

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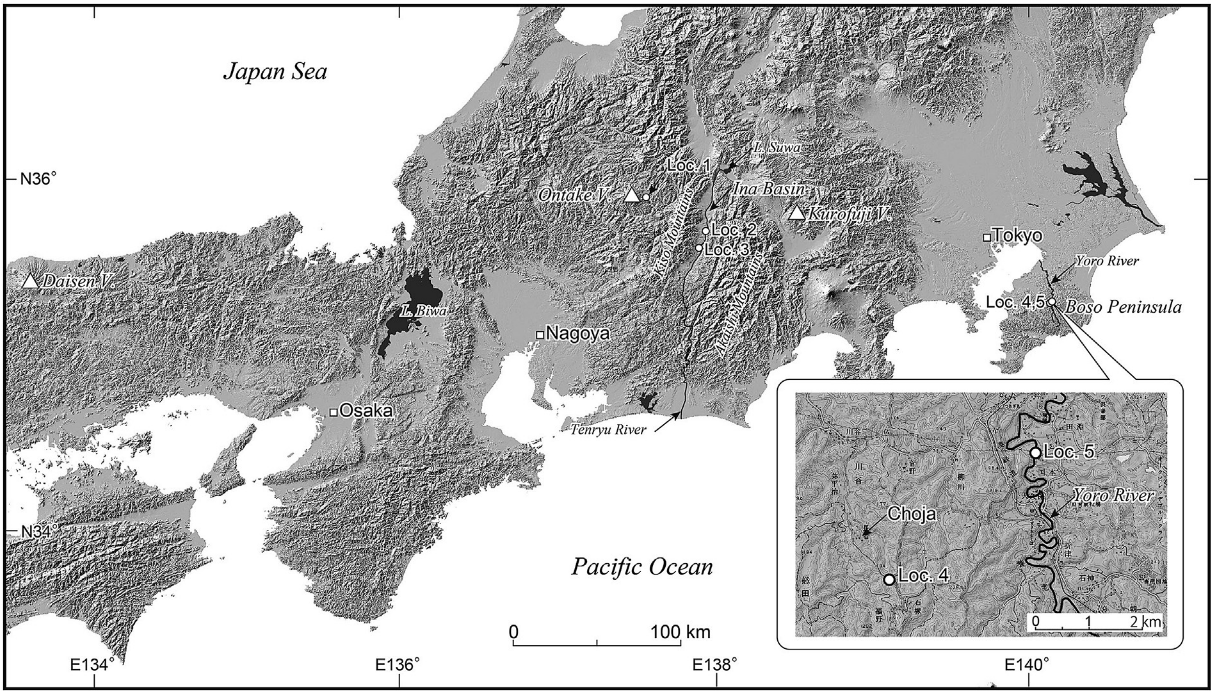

Fig. 1. Locations of the outcrops where the tephras YUT4, YUT5, Nzg, Mtj, and Byk-E have been identified. The Locality (Loc.) numbers correspond to those of the stratigraphic columns shown in Fig. 3. The relief map was produced by Kashmir 3D using the 50 m mesh DEM data published by the Geospatial information Authority of Japan.

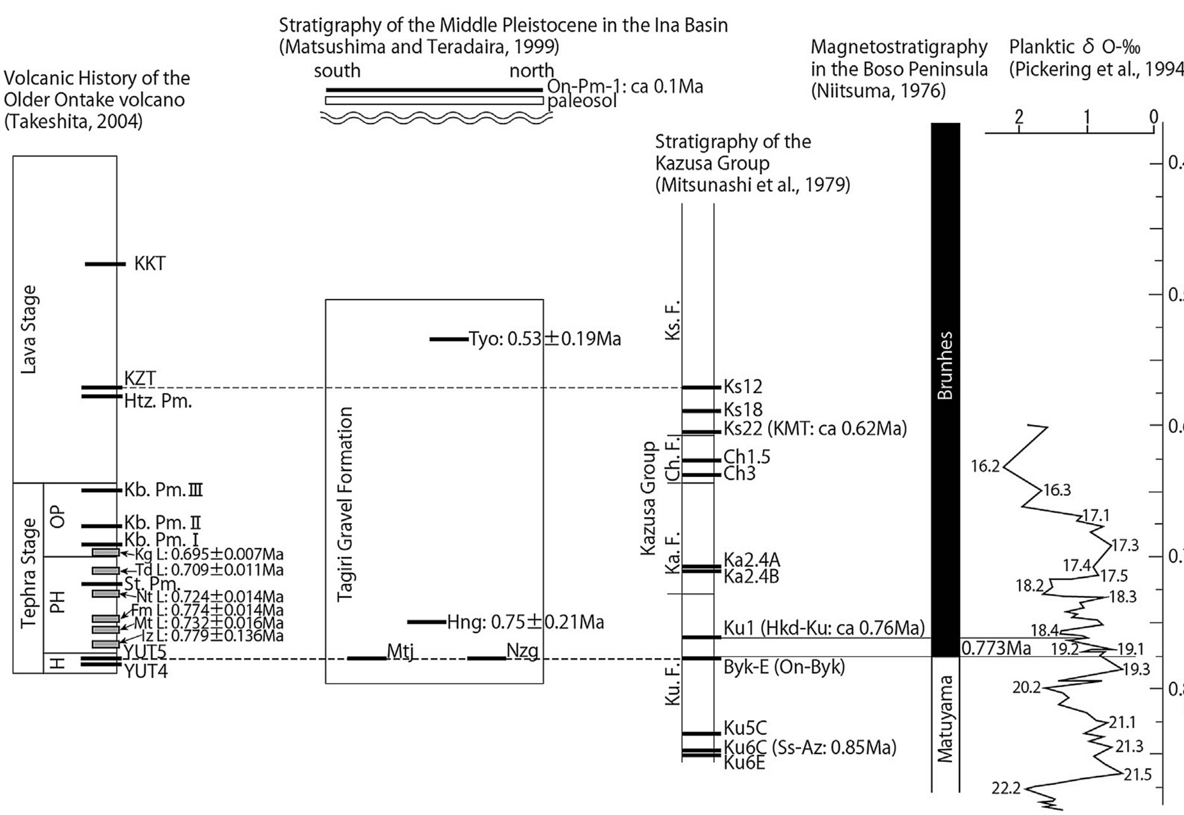

Fig. 2. Stratigraphic summaries of the Kazusa Group, the Tagiri Gravel Formation, and the Older Ontake volcano, along with magnetostratigraphy of the Boso Peninsula and MIS stratigraphy based on $\delta^{18}O$ in plankton. The correlation of KZT (Older Ontake volcano) with Ks12 (Kazusa Group) is after Takeshita et al. (2005). The ages of Ku6C (Ss-Az), Ku1 (Hkd-Ku), Ks12 (KMT), and On-Pm-1 are after Satoguchi and Nagahashi (2012), Suzuki et al. (2005), Suzuki (2008), and Machida and Arai (2003), respectively. The fission-track ages of the Tyo and Hng tephras are after Matsushima and Teradaira (1990). K–Ar age of lavas in the Older Ontake volcano are after Kioka et al. (1998). The Matuyama–Brunhes boundary age in the polarity column shows the average boundary age reported in Channell et al. (2010). Iz L, Iwaizawa lava; Mt L, Mitake lava; Fm L, Futamatazawa lava; Nt L, Nakatani lava; Td L, Taishoudaki lava; Kg L, Kuragoe lava; St. Pm., Satomiya Pumice; Kb. Pm. I–III, Kanbara Pumice I–III; Htz. Pm., Hottarusawa Pumice; KZT, Kamiurazawa tephra; KKT, Kamikurosawa tephra; H, Substage H; PH, Substage PH; OP, Substage OP; Ku, Kokumoto; Ka, Kakinokidai; Ch, Chonan; Ks, Kasamori; F, Formation.

that Byk-E is correlated with YUT5, not YUT4. Here, we propose to call the series of tephras that correlate with Byk-E the Ontake-Byakubi tephra (On-Byk).

2. Geological settings of the tephras

2.1. Yukawa tephra 4 (YUT4) and Yukawa tephra 5 (YUT5), tephra beds of the Older Ontake volcano

Ontake volcano, which is an active volcano is situated at the southern margin of the Norikura volcanic chain, central Japan (Fig. 1), consists of Older and Younger Ontake volcanoes (Yamada and Kobayashi, 1988). The Older Ontake volcano is estimated to have been active about 0.78–0.39 Ma, based on K–Ar ages of 47 lavas (Kioka et al., 1998). Younger Ontake volcano became active about 0.1 Ma and was the source of a phreatic eruption in 1979 and 2014 (Oikawa, 2014). The products of Younger Ontake volcano constitute the main part of the edifice of Ontake volcano (Kimura, 1993), whereas the products of Older Ontake volcano are widely distributed around the foot of the volcano (Matsumoto Basin Collaborative Research Group, 2002).

The activity of Older Ontake Volcano has been divided into a Tephra Stage (about 0.78–0.64 Ma) and a Lava Stage (0.64–0.39 Ma), based on the primary mode of eruption. The Tephra Stage was characterized by the eruption of many airfall tephras and pyroclastic flows, whereas the Lava Stage produced many thick lavas (Fig. 2). The Satomiya Pumice, Kambara Pumices I, II, and III (Tephra Stage), and the Hottaruzawa Pumice (Lava Stage) are key tephra layers that have been widely traced at the foot area of the volcano (Matsumoto Basin Collaborative Research Group, 2002). The Tephra Stage has been further subdivided on the basis of the dominant mafic minerals into substages H (ca. 0.78 Ma), PH (0.78–0.70 Ma), and OP (0.70–0.64 Ma), where H stands for hornblende, PH for pyroxenes and hornblende, and OP for olivine and pyroxenes (Takeshita, 2004). YUT4 and YUT5 belong to Substage H, and the Kamiurazawa tephra (KZT), which belongs to the Lava Stage, has been correlated with the Ks12 tephra (Takeshita et al., 2005), which is in the Kasamori Formation of the Kazusa Group.

The Yukawa tephras 1–5 (YUT1–5) are Substage H tephras (Takeshita, 2004), and their type locality is along the Yukawa River at the foot of the eastern slope of Older Ontake volcano (Locality 1; N35°54′15″, E137°34′03″, 1200 m a.s.l.; Fig. 1). YUT4 consists of a gray volcanic ash bed (36 cm thick) overlain by sorted white pumice fall deposits (46 cm thick) (Fig. 3). The upper part of YUT4 consists mainly of pumice grains up to 1.0–2.5 cm in diameter. YUT5 consists of sorted white pumice fall deposits, 53 cm thick, containing pumice grains as large as 1.0–2.0 cm in diameter. YUT4 and 5 overlies the slope of approximately 20°, which show mantle bedding (Fig. 4). A gravel bed (about 160 cm thick) lies between YUT4 and 5. Samples of YUT4 and YUT5 collected at Locality 1 (Takeshita, 2004) were used in this study.

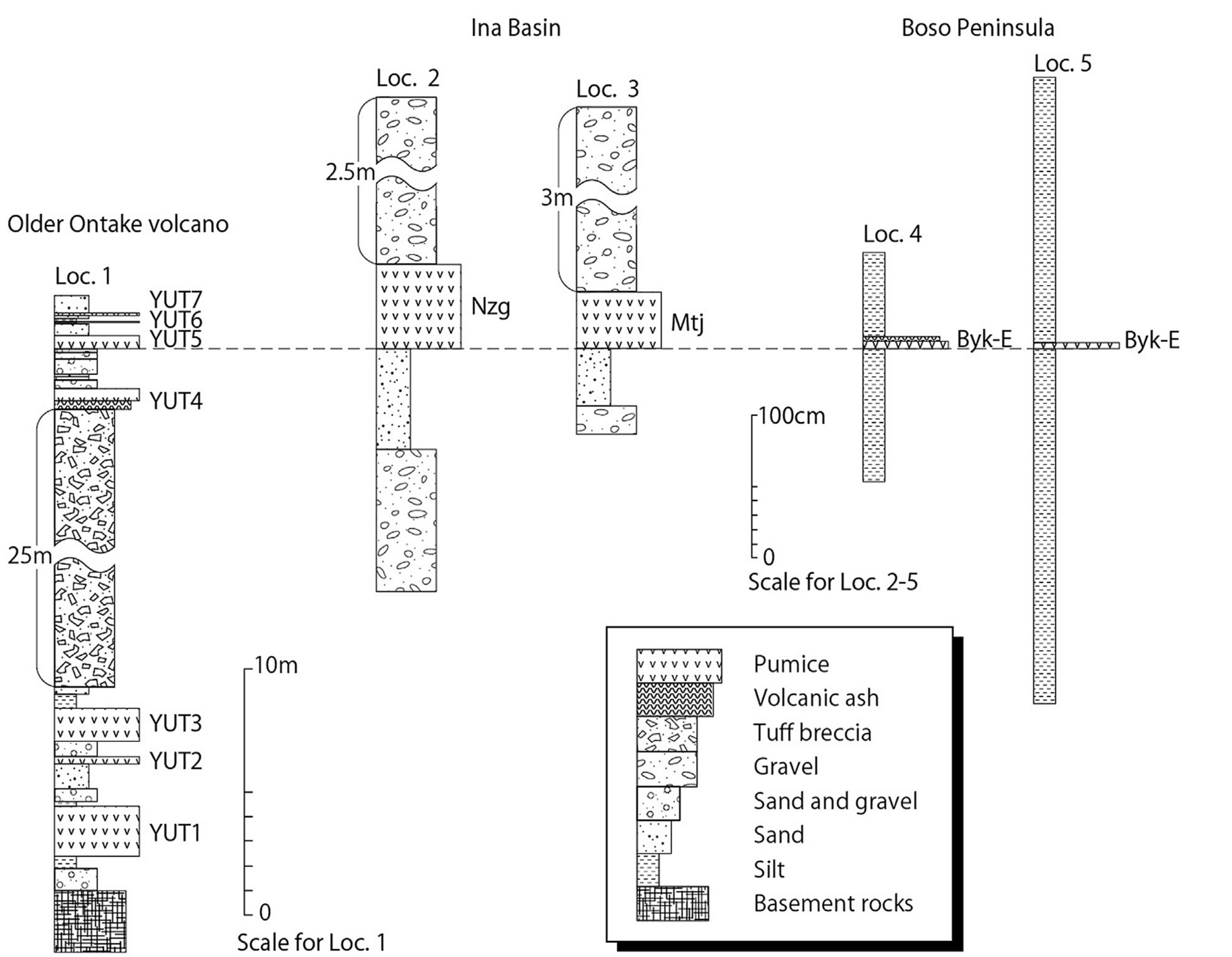

Fig. 3. Stratigraphic columns of Location 1 to Location 5 showing the relationships among YUT4, YUT5, Nzg, Mtj, and Byk-E tephra beds. The locations are shown in Fig. 1.

Fig. 4. Field photograph of Yukawa tephra 4 and 5 (YUT4, 5) at Locality 1. Location of the section is shown in Fig. 1. YUT4 and 5 overlies the slope of approximately 20°, which show mantle bedding.

2.2. Minamitajima (Mtj) and Nezumigawa (Nzg) tephras and the Tagiri Gravel Formation in the Ina basin

The Ina basin, 50 km east of Ontake volcano, is an elongated basin approximately 60 km long (north–south) and 15 km wide (east–west) (Fig. 1). It is bounded on the east by the Akaishi Mountains and on the west by the Kiso Mountains. The Tenryu River flows out of Lake Suwa and down the eastern side of the basin. The Middle Pleistocene Tagiri Gravel Formation occurs in the basin west of the Tenryu River (Matsushima, 1995). The Tagiri Gravel Formation is overlain by paleosol 1.0–1.5 m thick and the Ontake Pm-1 tephra (On-Pm-1, 0.1 Ma; Kobayashi et al., 1967; Machida and Arai, 2003) (Fig. 2). The composition of the gravel, which consists of rocks found in the Kiso Mountains, suggests that this formation was deposited during the uplift of the Kiso Mountains (Matsushima, 1995). Tephras interbedded in the Tagiri gravel include the Minamitajima (Mtj) (Matsushima and Teradaira, 1999), Nezumigawa (Nzg) (Matsushima et al., 2007), Hongo (Hng) and Toyooka (Tyo) tephras (Matsushima and Teradaira, 1990) (Fig. 2). The stratigraphic relations among these tephra beds have not been confirmed, because they have been identified in only local outcrops. Tyo and Hng have fission-track ages of 0.53 ± 0.19 Ma and 0.75 ± 0.21 Ma, respectively, measured on zircon crystals (Matsushima and Teradaira, 1990). From these fission-track ages, the Tagiri Gravel Formation is estimated to have been deposited during approximately 0.8–0.5 Ma (Matsushima, 1995).

The Nzg tephra was discovered and named at a site near Kamiakasu, Komagane City, Nagano Prefecture, N35°42′43″, E137°57′35″, 570 m a.s.l. (Locality 2, Fig. 1; Matsushima et al., 2007). Nzg is a yellowish white massive unstratified pumiceous deposite, 60 cm thick (Figs. 3 and 5), that consists mostly of pumice grains up to 0.5–1.0 cm in diameter.

The Mtj tephra was discovered in 1998 during roadworks near Minamitajima, Nakagawa Village, Nagano Prefecture; N35°37′11″, E137°54′54″, 545 m a.s.l. (Locality 3, Fig. 1; Matsushima and Teradaira, 1999). Mtj is a brownish yellow massive unstratified pumiceous deposit, 40–50 cm thick (Figs. 3 and 6), consisting of pumice grains up to 0.3–0.5 cm in diameter in a sandy matrix.

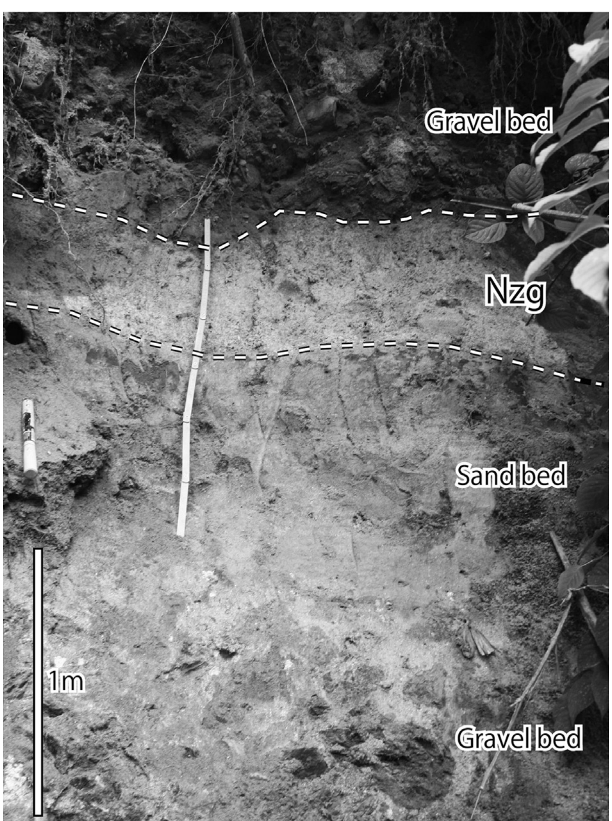

Fig. 5. Field photograph of Nezumigawa tephra (Nzg) at Locality 2. Location of the section is shown in Fig. 1.

2.3. Byakubi-E tephra (Byk-E) and the Kazusa Group on the Boso Peninsula

The Kazusa Group is composed of marine sediments and is up to 3000 m thick on the Boso Peninsula (Mitsunashi et al., 1979),

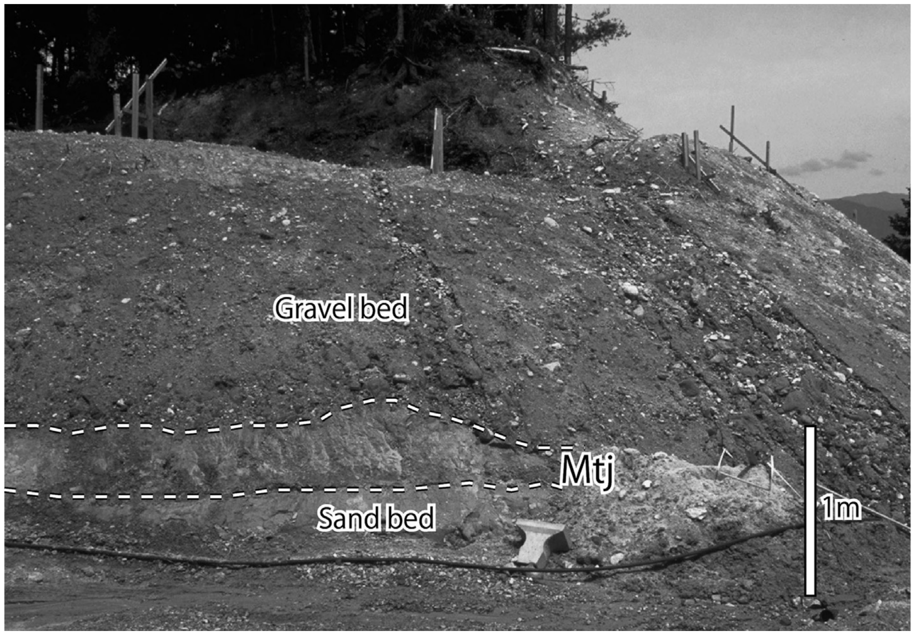

Fig. 6. Field photograph of Minamitajima tephra (Mtj) at Locality 3. Location of the section is shown in Fig. 1.

approximately 250 km east-southeast of Ontake volcano (Fig. 1). The Kazusa Group is one of the most important Lower and Middle Pleistocene sequences in Japan. Numerous tephra layers are intercalated with the Kazusa Group sediments (Mitsunashi et al., 1959; Machida et al., 1980; Tokuhashi and Endo, 1984; Satoguchi, 1995, 2006), and their detailed stratigraphy has been determined by using these tephra layers as key beds. On the basis of biostratigraphic (Oda, 1977; Sato and Takayama, 1988; Kanie et al., 1991; Kameo et al., 2003), magnetostratigraphic (Niitsuma, 1971, 1976), oxygen-isotope (Okada and Niitsuma, 1989; Pickering et al., 1999; Tsuji et al., 2005), and fission-track dating studies (Watanabe and Danhara, 1996; Suzuki et al., 1998), the depositional age of the Kazusa Group has been estimated as ca. 2.4–0.4 Ma (Satoguchi, 2006). The stratigraphy of the Kazusa Group has recently been reviewed and updated (Kazaoka et al., 2015).

In the central and eastern parts of the Boso Peninsula, the Kazusa Group is divided into the Kurotaki, Katsuura, Namihana, Ohara, Kiwada, Otadai, Umegase, Kokumoto, Kakinokidai, Chonan, Kasamori, and Kongochi formations in ascending order (Tokuhashi and Endo, 1984). The Kokumoto Formation is a part of the Kazusa Group that is of primary interest here. The lowermost part of the Kokumoto Formation consists of massive sandy mud, which is overlain by thick sand beds and alternating sand-dominated layers. Its middle part consists of massive sandy mud, and its upper part is

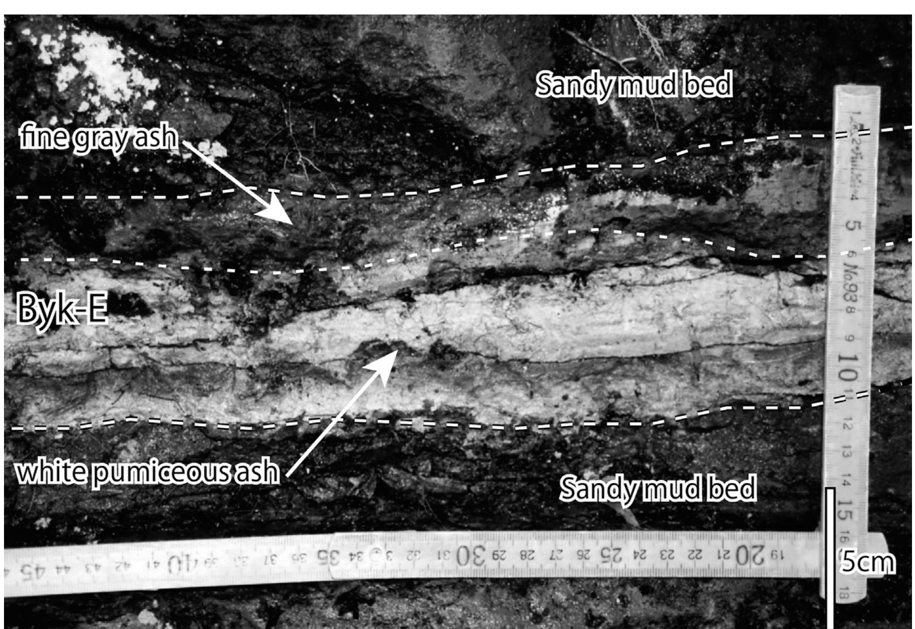

Fig. 7. Field photograph of Byk-E at Locality 4. Location of the section is shown in Fig. 1.

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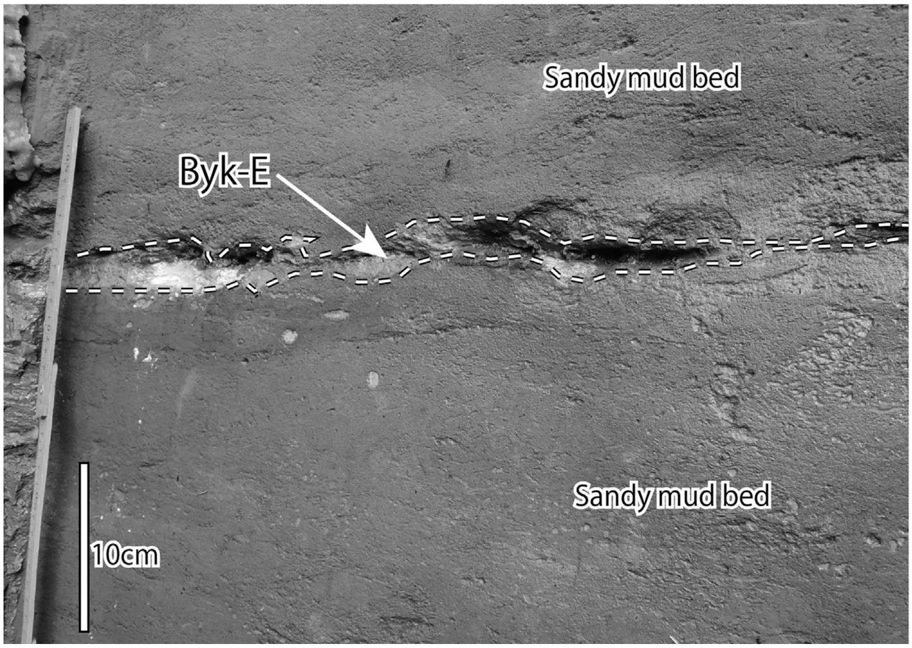

Fig. 8. Field photograph of Byk-E at Locality 5. This section is a candidate Global Boundary Stratotype Section and Point (GSSP) for the lower boundary of the Middle Pleistocene Subseries (Working Group for Quaternary Stratigraphy of Boso, 2009). Location of the section is shown in Fig. 1.

a sand-dominated alternation (Mitsunashi et al., 1959). In the middle part of the formation, more than 30 fallout tephra layers are intercalated (Workshop for Quaternary Stratigraphy of Boso, 1996). Among these tephras, Byk-E is the same as the TNTT ash layer described by Okada and Niitsuma (1989), and the Matuyama–-Brunhes boundary occurs just above Byk-E (Fig. 2; Kazaoka et al., 2015). Byk-E was collected at Locality 4 on the Boso Peninsula (Fig. 1; Choja, Kimitsu City, Chiba Prefecture; N35°16′21″, E140°06′59″, 190 m a.s.l.) (Takeshita et al., 2005). It is noteworthy that the Yoro River section including Locality 5 (Fig. 1; Byakubi, Ichihara City, Chiba Prefecture; N35°17′39″, E140°08′48″, 55 m a.s.l.), which is the type section of the Kokumoto Formation, is a candidate GSSP for the Early-Middle Pleistocene boundary (Working Group for Quaternary Stratigraphy of Boso, 2009). In the present study, Byk-E was collected at Locality 5 for the purpose of checking whether Byk-E at Locality 4 and Byk-E at Locality 5 were the same tephra.

At Locality 4, Byk-E consists of a well-sorted white pumiceous ash bed (2–4 cm thick) and a fine gray ash bed (2–3 cm thick) in ascending order (Figs. 3 and 7). Lower part of this tephra bed consists of pumice fragments with the size of fine to medium sand. At Locality 5, Byk-E consists of a well-sorted white pumiceous ash bed (1–4 cm thick) (Fig. 8). This tephra bed consists of pumice fragments with the size of fine to medium sand. At both locations, Byk-E is sandwiched between layers of dark gray sandy silt.

3. Analytical methods

The tephra samples collected for this study (Nzg, Mtj, and Byk-E from Locality 5) and from previously published studies (YUT4, YUT5, and Byk-E from Locality 4) were prepared as outlined in Fig. 9. The samples were washed ultrasonically after washing in a beaker. The dried residual grains were sieved to obtain the fractions from 1/4 to 1/8 mm and from 1/8 to 1/16 mm. The 1/8 to 1/16 mm fraction was used for analysis of the grain composition. Mafic minerals were separated with a neodymium magnet for determination of their mineral composition, as well as the major element composition of hornblende. The bulk grains and the mafic minerals of all samples were mounted on glass microscope slides by the Petropoxy 154 and then identified and counted under a polarizing microscope. The bulk grain and mafic mineral compositions were determined for at least 500 and 250 grains, respectively, in each

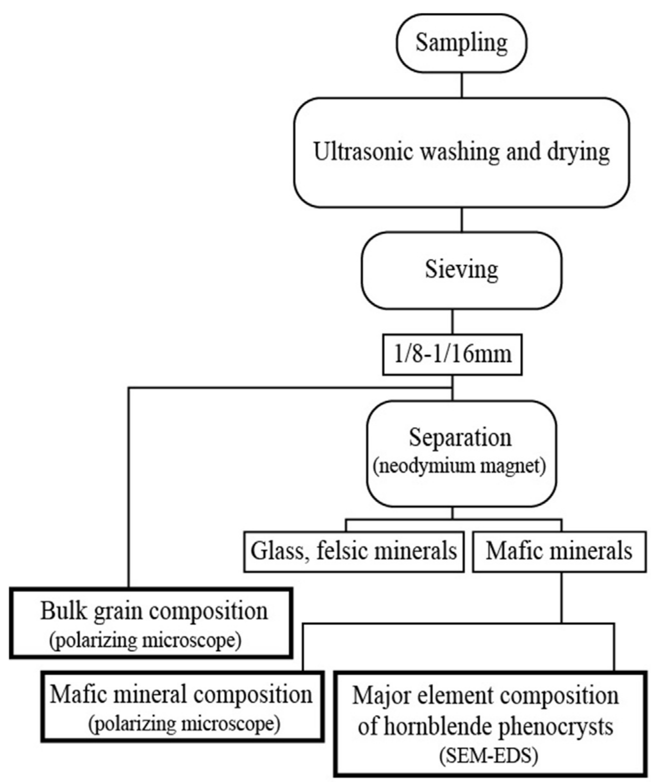

Fig. 9. Flowchart showing the sample preparation procedures for petrologic analysis and for determining the major element composition of hornblende phenocrysts.

tephra sample. The mafic minerals identified were hornblende, orthopyroxene, clinopyroxene, garnet, opaque minerals (Fe–Ti oxides), zircon, and apatite. In addition, the presence of biotite was confirmed, but the number of biotite grains was not determined because they were easily fragmented during sample preparation.

Measurement of the major element composition of hornblende was carried out following Takeshita (2004) by scanning electron microscopy (JEOL, JSM5310E)–energy-dispersive X-ray spectroscopy (EDAX, Phoenix) (SEM–EDS) using an acceleration voltage of 15 kV and a beam current of 700 pA. The apparent center of the hornblende was selected as the analytical point, and one point was measured in each grain. Phenocrysts in a tephra may become fractured during eruption, and for this reason discrimination of the rim and core was difficult. In addition, no zonal structure was observed in the hornblende phenocrysts. In each sample, 9–24 hornblende phenocrysts were analyzed.

4. Results

The petrographic properties of YUT4 and YUT5, Mtj, Nzg, Byk-E (Locality 4), and Byk-E (Locality 5) tephras are shown in Table 1.

Table 1
Petrographic properties of the YUT4, YUT5, Nzg, Mtj, and Byk-E.

Name of tephra	Sampling locality	Bulk grain composition (%)				Mafic mineral composition (%)								Glass morphology	Reference
		Gl	Pl	R.F.	M.M.	Hbl	Cpx	Opx	Bt	Opq	Ap	Zr	Gr		
YUT5	Loc. 1	36.4	50.8	2.6	1.1	88.1	0.4	0.8	–	10.7	+	+	–	P	1
YUT4	Loc. 1	34.6	46.9	4.7	2.8	70.0	0.8	0.4	+	24.5	–	–	–	P	1
Nzg	Loc. 2	–	88.3	2.5	9.2	43.8	0.7	0.4	–	55.1	+	–	–	*	This study
Mtj	Loc. 3	–	86.6	4.7	8.7	39.1	0.8	0.8	+	59.3	–	–	+	*	This study
Byk-E	Loc.4	61.2	34.6	1.7	2.5	85.4	+	1.0	–	13.2	0.3	–	–	P	2
Byk-E	Loc.5	63.6	31.2	2.1	3.1	88.3	+	0.7	–	11.0	+	–	–	P	This study

Gl, volcanic glass; Pl, plagioclase; R.F., rock fragment; M.M., mafic minerals; Hbl, hornblende; Cpx, clinopyroxene; Opx, orthopyroxene; Bt, biotite; Opq, opaque mineral; Ap, apatite; Zr, zircon; Gr, garnet; +, trace; –, absent. Glass morphology: P, pumice-type shards; *, none. References: 1, Takeshita (2004); 2, Takeshita et al. (2005).

Volcanic glass shards from YUT4 are mostly of the pumice type, but some are fiber-type shards. The hornblende content is high, and the other mafic minerals include opaque minerals and small amounts of orthopyroxene, clinopyroxene, and biotite. YUT5 is similar to YUT4 with respect to the shape of glass shards and the grain and mafic mineral compositions, but it includes apatite and zircon and lacks biotite.

The volcanic glass of Nzg has been altered by weathering. The hornblende and opaque mineral contents of Nzg are high, and other mafic minerals include small amounts of orthopyroxene and clinopyroxene. The grain and mafic mineral compositions of Mtj are similar to those of Nzg, but Mtj includes small amounts of biotite and garnet.

Byk-E (Locality 4) contains abundant volcanic glass shards. The shards are mostly of the pumice type, with some fiber-type shards. The hornblende content is high, and other mafic minerals include opaque minerals and small amounts of orthopyroxene, clinopyroxene, and apatite. Byk-E from Locality 5 is very similar to Byk-E from Locality 4 with respect to the shape of the glass shards and bulk grain and mafic mineral compositions.

The major element compositions of hornblende from YUT4 and 5, Mtj, Nzg, Byk-E (Locality 4), and Byk-E (Locality 5) are shown in Table 2 and Fig. 10. The major element composition of hornblendes from YUT5, Mtj, Nzg, and Byk-E (Locality 5) closely resemble each other. Although the major element composition of hornblende from YUT4 resembles those of the other tephras, in YUT4 Si, Al, and mg* [Mg/(Mg + Fe)] are concentrated within a narrower range than in the other tephras.

5. Discussion

5.1. Potential of major element composition of hornblende for tephra identification and correlation

The correlation and identification of tephra layers are often undertaken by using glass shard characteristics (morphology, refractive index, major and trace element compositions) in addition to lithofacies, mineral composition, stratigraphic relationships, and radiometric age (Machida and Arai, 1992; Lowe, 2011). However, the volcanic glass shards of Mtj and Nzt have been altered by weathering. Thus, the major element composition of hornblende phenocrysts was used to characterise the tephras in this study.

Nine Lower and Middle Pleistocene tephra layers (Ku6E, Ku5C, Byk, Ka2.4A, B, Ch3 and 1.5, Ks18, and Ks12) in the Kazusa Group had previously been distinguished on the basis of the major element composition of their hornblende phenocrysts (Fig. 11; Takeshita et al., 2005). Moreover, it has been shown that tephras from Older Ontake volcano, Kurofuji volcano (central Japan), and Daisen volcano (southwest Japan) can be discriminated on the basis of the major element composition of hornblende (Takeshita et al., 2005; Kotaki et al., 2011). Furthermore, the major element composition of hornblende in tephra from Older Ontake volcano is different at every stage of volcanic activity (Fig. 12; Takeshita, 2004). These findings indicate that the major element composition of hornblende can be a useful tool for identification and correlation of tephras.

5.2. Correlations of tephra layers

5.2.1. Correlation of Byk-E (Locality 4) and Byk-E (Locality 5)

Byk-E (Locality 4) and Byk-E (Locality 5) were both recognized in sandy silt in the central part of the Kokumoto Formation, and the two localities are only 3.6 km apart (Fig. 1). Although at Locality 5, Byk-E lacks a lower part consisting of gray volcanic ash, in its thickness, grain size, grain composition, mafic mineral composition, and glass shard type, Byk-E (Locality 5) is very similar to Byk-E (Locality 4) (Table 1). Moreover, the major element compositional ranges of hornblende from Byk-E (Locality 4) are very similar to those of Byk-E (Locality 5) (Table 2, Fig. 10). From these results, we infer that Byk-E (Locality 4) and Byk-E (Locality 5) are certainly the same tephra.

5.2.2. Correlation of Byk-E (Boso), Mtj, Nzg (Ina), and YUT5 (Older Ontake volcano)

Byk-E was previously correlated with YUT4 or YUT5 from the Older Ontake volcano on the basis of their lithofacies, glass shard type, grain composition, mafic mineral composition, major

Table 2
Major element compositions of hornblende phenocrysts in the YUT4, YUT5, Nzg, Mtj, and Byk-E.

Name of tephra	Sampling locality	Oxides (wt%)										N	Cation (O = 23)											Reference
		SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total		Si	Ti	Al	Fe*	Mn	Mg	Ca	Na	K	Total	mg*	
YUT5	Loc. 1	**43.48**	**1.94**	**10.84**	**13.48**	**0.61**	**13.38**	**10.72**	**1.98**	**0.68**	**97.11**	23	**6.45**	**1.90**	**0.22**	**1.67**	**0.08**	**2.96**	**1.71**	**0.57**	**0.13**	**15.68**	**0.64**	1
		1.22	0.42	1.11	0.86	0.28	0.58	0.39	0.18	0.10	0.52		0.17	0.20	0.05	0.11	0.03	0.12	0.06	0.05	0.02	0.07	0.23	
YUT4	Loc. 1	**43.25**	**2.05**	**11.52**	**14.11**	**0.65**	**12.97**	**11.17**	**2.02**	**0.79**	**98.53**	24	**6.36**	**2.00**	**0.23**	**1.74**	**0.08**	**2.84**	**1.76**	**0.58**	**0.15**	**15.73**	**0.62**	1
		1.00	0.29	0.85	0.56	0.19	0.49	0.25	0.16	0.07	0.73		0.13	0.15	0.03	0.07	0.02	0.10	0.04	0.04	0.01	0.05	0.16	
Nzg	Loc. 2	**43.33**	**2.13**	**10.98**	**13.20**	**0.62**	**13.42**	**10.77**	**2.03**	**0.69**	**97.17**	21	**6.43**	**1.92**	**0.24**	**1.64**	**0.08**	**2.97**	**1.71**	**0.58**	**0.13**	**15.70**	**0.64**	This study
		1.09	0.37	0.96	0.72	0.24	0.70	0.24	0.17	0.07	0.44		0.14	0.17	0.04	0.10	0.03	0.14	0.04	0.05	0.01	0.05	0.23	
Mtj	Loc. 3	**43.35**	**2.06**	**11.23**	**13.48**	**0.63**	**13.56**	**10.73**	**2.13**	**0.65**	**97.82**	24	**6.41**	**1.96**	**0.23**	**1.67**	**0.08**	**2.99**	**1.70**	**0.61**	**0.12**	**15.75**	**0.64**	This study
		1.26	0.38	1.09	0.83	0.19	0.72	0.34	0.17	0.08	0.70		0.17	0.20	0.04	0.11	0.02	0.15	0.06	0.05	0.02	0.07	0.25	
Byk-E	Loc.4	**44.30**	**1.85**	**10.67**	**13.54**	**0.75**	**13.56**	**10.86**	**2.01**	**0.69**	**98.22**	24	**6.50**	**1.85**	**0.20**	**1.66**	**0.09**	**2.97**	**1.71**	**0.57**	**0.13**	**15.68**	**0.64**	2
		1.25	0.28	1.08	0.67	0.23	0.82	0.33	0.16	0.14	0.72		0.16	0.19	0.03	0.09	0.03	0.17	0.06	0.04	0.03	0.06	0.02	
Byk-E	Loc.5	**43.90**	**1.69**	**10.22**	**13.53**	**0.81**	**13.42**	**10.60**	**1.98**	**0.65**	**96.79**	9	**6.54**	**1.80**	**0.19**	**1.69**	**0.10**	**2.98**	**1.69**	**0.57**	**0.12**	**15.69**	**0.64**	This study
		1.41	0.15	1.10	0.88	0.19	0.97	0.19	0.12	0.11	0.48		0.15	0.21	0.02	0.12	0.02	0.19	0.04	0.04	0.02	0.06	0.03	

For each tephra, the upper row shows mean values (bold) and the lower row shows the standard deviation. *N*, number of measured grains. References: 1, Takeshita (2004); 2, Takeshita et al. (2005).

element composition of hornblende, K–Ar ages of lava, and stratigraphic relationships with the Matuyama–Brunhes boundary (Takeshita et al., 2005). Mtj and Nzg are both hornblende-rich pumiceous deposits, and their mafic mineral compositions are similar to those of Byk-E, YUT4, and YUT5. Measurements of the major element compositions of hornblende showed that, unlike in YUT4, in YUT5, Byk-E, Mtj, and Nzg, the range of variation in Si and mg* was large; moreover, the variation range of Al was lower in YUT4 than in these other tephras (Fig. 10). This result suggests that Byk-E, Mtj, and Nzg are correlated with YUT5 but not with YUT4 (Fig. 2), and that the composition ranges of Si, Al, and mg* in hornblende phenocrysts can be used to distinguish YUT5 from YUT4.

Among the tephra layers that are the focus of this study, only Mtj includes small amount of garnet and biotite grains, which tend to be rounded and fragmental. Both garnet and biotite are found in the granitic and metamorphic rocks of the Kiso Mountains (Murayama and Katada, 1957) and a large amount of the gravel in the Tagiri Gravel Formation is derived from those rocks. We suggest, therefore, that fragments of garnet and biotite probably became mixed in with the Mtj tephra by resedimentation, because Mtj is massive unstratified pumiceous deposit consisting of pumice grains and sandy matrix.

Next, we investigated correlations among Byk-E, Mtj, Nzg, and YUT5 from the viewpoint of chronology and volcanology. The Matuyama–Brunhes boundary occurs just above Byk-E at Chiba section (Kazaoka et al., 2015), and chronologically it is positioned at the boundary between marine oxygen-isotope substages (MIS) 19.3 and 19.2 (Hyodo et al., 2006; Hyodo, 2014). The Ku1 tephra, which occurs about 50 m above Byk-E, correlates with the widespread Hakkoda–Kokumoto tephra (Hkd-Ku: Suzuki et al., 2005), which has been correlated in turn with the Imakuma I tephra, Osaka Group (Itihara et al., 1975), and the Hakkoda first-stage pyroclastic flow deposits in northernmost Honshu (Muraoka and Takakura, 1988). Ku1 (Hkd-Ku) was erupted around 0.76 Ma, between MIS 19.1 and MIS 18.4 (Suzuki et al., 2005). Consequently, we can estimate the age of Byk-E as ca. 0.773 Ma (Fig. 2). On the other hand, Mtj and Nzg are intercalated in the Tagiri Gravel Formation, the estimated depositional age of which is approximately 0.8–0.5 Ma, based on its stratigraphic relation with On-Pm1 (0.1 Ma) and fission-track ages from Tyo (0.53 ± 0.19 Ma) and Hng (0.75 ± 0.21 Ma) (Matsushima, 1995). Therefore, the correlation of Mtj and Nzg with Byk-E (YUT5) is congruent with the chronological framework.

Thickness of the Mtj and Nzg in the Ina Basin is almost same as that of YUT5 at the foot of Ontake volcano. However, those of Mtj and YUT5 probably not original thickness, because YUT5 overlies the slope landform at Locality 1 (Fig. 4), and Mtj is probably reworked pumice-fall deposits. Therefore, we confirm this correlation depending on the size of pumice grains and lithofacies of these tephra beds. YUT5 is considered a Plinian pumice-fall deposit because it consists of sorted pumice clasts up to 1.0–2.0 cm in diameter (Takeshita, 2004). Byk-E is thought to be distal ashfall deposits associated with a Plinian eruption because it includes pumice fragments the size of fine to medium sand (Takeshita et al., 2005). Mtj and Nzg in the Ina Basin are regarded as, possibly reworked, Plinian pumice-fall deposits because they consist of pumice grains up to 0.3–1.0 cm in diameter. The pumice size of Mtj and Nzg is thus smaller than that of YUT5 and larger than that of Byk-E, consistent with the location of the Ina Basin between Ontake volcano and the Boso Peninsula (Table 1). Accordingly, it is reasonable to infer that YUT5, Mtj, Nzt, and Byk-E are volcanic products from the same eruption.

YUT5, Mtj, and Nzg, which are correlated with Byk-E, cannot be called volcanic ash, because they consist of pumice clasts coarser

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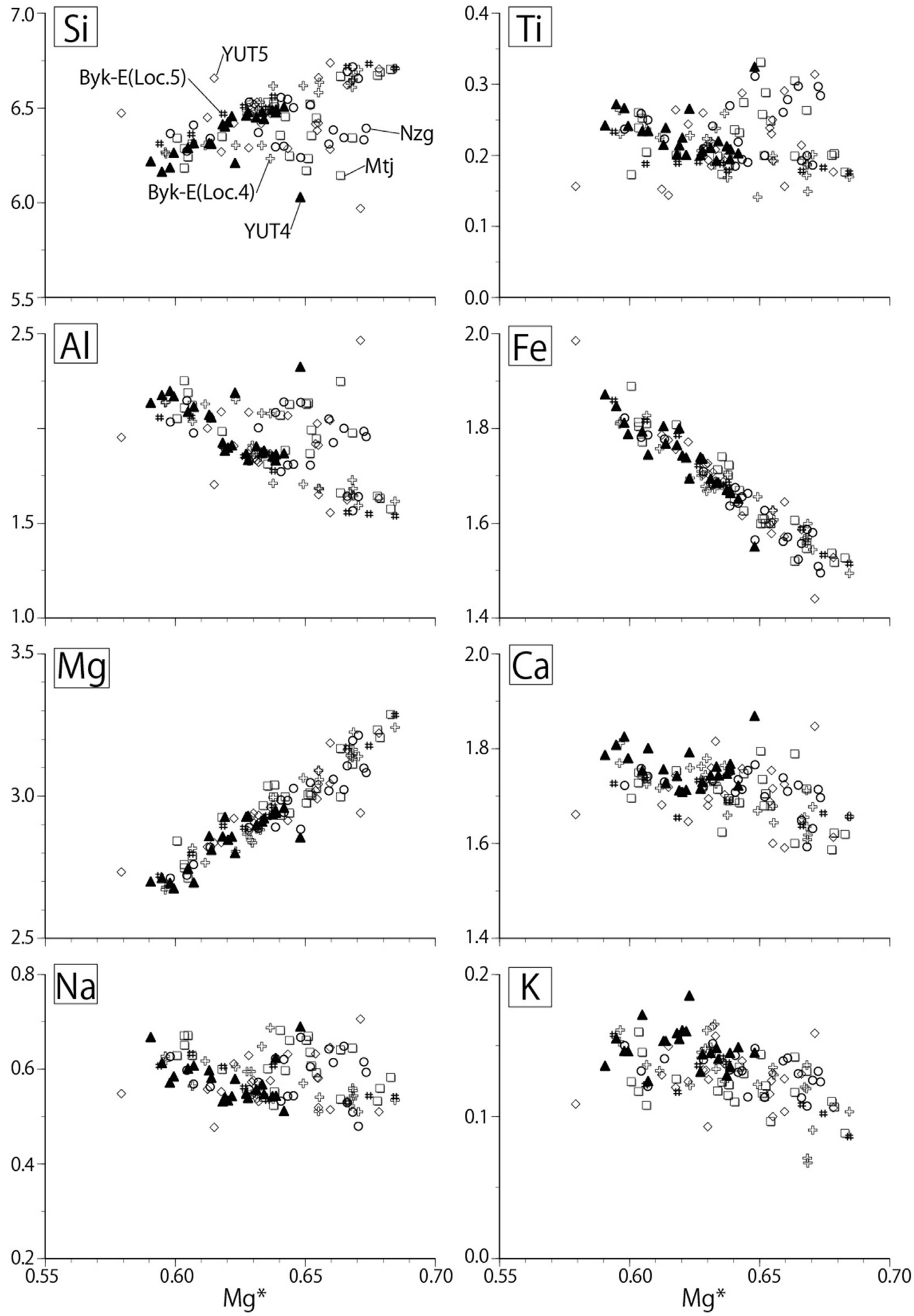

Fig. 10. Atomic ratios (O = 23) of cations relative to mg* (Mg/(Mg + Fe)) in hornblende phenocrysts of YUT4, YUT5, Nzg, Mtj, and Byk-E. The chemical compositions of hornblende from YUT4 and YUT5 are after Takeshita (2004). Those from Byk-E (Locality 4) are after Takeshita et al. (2005).

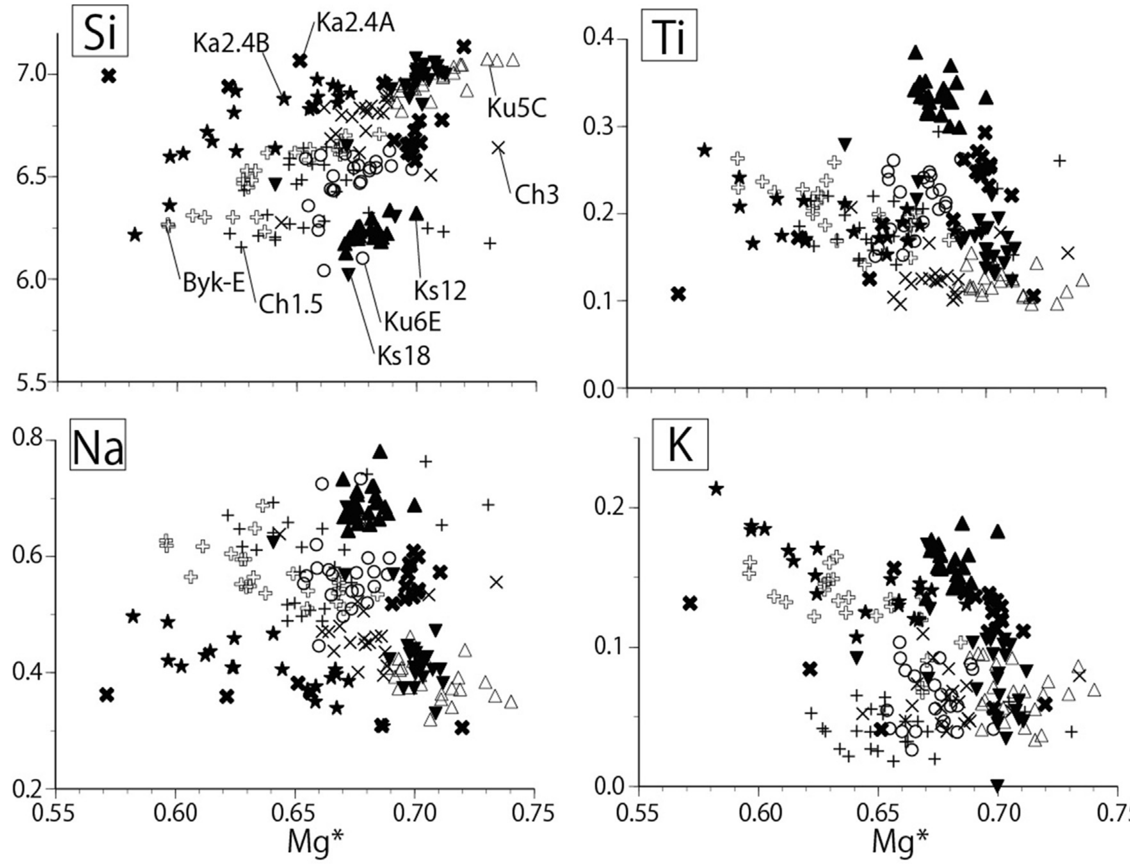

Fig. 11. The atomic ratios of Si, Ti, Na, and K in relation to mg* in hornblende phenocrysts from the nine Lower and Middle Pleistocene tephras in the Kazusa Group. The compositions of hornblende from Ku6E, Ku5C, Byk-E (Kokumoto Formation), Ka2.4A, B (Kakinokidai Formation), Ch3 and 1.5 (Chonan Formation), Ks18, and Ks12 (Kasamori Formation) are after Takeshita et al. (2005).

than 2 mm. Thus, we propose to call the series of tephras correlated with Byk-E the Ontake-Byakubi Tephra Bed (On-Byk Tephra), following the naming convention in which the tephra name consists of the names of the source volcano and the type location (Machida and Arai, 1992).

5.3. *Significance of the Ontake-Byakubi tephra*

In Japan, most volcanic glass shards included in Middle Pleistocene tephra beds are sandwiched within nonmarine sediments, such as fluvial or tephric soil (eolian) deposits, and have been altered by weathering (Takeshita et al., 2007; Suzuki, 2008; Kotaki et al., 2011). In this study, strongly weathered tephra beds such as Mtj and Nzg have been correlated with the On-Byk Tephra by using the major element composition of hornblende as a means of tephra identification. Furthermore, we distinguished YUT5 from YUT4 and showed that Byk-E is correlated with YUT5 by using the major element composition of hornblende determined for Mtj and Nzg. These results clearly show that On-Byk Tephra is an important marker tephra that can provide a datum plane that approximates the Lower-Middle Pleistocene boundary.

Deposition of the Tagiri Gravel Formation began before about 0.773 Ma, because On-Byk Tephra (Mtj and Nzg) is intercalated within this formation (Fig. 2). It follows, therefore, the Kiso Mountains had uplifted sufficiently to provide gravel to the Ina basin by about 0.78 Ma. Thus, as a high-precision datum plane, On-Byk Tephra can contribute to the reconstruction of the geomorphologic and geologic evolution of the Chubu district, central Japan, in nonmarine sediments that otherwise lack chronological indices.

In Japan, most late Quaternary tephras are distributed to the east of their source volcanoes, because the plumes were transported by the prevailing westerlies (Machida and Arai, 2003). Some Middle to Upper Pleistocene tephras such as the Aso-4 and Ata-Torihama (Machida, 1999) tephras have been identified in the northwest Pacific Ocean (Suganuma et al., 2006; Aoki, 2008; Aoki et al., 2008). Therefore, it is possible that On-Byk, which has a thickness of 1–7 cm on the Boso Peninsula, also occurs in the northwest Pacific Ocean. Thus, On-Byk Tephra, because it approximates the Middle Pleistocene boundary, may contribute to the development of a high-precision chronology close to the Matuyama–Brunhes transition.

6. Conclusion

Petrographic features including bulk grain and mafic mineral compositions and the major element composition of hornblende from tephras Mtj and Nzg in the Ina basin have been described and compared with previously published data for tephras YUT4, YUT5, and Byk-E.

We are able to distinguish YUT5 from YUT4 and to correlate Byk-E, Mtj, and Nzg with YUT5 on the basis of the major element composition of hornblende.

We propose that the series of tephras correlated with Byk-E be called the Ontake-Byakubi Tephra Bed (On-Byk Tephra). On-Byk is an important marker tephra because it provides a datum plane that closely approximates the Lower-Middle Pleistocene boundary.

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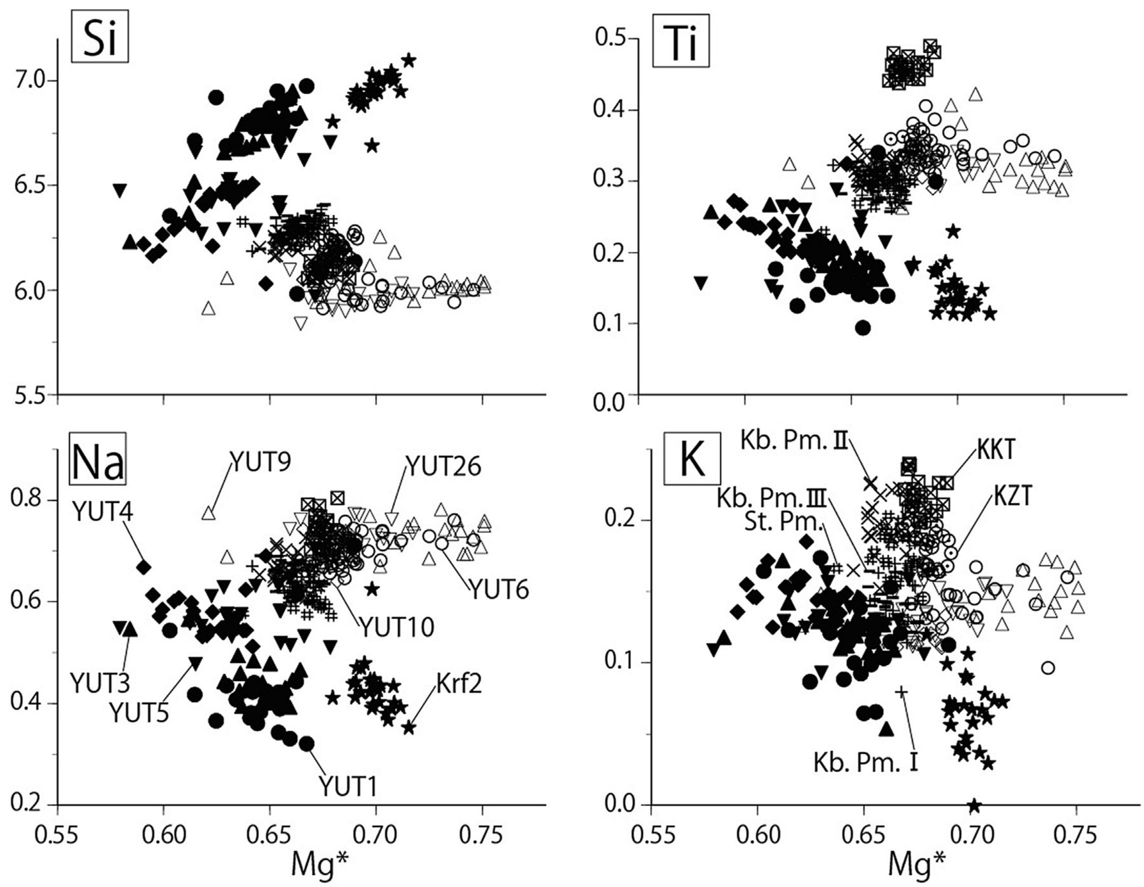

Fig. 12. The atomic ratios of Si, Ti, Na and K in relation to mg* in hornblende phenocrysts from the tephras from Older Ontake volcano and Kurofuji volcano. The chemical compositions of hornblende in tephras from Older Ontake volcano (Substage H, YUT1, 3, 4, 5; Substage PH, YUT6, 9, 10, 26; key tephra beds, St. Pm., Kb. Pm. I–III; Lava Stage, KZT, KKT) are after Takeshita (2004), and data from Kurofuji volcano (Krf2) are after Takeshita et al. (2005).

The present study also shows that the major element composition of hornblende phenocrysts can a useful tool for correlating strongly weathered tephra layers in which all the volcanic glass shards have been altered.

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