# RE-EXAMINATION OF PREVIOUS CORRELATION OF DISTAL KS5 TEPHRA AND PROXIMAL ODA PYROCLASTIC FLOW DEPOSITS IN SOUTH KYUSHU, SW JAPAN

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*Abstract* Two pyroclastic flow deposits named Nabekura (Nb) and Oda (Oda) Pyroclastic Flow Deposits in ascending order, in the southern Kyushu Island, SW Japan, are intercalated in the Kokubu Group distributed around the northern coastal area of the Kagoshima Bay. The purpose of this study is to reveal their differences in petrographic properties such as glass chemistry and refractive indices of volcanic glass shards, hornblende, and orthopyroxene. Nb and Oda are evidently distinguished by refractive indices of orthopyroxene and variation in the chemical composition of glass shards. We re-examined the proposed correlation of Oda with Ks5 (Boso Peninsula, Central Japan) by previous studies, comparing other two distal tephras petrographically similar to Ks5. It is concluded that Oda is not correlated to Ks5, OgA, and Hg-7.

**Key words:** tephra, correlation, Middle Pleistocene, Oda pyroclastic flow deposits, Ks5

## 1. Introduction

Ks5 Tephra (Ks5; Machida *et al.* 1980; Tokuhashi and Endo 1984) in the Kasamori Formation of the Kazusa Group in the Boso Peninsula, Central Japan, was considered to be one of Middle Pleistocene widespread tephras that have been derived from a certain caldera in the Kyushu Island, SW Japan. Thus, Ks5 of which eruptive age is 450 ka (Machida 1999) was correlated to Oda Pyroclastic Flow Deposits (Oda; Otsuka and Nishiinoue 1980) distributed in the northwest area facing the Kagoshima Bay (Fig. 1), based on the glass chemistry (Mizuno 1997; Suzuki and Fujiwara 1998). The tephras correlated to Ks5 were also recognized in the Osaka Group (Minatojima I Tephra; Yoshikawa *et al.* 2000), the Kobiwako Group (Ikadachi II Tephra; Satoguchi and Hattori 2008) and the Shibikawa Formation distributed in the Oga Peninsula (Wkm Tephra; Machida and Arai 2003). However, these correlations are inconsistent with the stratigraphical relationship of Ks5 and another distal tephra in the Boso Peninsula as mentioned below. The Kokubu Group (KKG; Ida *et al.* 1950) which containing tephras derived from mainly pre-Aira caldera is distributed around the coastal area of the northern Kagoshima Bay. Oda is intercalated in KKG with a petrographically similar ignimbrite (indiscernible by mineral assemblage) named Nabekura Pyroclastic Flow Deposits (Nb; Otsuka and Nishiinoue 1980). According to Sato *et al*. (2000), the KKG is overlain by the Kobayashi Pyroclastic Flow Deposits. Kikkawa *et al*. (1991) correlated the Kobayashi Pyroclastic Flow Deposits to Ks11 in the Kasamori Formation, defined Kb-Ks (520–530 ka; Machida and Arai 2003), one of the most important Middle Pleistocene marker tephras distributed from the southern Kyushu to eastern Honshu. However, Kb-Ks (Ks11) correlated

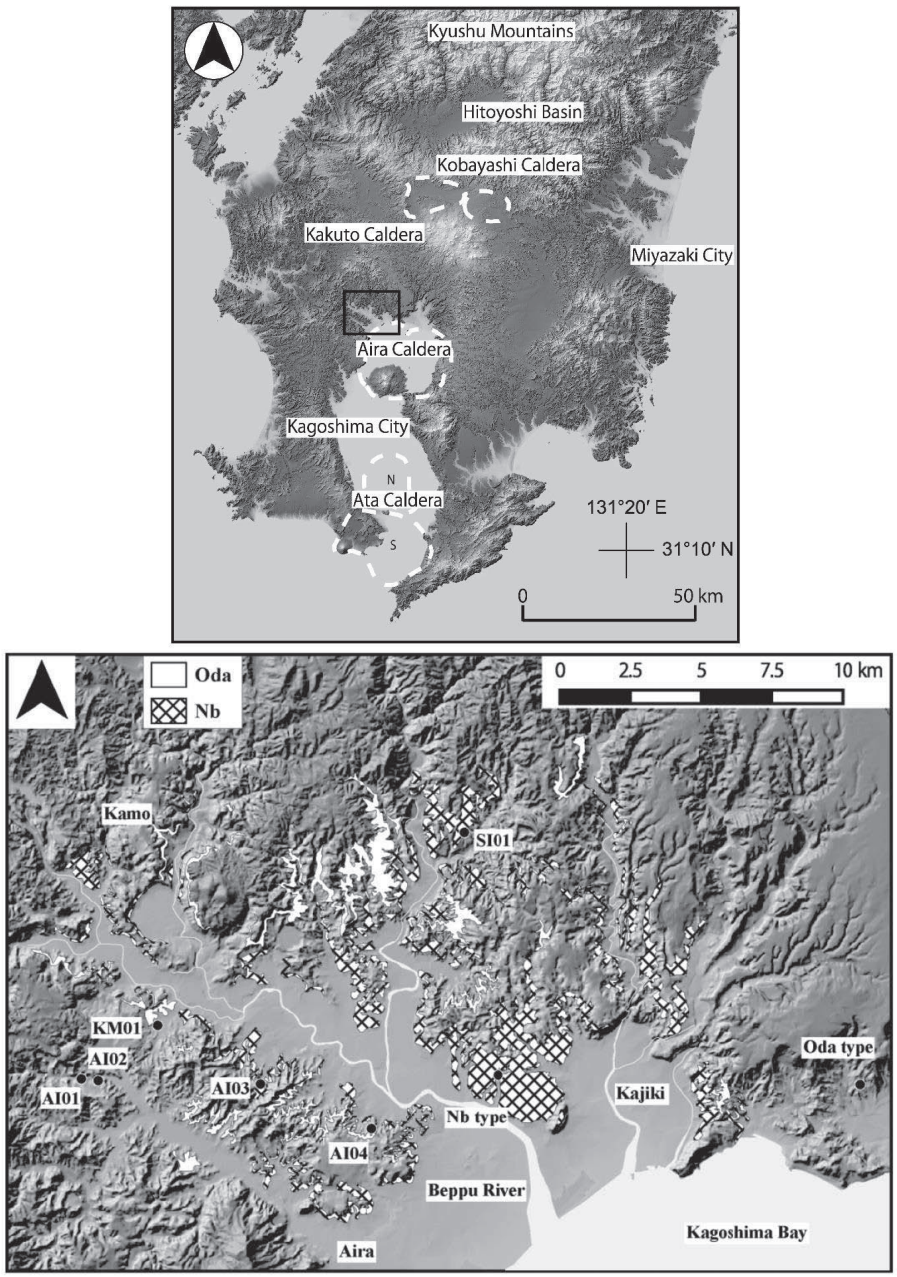


**Fig. 1** Regional setting and the study area. The distribution of Nb and Oda are after Hase *et al*. (1987).

to the Kobayashi Pyroclastic Flow Deposits is positioning under Ks5 correlated to Oda in KKG.

The purpose of this study is to examine the correlation of Oda with Ks5, considering the petrographic properties of Nb and Oda, based on detailed petrographic properties of them, such as glass chemistry, refractive indices of volcanic glass shards, hornblende, and orthopyroxene.

## 2. Study Area and Stratigraphy

The 1000 km-long southern Kyushu-Ryukyu arc includes several large calderas such as the Kikai, Ata, Aira, Kakuto, and Kobayashi calderas from south to north. These are developed in the Kagoshima Graben which is the eastern margin of the volcano-tectonic depression. These calderas except the Kikai caldera provided huge ignimbrites by large caldera eruptions through the Middle to Late Pleistocene (Moriwaki *et al.* 1991) (Fig.1).

Along the northwest coast of the Kagoshima Bay, the KKG was firstly described by Ida *et al*. (1950) as a lacustrine sediment, and afterward redefinded by several authors (e.g. Otsuka and Nishiinoue 1980; Hase *et al*. 1987; Otsuka and Furukawa 1988; Sato *et al*. 2000). Otsuka and Furukawa (1988) argued that KKG has accumulated in shallow waters, consisting of massive silt, alternation of silt and sand layers, and tuff. Otsuka and Nishiinoue (1980) defined two pyroclastic flow deposits, Nb and Oda in ascending order. Nb and Oda are corresponded to the Komiyaji tuff breccia member and the Oda tuff member defined by Hase *et al*. (1987) in the KKG, respectively. According to the recent research by Sato *et al*. (2000), KKG is subdivided into the six geologic units, including the Kuwanomaru pumiceous tuff member (Shimokado PFD; Oki and Hayasaka 1970) newly defined (Fig. 2). In this paper, we refer to the stratigraphy of KKG (Fig. 2) shown by Sato *et al*. (2000). Figure 2 shows the correlations of the distal tephras in the Kasamori Formation and proximal ignimbrites in the southern Kyushu by previous studies (Kikkawa *et al*. 1991; Mizuno 1997; Suzuki and Fujiwara 1998; Machida and Arai 2003). Zircon-FT ages of 0.96 ± 0.17 Ma, 0.97 ± 0.22 Ma were obtained for Nb and Oda, respectively (Hase and Danhara 1985). Recently, an ITPFT age of 0.49 ± 0.06 Ma for Nb was obtained by Moriwaki *et al*. (2000).

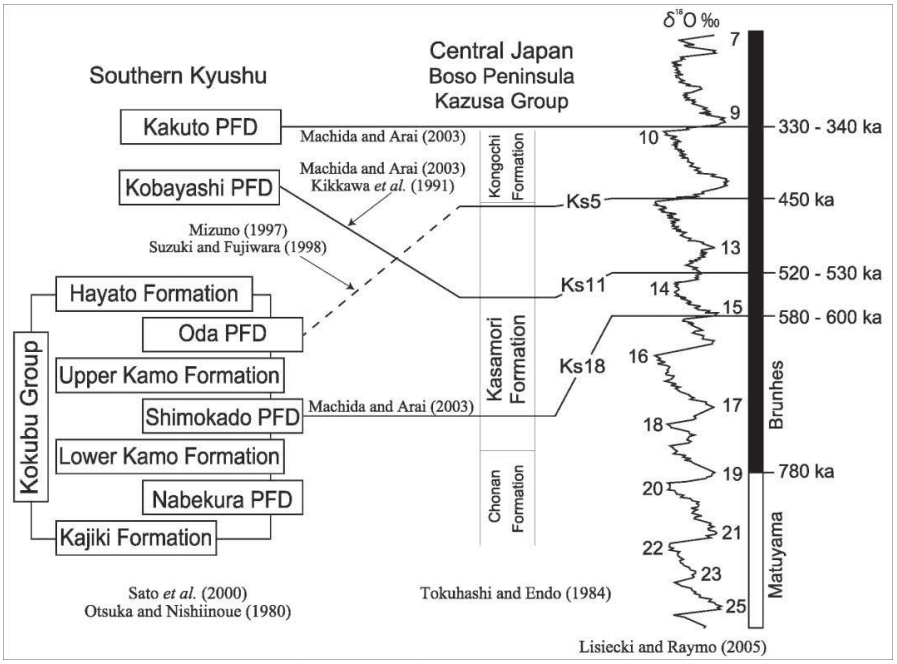


**Fig. 2** Correlation of the Middle Pleistocene ignimbrites distributed around the northwest area of the Kagoshima Bay and Ks-tephras in the Kasamori Formation.
The eruptive ages are after Machida (1999) and Machida and Arai (2003).

## 3. Method

The localities around the northern coastal area of the Kagoshima Bay are shown in Fig. 1. Samples of Nb and Oda were collected at outcrops shown in the geologic map by Hase *et al*. (1987). In the central Boso Peninsula, Ks5 was sampled at Uchihata in the Chiba prefecture (N35°27′38″, E140°14′02″ with WGS84).

Each sample was washed several times. Pumice clast was crushed into coarse sand-sized grains. The crushed samples were cleaned using an ultrasonic bath until the clay and silt had been removed. After drying and sieving, the grains 0.25 to 0.063 mm in diameter were used for fingerprinting. Refractive indices of volcanic glass shards, hornblende, and orthopyroxene were determined by the thermal immersion method (Danhara *et al.* 1992) using the RIMS2000 Refractive Index Measuring System (Kyoto Fission-Track Co., Ltd.). Major element compositions of volcanic glass shards from pyroclastic flow deposits and ash fall deposits were determined by an energy dispersive X-ray spectrometer (EDAX GENESIS APEX2 and JEOL JSM-6390) according to the method shown by Suzuki *et al*. (2014).

## 4. Results and Discussion

### Description

In this section, we describe the lithological and petrolographic properties of three tephra layers, that is, two pyrocrastic deposits as Nb and Oda, and one volcanic ash fall deposit as Ks5.

*Nabekura Pyroclastic Flow Deposits (Nb)*

At the type locality (Fig. 1), the cliff of the Tenpukuji in the Aira city, Nb is exposed with a thickness of > 60 m, as non-welded pyroclastic flow deposit. Nb is unconformably underlain by the Kajiki Formation around the type locality (Otsuka and Nishiinoue 1980). The base of the pyroclastic flow deposit cannot be observed. This lithofacies is massive, light to dark gray colored deposit with no internal structures. The basal part of Nb is a tuff breccia dominated by 10–50 mm lapilli and blocks approximately 10 cm in diameter within a matrix of medium-coarse ash. Nb is poorly sorted, matrix-supported, and rich in white pumice clasts. The pumice clasts are moderately vesiculated, angular to subangular, mainly 1–5 cm, up to 20 cm in length. The accessory fragments of andesite are angular with diameters of several centimeters.

Nb contains abundant orthopyroxene, and small numbers of clinopyroxene and hornblende. The average grain size of phenocrysts is smaller than 1 mm. The refractive indices of orthopyroxene and hornblende are $\gamma$: 1.705–1.708 and $n_2$: 1.669–1.686, respectively (Table 1). Nb is characterized by fiber type and sponge type of volcanic glass shards whose refractive index and chemical composition are n: 1.499–1.505 (1.502–1.503), $SiO_2$: 76.2–77.6 wt.%, $Al_2O_3$: 12.6–12.8 wt.%, FeO*: 1.2–1.6 wt.%, CaO: 1.2–1.5 wt.%, $K_2O$: 3.3–3.6wt.%, and $Na_2O$: 2.7–3.4 wt.% (Tables 1 and 2).

*Oda Pyroclastic Flow Deposits (Oda)*

At the type locality of Oda, the Forestry Road in Odanishi, the north-west of the Hayato Town (Fig. 1), Oda with a thickness of > 70 m is exposed, as non-welded pyroclastic flow deposit. Oda is overlain by a greyish silt layer of the Hayato Formation. This lithofacies is composed of massive, light brown colored deposit with no internal structures. The basal part of Oda is a tuff breccia dominated by 10–30 mm lapilli within a matrix of coarse-fine ash. Oda is poorly sorted, matrix-supported, and including white pumice clasts. The pumice clasts are poorly to moderately

vesiculated, angular to subangular, mainly 3 cm, up to 15 cm in length. The accidental fragments are subangular, composed of andesite, up to 10 cm in length.

Oda contains abundant orthopyroxene, and relatively few hornblende and clinopyroxene. The average grain size of phenocrysts is smaller than 2 mm in diameter. The refractive indices of orthopyroxene and hornblende are γ: 1.708–1.712 and $n_2$: 1.669–1.686, respectively (Table 1). Oda is characterized by abundant fiber type and stripe type of volcanic glass shards whose refractive index and chemical composition are n: 1.501–1.504 (1.503–1.504), $SiO_2$: 76.3–76.9 wt.%, $Al_2O_3$: 12.7–12.9 wt.%, FeO*: 1.5–1.8 wt.%, CaO: 1.4–1.6 wt.%, $K_2O$: 3.0–3.3 wt.%, and $Na_2O$: 3.4–3.8 wt.% (Tables 1 and 2).

We recognized Oda at six localities (Fig. 1; AI01 to AI04, KM01, and IS01). The mode of refractive index and chemical composition of the volcanic glass shards in these pyroclastic flow deposits are n: 1.504–1.505, $SiO_2$: 76.1–77.5 wt.%, $Al_2O_3$: 12.6–13.0 wt.%, FeO*: 1.3–1.7 wt.%, CaO: 1.4–1.6 wt.%, $K_2O$: 2.9–3.3wt.%, and $Na_2O$: 3.0–3.8 wt.% (Tables 1, 2 and Fig. 3).

**Table 1** Petrographic properties of tephras

| Sample | Composition<br>volcanic glass; heavy mineral | Refractive index<br>(gl: n, ho: $n_2$, opx:γ) | | |
|---|---|---|---|---|
| AI01 | fib, spg, str, bw; opx, cpx ≫ ho | gl: 1.502-1.506 (1.505) | ho: 1.670-1.686 | opx: 1.707-1.712 |
| AI02 | fib, str, spg, bw; opx, cpx ≫ ho | gl: 1.501-1.505 (1.504-1.505) | ho: 1.670-1.684 | opx: 1.709-1.714 |
| AI03 | fib, spg, bw; opx, cpx ≫ ho | gl: 1.502-1.505 (1.504-1.505) | ho: 1.669-1.683 | opx: 1.708-1.713 |
| AI04 | fib, spg, bw; opx, cpx ≫ ho | gl: 1.503-1.506 (1.504-1.505) | ho: 1.666-1.685 | opx: 1.707-1.712 |
| KM01 | bw, fib, spg; opx > cpx ≫ ho | gl: 1.502-1.505 (1.504-1.505) | ho: 1.670-1.683 | opx: 1.708-1.713 |
| IS01 | bw, fib, str, spg; opx, cpx ≫ ho | gl: 1.502-1.506 (1.504-1.506) | ho: 1.668-1.689 | opx: 1.706-1.712 |
| Oda | fib, str > bw; opx > ho, cpx | gl: 1.501-1.504 (1.503-1.504) | ho: 1.669-1.686 | opx: 1.708-1.712 |
| Nb | fib, spg > str, bw; opx > cpx, ho | gl: 1.499-1.505 (1.502-1.503) | ho: 1.669-1.686 | opx: 1.705-1.708 |
| Ks5 | bw; opx, ho | gl: 1.505-1.506 (1.505) | ho: ——— | opx: ——— |
| OgA | ——— | gl: 1.502-1.505 (1.503-1.504) | ho: ——— | opx: ——— |
| Hg-7 | ——— | gl: 1.503-1.504 | ho: ——— | opx: ——— |

† fib: fiber type, spg: sponge type, str: stripe type, bw: bubble wall type, opx: orthopyroxene, cpx: clinopyroxene, ho: hornblende.
Refractive indices of OgA and Hg-7 of volcanic glass shards are shown by Nakazato *et al.* (2005) and Takahashi and Hayakawa (1995).

**Table 2** Major element composition of volcanic glass shards

| Sample | Type | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO* | MnO | MgO | CaO | $K_2O$ | $Na_2O$ | Total | n |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AI01 | pfl | 76.7 | 0.4 | 12.8 | 1.5 | 0.1 | 0.4 | 1.5 | 3.2 | 3.4 | 94.2 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.7 | |
| AI02 | pfl | 76.7 | 0.4 | 12.8 | 1.6 | 0.1 | 0.4 | 1.5 | 3.1 | 3.4 | 94.7 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 | 0.1 | 0.8 | |
| AI03 | pfl | 76.9 | 0.4 | 12.8 | 1.5 | 0.1 | 0.4 | 1.5 | 3.0 | 3.5 | 95.9 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 1.0 | |
| AI04 | pfl | 76.9 | 0.4 | 12.8 | 1.5 | 0.1 | 0.4 | 1.5 | 3.1 | 3.4 | 95.2 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 | 0.1 | 0.5 | |
| KM01 | pfl | 76.7 | 0.4 | 12.8 | 1.5 | 0.1 | 0.4 | 1.5 | 3.1 | 3.6 | 98.4 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 0.6 | |
| IS01 | pfl | 76.8 | 0.3 | 12.8 | 1.6 | 0.1 | 0.4 | 1.5 | 3.1 | 3.5 | 91.8 | 16 |
| | | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 1.0 | |
| Oda | pfl | 76.8 | 0.4 | 12.8 | 1.6 | 0.1 | 0.4 | 1.5 | 3.1 | 3.5 | 93.6 | 16 |
| | | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 0.7 | |
| Nb | pfl | 77.2 | 0.3 | 12.7 | 1.4 | 0.1 | 0.4 | 1.4 | 3.4 | 3.1 | 92.1 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.2 | 0.6 | |
| Ks5 | afa | 77.2 | 0.4 | 12.6 | 1.4 | 0.1 | 0.4 | 1.4 | 2.9 | 3.7 | 96.6 | 16 |
| | | 0.2 | 0.0 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 | 0.1 | 0.7 | |
| OgA | afa | 77.0 | 0.3 | 12.7 | 1.5 | 0.1 | 0.4 | 1.4 | 2.9 | 3.7 | 92.6 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.4 | |
| Hg-7 | afa | 77.3 | 0.3 | 12.6 | 1.4 | 0.1 | 0.4 | 1.4 | 3.0 | 3.6 | 92.8 | 16 |
| | | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 0.5 | |

Analysis recalculated to 100 % on a volatile-free basis and presented as mean and standard deviation of n shards analysis. FeO*, total iron oxide as FeO.

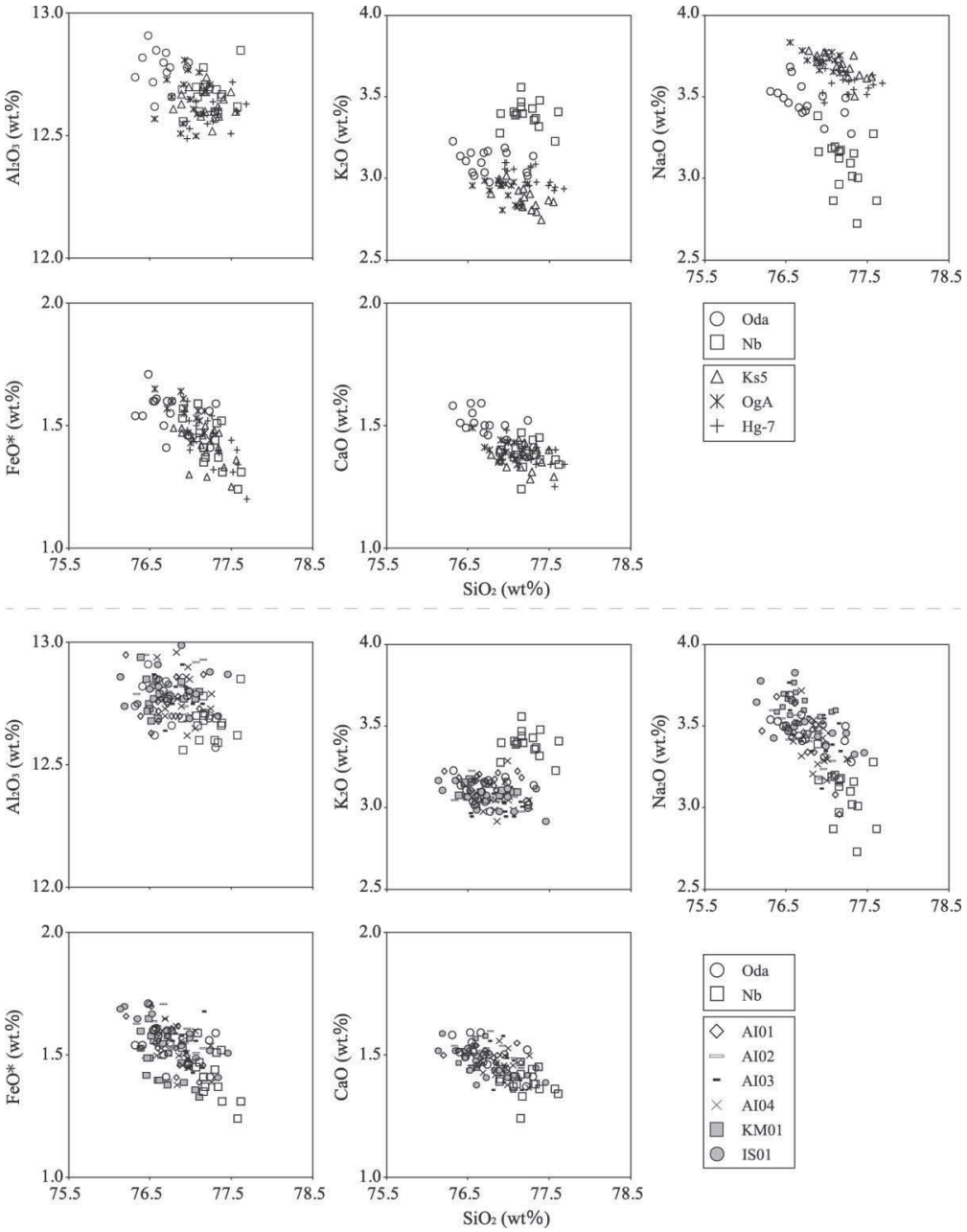


**Fig. 3** Comparison of chemical composition of glass shards.

*Ks5 Tephra*

Ks5 is a whitish fine vitric ash layer with a thickness of 20 cm, exposed at Uchihata in Nagara Town (N35°27′38″, E140°14′02″). The sample for the analysis was collected from the basal part. Ks5 is characterized by an abundant bubble-wall type glass shards and small amount of hornblende

and orthopyroxene. Refractive index and chemical composition of Ks5 glass shards are n: 1.505–1.506 (1.505), $SiO_2$: 76.8–77.6 wt.%, $Al_2O_3$: 12.5–12.7 wt.%, FeO*: 1.3–1.5 wt.%, CaO: 1.3–1.4 wt.%, $K_2O$: 2.8–3.0 wt.%, and $Na_2O$: 3.5–3.8 wt.% (Tables 1, 2 and Fig. 3).

**Difference in petrographic properties between Nb and Oda**

The mineral assemblage of mafic minerals in Nb is similar to that in Oda, both containing orthopyroxene and small amount of hornblende and clinopyroxene (Table 1). The range of refractive index of volcanic glass shards is also similar between Nb (n: 1.499–1.505) and Oda (n: 1.500–1.504), whereas that of orthopyroxene are evidently different. Oda bears orthopyroxene with higher refractive index (γ: 1.708–1.712) compared with that of Nb (γ: 1.705–1.708). The difference in glass chemistry between Nb and Oda is also obvious as shown in the $SiO_2$-$K_2O$, $SiO_2$-CaO, and $SiO_2$-$Na_2O$ diagrams particularly (Fig. 3). Nb glass shards have higher $SiO_2$ and $K_2O$ contents, and lower $Al_2O_3$, FeO, CaO, and $Na_2O$ contents than those of Oda glass (Table 2 and Fig. 3). Thus, Oda is clearly distinguished from Nb in each petrographic property.

**Re-examination of the correlation of Oda and Ks5**

We re-examined the correlation of Oda to Ks5 proposed by previous studies, considering other Middle Pleistocene distal vitric tephras petrographically similar to Ks5 such as Ogoyama Volcanic Ash (OgA; Nakazato *et al.* 2005) in Northeast Kanto Plain, central Japan, and Hikage 7 Volcanic Ash (Hg-7; Takahashi and Hayakawa 1995) in the Nakanojo Basin, North Kanto. OgA and Hg-7 are correlated to BT72 tephra in the Osaka Group (Nakazato *et al.* 2005). The estimated age of BT72 is 349 ka (Nagahashi *et al.* 2004). The ranges of refractive indices of volcanic glass shards in OgA and Hg-7 are n: 1.503-1.504 and n: 1.502-1.505, respectively, shown by Nakazato *et al*. (2005) and Takahashi and Hayakawa (1995). The chemical compositions of volcanic glass shards in OgA and Hg-7 are $SiO_2$: 76.6–77.6 wt.%, $Al_2O_3$: 12.5–12.8 wt.%, FeO*: 1.3–1.7 wt.%, CaO: 1.3–1.4 wt.%, $K_2O$: 2.8–3.1 wt.%, and $Na_2O$: 3.5–3.8 wt.% (Table 2 and Fig. 3).

In comparison of chemical compositions of volcanic glass shards, it was found that the compositions are very similar among Ks5, OgA, and Hg-7, however differ from Nb and Oda (Table 2 and Fig. 3). Oda glass shards have higher $Al_2O_3$, FeO and CaO contents, and lower $SiO_2$ contents than those of others (Table 2 and Fig. 3). The difference in glass chemistry between Oda and Ks5 is clear as shown in the $SiO_2$-$K_2O$ and $SiO_2$-$Al_2O_3$ diagrams (Fig. 3). As shown in Table 2, Oda glass shards show 0.4 wt.% lower mean $SiO_2$ content (76.8 wt.%) than Ks5 glass (77.2 wt.%). Thus, the major oxide compositions of the Oda are different beyond analytical uncertainties from those of distal fallout ashes. Consequently, Oda is not correlated to Ks5. These results are inconsistent with previous correlation by Mizuno (1997) and Suzuki and Fujiwara (1998).

## 5. Conclusion

In this study, we discussed the petrographic differences between two pyroclastic flow deposits (Oda and Nb) intercalated in the Kokubu Group in the northwest area of the Kagoshima Bay, and re-examined the correlation of Oda with Ks5 intercalated in the Kasamori Formation of the Kazusa Group in the Boso Peninsula. As a result, Nb and Oda are clearly distinguished by refractive indices of orthopyroxene and variation in the chemical composition of volcanic glass shards. The previous correlation of Oda is denied not only with Ks5, but also with similar distal tephras such as OgA and Hg-7. This result solves the inconsistency caused by the correlation of Oda with Ks5 as its

widespread tephra. On the other hand, the similarity indicates that Ks5 is most likely originated from the volcano in the Kyushu Island. It means that the proximal tephra of Ks5 should be found.


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