Abstract

The purpose of this study is to clarify the stratigraphy and distribution of Middle Pleistocene pyroclastic flow deposits in the southern Kyushu Caldera Region based on petrographic characteristics and to delineate the history of huge caldera-forming eruptions in the caldera region including the eruptive ages estimated from stratigraphic positions. The author analyzed the lithology and samples from the pyroclastic flow deposits in the northern coastal area of Kagoshima Bay in southern Kyushu. The author also identified the petrographic characteristics of the pyroclastic flow deposits and examined their correlation with co-ignimbrite ash fall deposits (CAFDs) derived from large-scale pyroclastic flow. The author comprehensively studied the eruptive ages of tephras based on the radiometric ages and stratigraphic locations of proximal pyroclasts and CAFDs in several areas. Based on the eruptive ages, the author discussed the frequency of large-scale explosive eruptions in the southern Middle Pleistocene Kyushu Caldera Region.

Eight pyroclastic flow deposits were identified. In ascending order, they are: Komiyaji (Kmj), Sagise (Sgs), Nabekura (Nb), Shimokado (Smkd), Oda (Oda), Fumoto Tuff, Kobayashi (Kb-Ks), Takeyama (Tkym) and Hegawa (Hgw). The tuff originated from the Aira Caldera, as Middle Pleistocene tephra stratigraphically below Kb-Ks (520–530 ka). In addition, three new widespread tephras were identified based on the re-examination of correlations between the pyroclastic flow deposits and distal ash fall deposits: Shimokado-Ks18 (Smkd-Ks18), Takeyama-Ks10 (Tkym-Ks10), and Hegawa-Ks5 (Hgw-Ks5).

Based on previous isotope stratigraphy studies, the eruptive ages of Smkd-Ks18, Tkym-Ks10, and Hgw-Ks5 are 570–580 ka (MIS 15), 480–530 ka (MIS 13), and 430–450 ka (MIS 12), respectively. The apparent volume of each tephra estimated from the distribution area and thickness of the CAFD is approximately 100 km^3, assuming that each CAFD originating from the Aira Caldera is distributed concentrically. Therefore, a Volcanic Explosivity Index (VEI) of 7 was assigned to the eruptions.

A gigantic eruption leading to a CAFD occurred on average once every ~40 ka during the period from 580 to 450 ka, with longer intervals of large-volume eruptions after the eruption of Hgw-Ks5 (430–450 ka). Between the Smkd-Ks18 to Hgw-Ks5 eruptions, gigantic eruptions occurred at intervals of 40 ka, whereas they took place at an interval of ~100 ka after that period, up to the Ata (105 ka) eruption. The volcanic activity of the Middle Pleistocene in the southern Kyushu Caldera Region was considered to be more active between the Sgs and Hgw-Ks5 eruption, approximately 600 to 400 ka.

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1 Introduction

The southern Kyushu caldera region composed of the several large calderas, located in southwest of the Japanese islands, is one of the most active volcanic regions providing widespread or volumious tephras. Although the widespread tephras are a common chronological tool, controversies remain in the studies of the proximal tephrostratigraphy such as the stratigraphy of the Early–Middle Pleistocene pyroclastic flow deposits (PFDs) in southern Kyushu. Many geological studies (e.g. Oki and Hayasaka 1970; Oki 1974; Hase 1978; Hase *et al*. 1987; Otsuka and Nishiinoue 1980; Sato *et al*. 2000) described and integrated the succession of Quaternary PFDs in the southern Kyushu to identify the local stratigraphy. The purpose of previous studies was to clarify the distribution and stratigraphic relationships of Quaternary volcanic and non-volcanic deposits in this region. However, there is no unified stratigraphy, especially in the Early to Middle Pleistocene due to difficulties in confirming the stratigraphic relationships among older PFDs and due to the fact that the lithofacies are only based on field observations in the proximal caldera area. Lithofacies of PFDs generally depends on the sedimentary environment, which affects the mode of emplacement. Moreover, the older PFDs are usually buried under younger deposits or eroded. Particularly, depositions of gigantic PFDs with thicknesses large enough to bury low-relief landforms, such as valleys and hills, hinder the establishment of their stratigraphy. At the same time, it is problematic that the eruptions generating such massive deposits occur repeatedly. Outcrops displaying the boundaries among the ignimbrites are therefore limited and few. According to Moriwaki (2010), approximately 100 or more tephras have been documented in southern Kyushu in the late Quaternary period since the 1970s. This means that more detailed tephrostratigraphical information of the Late Quaternary in this region has become available during the last three (to four) decades. Nevertheless, compared with the tephras of the Late Pleistocene to Holocene, widespread markers of the Early to Middle Pleistocene ages have not been well identified. Eight widespread tephras have been reported from the southern Kyushu caldera region since 1 Ma. Five of them occurred in a cluster after the eruption of the Kakuto tephra (330–340 ka; Machida and Arai 2003). It is difficult to evaluate the frequency of large-scale eruptions using previously published data, which lack a sufficient identification and detailed petrographic PFD properties such as glass chemistry. It is necessary to establish the comprehensive stratigraphy of the PFDs to examine the spatial–temporal transition of the Quaternary volcanism in southern Kyushu. Indeed, previous petrographic studies attempted to distinguish and correlate the described and locally named PFDs (Aramaki and Ui 1976; Miyachi 1987). However, these studies do not include detailed petrographic property descriptions of the PFDs, including the chemistry of volcanic glass shards. The chemical composition of volcanic glass shards is one of the important properties for the clarification of source caldera and identification of tephra (e.g. Smith and Westgate 1969; Stokes and Lowe 1988; Koehn and Foit 2006).

It is well known that there are petrographically similar proximal PFDs and distal ash fall deposits similar to these PFDs, which leads to difficulties and mistakes in the widespread correlation. The Kokubu Group (Ida *et al.* 1950; Otuka and Nishiinoue 1980; Hase 1978; Hase *et al*. 1987; Otsuka and Furukawa 1988; Sato *et al*. 2000; Kagawa and Otsuka 2000), which accumulated in shallow waters, intercalates three PFDs with unclear stratigraphic positions: Nabekura Pyroclastic Flow Deposits (Nb; Otsuka and Nishiinoue 1980), Shimokado Pyroclastic Flow Deposits (Smkd; Oki and Hayasaka 1970) and Oda Pyroclastic Flow Deposits (Oda: Otsuka and Nishiinoue 1980). The Smkd and Oda PFDs are widely distributed and similar to the Hiwaki (Hwk; Machida and Arai 2003) and Oda-Ks5 tephra (Machida 1999), respectively. For each tephra, there are petrographically similar distal ash fall deposits as the candidate to correlate with proximal ignimbrites. Nishizawa and Suzuki (2015) distinguished the petrographically similar ignimbrites (indiscernible by mineral assemblage) Oda and Nb and solved the inconsistency caused by the correlation of Oda with Ks5 as its widespread tephra. On the other hand, the proximal ignimbrite of Ks5 has not yet been determined, although the petrographical similarity between Oda and Ks5 suggests that Ks5 most likely originated from southern Kyushu (Mizuno 1997). The Hiwaki tephra, which erupted from a certain caldera in southern Kyushu during the Middle

Pleistocene, is one of the most important key beds in the whole area of the Japanese Islands (Machida and Arai 2003). Machida and Arai (2003) correlated Smkd to Ks18 (Ksm18 vitric ash fall deposit) in the Kasamori Formation of the Kazusa Group in the Boso Peninsula, central Japan.

Hwk is a unified name that summarizes PFDs, which have various local names (including Smkd) in each area in southern Kyushu. However, correlation and identification of Smkd in southern Kyushu are problematic as discussed in this study. Furthermore, Ks10 above Ks18, both in the Kasamori Formation, is petrographically similar to Smkd, resulting in a complex widespread correlation of Smkd. Nishizawa and Suzuki (2013) discussed the petrographic similarities among Smkd, Ks18 and Ks10. They suggest the necessity for the re-examination of the correlation of other distal ash fall deposit that have already been unified as Hwk.

As discussed above, the identification of the Middle Pleistocene PFDs in the southern Kyushu and their widespread correlations are still unsolved. In this study, the author reveals the petrographic properties of tephras, including resedimented pyroclasts, to establish the stratigraphy of the Middle Pleistocene PFDs in the southern Kyushu caldera region. In addition, the author proposes a new correlation of widespread distal ash fall deposits with proximal PFDs based on petrographic properties. Finally, the spatial-temporal transition of volcanic activity of the Middle Pleistocene is discussed. This study is significant for volcanology and Quaternary chronological studies. The definition of widespread tephras based on precise correlations of detailed petrographic properties contributes to the delineation of the history of explosive eruptions around the Kagoshima Graben and general tephrostratigraphical framework of an active caldera region in southern Kyushu. It is powerful tool to qualitatively elucidate the stratigraphy of caldera regions qualitatively.

2 Previous studies

2.1 Regional settings and Quaternary explosive volcanism in the southern Kyushu caldera region

Tectonic setting of southern Kyushu and formation of the Kagoshima Graben

The western margin of the Philippine Sea Plate subducts beneath the Eurasian Plate (Fig.1), creating the Ryukyu arc-trench system along the 1000-km-long. The active volcanisms of southern Kyushu Island are dominated by the interactions of the Philippine Sea Plate and Amur Plate (Seno 1977; Taira 2001). Kyushu-Ryukyu arc includes several large calderas such as the Kikai, Ata, Aira, Kakuto, and Kobayashi calderas from south to north (Fig.2) (Matumoto 1943; Tajima and Aramaki 1980). These calderas lie on the Kagoshima Graben (Tsuyuki 1969), which is recognized as a volcano-tectonic depression. This depression is formed more than 100 km long, trending N-S, and 20-30 km wide across southern Kyushu of the Shimanto Supergroup (Uto *et al*. 1997). These calderas had provided huge ignimbrites by large caldera-forming eruptions through the Quaternary period (Moriwaki *et al*. 1991).

The Aira caldera (approximately 20 x 18 km) occupies northern end of the Kagoshima Bay (Figs. 2 and 3). The Aira pyroclastic eruption (Aramaki 1969; Machida and Arai 1976; Kobayashi *et al*. 1983; Fukushima and Kobayashi 2000), which produced the Aira caldera, occurred 30,000 years ago (30.009 ± 0.189 cal ka BP: Smith *et al*. 2013). Ito pyroclastic flow, which is the final catastrophic eruption of the Aira pyroclastic eruption, generated a vast ignimbrite plateau over southern Kyushu. Machida and Arai (1976, 1983) firstry described Aira-Tn tephra (AT) originated from the Aira eruption as co-ignimbrite ash fall deposits (Sparks and Walker 1977) and found it up to 1,400 km from south Kyushu. This eruption has been classed as Volcanic Explosivity Index 7 (VEI; Newhall & Self 1982) and one of the largest eruptions in Late Pleistocene in Japan (Machida and Arai 2003).

Matumoto (1943) thought that “Ata caldera” is located at the the southern end of the Kyushu Island and the Ata pyroclastic flow eruption has formed “Ata caldera” (the western margin of Onkadobira Fault Scarp). However, Aramaki and Ui (1966) pointed out that Ata Pyroclastic Flow Deposit (Ata) is not distributed in the "Ata caldera" because of its depositional structure, xenolith's composition and gravity anomaly. The opinion that the source of Ata pyroclastic flow is located in the Kagoshima Bay on the northside of "Ata caldera" has become more dominantly (Kawanabe and Sakaguchi 2005). On the other hand, according to Machida and Moriwaki (2001), the "Ata caldera" proposed by Matumoto (1943) is called South Ata caldera. They considered the possibility that "Ata caldera" was the source of the Ata Toihama eruption (Nagaoka 1988), which produced Ata-Th tephra (240 ka; Machida and Arai 2003) and erupted before Ata eruption (105 ka; Matsumoto and Ui 1997). In this study, the author follows their interpretations and shows show as North and South Ata calderas in Figure 2.

The northern volcanic center in the Kagoshima Graben (Fig. 2) is comprised by two calderas: Kakuto and Kobayashi calderas. They are located northwest of Kirishima volcano and formed in 340–330 ka and 530–520 ka, respectively (Tajima and Aramaki 1980; Machida and Arai 2003). The active phase of Kirishima volcano has been divided into two stages by the eruption of Kakuto Pyroclastic Flow Deposits (Kkt) (Imura and Kobyashi 2001). The former period began around 600 ka (Nagaoka *et al*. 2010; Nagaoka and Okuno 2011). Nagaoka *et al*. (2010) established the last 1 myr tephrostratigrapy in the Miyazaki plain, describing not only the tephras derived from Kirishima volcano but also those from other volcanoes, in the southern Kyushu. Nagaoka *et al*. (2010) is the first study to attempt to construct the continuous and comprehensive tephrostratigraphy of the Middle Pleistocene to Holocene in the southern Kyushu caldera region and is an important study for the history of volcanic activity in this region.

Although the process of the graben formation is unknown in detail, it is inferred that the Kagoshima Graben had activated of at least 3 Ma as volcano-tectonic depression, judged from the following evidence.

First, on the bottom of the Kagoshima Bay in the western part of the Aira Caldera, the Terukuni Pyroclastic Flow Deposits (Hayasaka and Oki 1971; Oki *et al*.

1990) are overlying the basement Shimanto Group with step-faulting. In addition, the sedimentation of the marine deposits named the Kekura Formation without the step-fault structure is above the Terukuni Pyroclastic Flow Deposits. This means that Kagoshima Graben has been down-faulted immediately after the eruption of Terukuni Pyroclastic Flow Deposits (2.9 Ma; Shibata *et al*. 1978). Also, the eruptive age of this ignimbrite reffered to as Izaku Pyroclastic Flow Deposits (Izk-Hs; Torii and Oda 2001) (Aramaki and Ui 1966) is estimated to be 3.3 Ma on the basis of the correlation of HST-4 tuff intercalated in the Miyazaki Group (Torii and Oda 2001).

That is, second, effusion of lavas distributed around the Aira caldera. Sudo *et al*. (2000, 2001) constructed a volcanic history before the explosive Aira pyroclastic eruption by K-Ar dating method, and showed the times-space distribution of the pre-caldera volcanism after 3 Ma, that is, 1) effusions of andesitic lava flows (Hokusatsu volcanic rocks) (3 to 1 Ma), 2) effusions of andesitic lava flows (Yuwandake andesite) at the northern area, and basaltic to rhyolitic lava and pyroclastic flows at the western area(1 to 0.5 Ma), 3) effusions of basaltic (Ushine basalt) and rhyolitic (Okoga-shima rhyolite) lava flows at the southern area (0.5 to 0.1 Ma), 4) effusions of andesitic lava (Shikine andesite) and pyroclastic flows at the northern area and rhyolitic lava flows (Shimizu and Ushine rhyolites) both at the northern and southern areas (0.1 to 0.025 Ma). Third, Yamaji (2003) indicates the back-arc rifting started ~4 Ma in association with slab rollback based on the fault sets developed in the deposits of the Miyazaki basin on the fore-arc side of Kagoshima Graben. Fore-arc stress changed from compression to extension about 4 Ma and has remained unchanged since that time (Yamaji 2003).

Studies on identification of the Early to Middle Pleistocene pyroclastic flow deposits

It is presumed that the explosive volcanism of silicic magma simultaneously induced the development of rifting of the graben. In Early to Middle Pleistocene periods, many large-scale pyroclastic flows, including those of which source calderas have not yet been identified, were reported by previous works (e.g. Aramaki 1969; Oki and Hayasaka 1970; Oki 1974; Aramaki and Ui 1976; Aramaki 1977; Otsuka and

Nishiinoue 1980; Suzuki *et al*. 1985; Miyachi 1987; Uchimura *et al*. 2007). Excluding local stratigraphic studies, Aramaki & Ui (1976) and Miyachi (1987) had examined to identify and integrate several Quaternary PFDs focusing on petrographic methods.

Tephra layers from discrete eruptions often differ in such their glass and mineral compositions, types of glasss shard, relative proportions of minerals and glass. These characteristics, together with stratigraphic position, can be used to identify the source eruption or source volcano of tephras. Use of the electron microprobe analysis (EPMA) to determine the geochemical signature (9 to 12 major and minor elements) of volcanic glass shards is a well-established, widely used technique. The first application of electron probe technique for characterising pyloclasts was conducted by Smith and Westgate *et al*. (1969). Applications for tephrochronological purposes in Japan can be recognized by Furuta *et al*. (1986). In Japanese studies, refractive indices of volcanic glass shards and phenocrysts (especially orthopyroxene, hornblende, cummingtonite) are often used for identification of tephras, and it is one of the fundamental petrolographic properties that makes it possible to identify tephras (Arai 1972).

Aramaki and Ui (1976) attempted to correlate many PFDs in the southern Kyushu using Ca-Mg-Fe ratios of the specific phenocrysts such as orthopyroxene, and identified more than fifty ignimbrites. Miyachi (1987) also attempted to identify PFDs utilizing five criteria such as 1) mineral assemblages, 2) refractive indices of glass shards and some phenocrysts, 3) chemical compositions of volcanic glass shard, 4) paleomagnetic polarity and 5) zircon fission-track (Zr-FT) ages. They concluded that the most of pyroclastic flow deposits (122 PFDs) in southern Kyushu are classified into 19 units. However, Miyachi (1987) had not specified analytical method and measurement condition for Energy dispersive X-ray spectrometry, so that reproducibility had not been obtained from their examination.

Geological studies in the north and western part of Kagoshima City, including the Yoshino Plateau, were conducted by Oki & Hayasaka (1970), Hayasaka & Oki (1971), and Oki (1974). In this study, the author does not discuss the Quaternary stratigraphy of these areas, but briefly remark on the studies describing several Middle Pleistocene PFDs. PFDs described below have insufficient petrolographical examination. Oki and Hayasaka (1970) investigated Quaternary stratigraphy of the northern part of Kagoshima City in detail. They defined Shimokado Pumice Flow (Smkd), and positioned Yoshino Pumice Flow (Yoshino PFD: Ysn) stratigraphically below the Smkd. In addition, the Iso Tuffaceous Sand Member (Oki and Hayasaka 1970), the uppermost part of the Kekura Formation constituting the Yoshino Plateau (Fig. 3), unconformably covered by Yoshino PFD, is referred to as Iso Pyroclastic Flow Deposits (Iso) (Suzuki *et al*. 1985). However, the stratigraphic relationship between Yoshino PFD and Smkd is not mentioned. Hayasaka and Oki (1971) described subsurface geology of Kagoshima City by the boring core survey, and they showed the occurrence of Arata and Yoshino PFDs above the Kekura Formation, in ascending order. According to Oki (1974), at least four PFDs have been recognized as Pleistocene PFDs stratigraphically below the Smkd, such as the Kukida, Keno, Ishiki and Kamogahara PFDs, in ascending order (Oki 1974). These are positioned between the marine Kogashira and the Kekura Formations. The former is directly covered by Smkd. Miyachi (1980) also found seven PFDs referred as the Omine Pyroclastic Flow Deposits 1 to 7 in a 250-meter core from Omine town, Kagoshima City. Based on their mineral composition, some of them are correlated with previous PFDs by Miyachi (1980), such as Omine-1 to Goino Pyroclastic Flow (Taneda and Miyachi 1969), Omine-6 to Kkt, and Omine-7 to AT (Miyachi 1980), in ascending order.

2.2 Quaternary stratigraphy of the northwest coastal area of the Kagoshima Bay and stratigraphic problems of Early to Middle Pleistocene tephras

The study area shown in Figure 3 is comprised of alluvial plain, hill, maars, and broad ignimbrite uplands. The Kokubu Group (KKG) which contains tephras derived mainly from pre-Aira caldera is distributed around the coastal area of the northern Kagoshima Bay. Ida *et al*. (1950), Hase (1978), Otsuka & Nishiinoue (1980) and Hase *et al*. (1987), Kagawa & Otsuka (2000) and Sato *et al*. (2000) described PFDs of the late Pliocene to Pleistocene period and interbedded marine strata.

The KKG was firstly described by Ida *et al*. (1950) as a lacustrine sediment, and afterward redefinded by several authors such as Hase (1978), Otsuka and Nishiinoue (1980), Hase *et al*. (1987), Otsuka and Furukawa (1988) and Sato *et al*. (2000). Hase (1978) divided the KKG into two formations, the Kajiki Formation as the lower part and the Kokubu Formation as the upper part, due to the existence of uncomformity in the KKG defined by Ida *et al*. (1950). In addition, Hase (1978) distinguished two main Quaternary tuffs: the Komiyaji Tuff Member (Hase 1978) and the Hayato Pumice Flow (younger tuff termed by Ota 1967). Otsuka and Nishiinoue (1980) surveyed around the northern coastal area of the Kagoshima Bay more broadly than previous studies and divided the KKG into five stratigraphic units; the Kajiki Formation, the Nabekura PFD (Nb), the Kamo Formation, the Oda PFD (Oda) and Hayato Formation in ascending order. They concluded that Nb corresponds to Komiyaji Tuff Member (Hase 1978) and Oda to Hayato Pumice Flow (Ota 1967, Hase 1978), respectively. On the other hand, without using the term of "the Kokubu Group", Hase *et al*. (1987) subdivided the Kokubu Formation and the Kajiki Formation based on the occurrence of Oda Tuff Member (PFD) and the Komiyaji Tuff Member (PFD), respectively (Fig. 4a). Otsuka and Furukawa (1988) concluded that the KKG is a continuous sucession, consisting of massive silt, alternating layers of silt, sand and tuff, which have accumulated in shallow waters. According to the recent research by Sato *et al*. (2000), the KKG was subdivided into the six geologic units, including the Kuwanomaru Pumiceous Tuff Member (Smkd; Oki and Hayasaka 1970) which is stratigraphically below Oda (Fig. 4a). On the other hand, Kagawa and Otsuka (2000) indicated that the Yoshidaji Pyroclastic Flow deposits which correlated to Smkd overlays the Hayato Formation stratigraphically above Oda (Fig. 4a). This discrepancy is caused by misidentification of the upper Kamo Formation as the Hayato Formation. Thus, stratigraphy of PFDs constructed by previous studies reviewed above is inconsistent. In this study, the author refers to the stratigraphy of the KKG shown by Sato *et al*. (2000) (Fig. 4a). Zr-FT ages of 0.96 ± 0.17 Ma, 0.97 ± 0.22 Ma were obtained for Nb and Oda, respectively (Hase and Danhara 1985).

The Kasamori Formation rests in the middle of the Plio-Pleistocene Kazusa Group, forearc basin-fill deposits up to 3 km thick in Boso Peninsula, Central Japan, 1,000 km northeast of the southern Kyushu (Fig. 1). The Kazusa Group is well-exposed and contains a remarkably continuous and thick, deep- and shallow-water marine sedimentary succession. This group also contains well-preserved marine microfossils, pollen, paleomagnetic reversal events, geochemical signatures, and a large number of tephra beds (e.g. Niitsuma 1976; Sato *et al*. 1988; Tokuhashi and Endo 1984; Kazaoka *et al*. 2015). The Kasamori Formation is approximately 300 m in thickness (Nanayama *et al.* 2016). The main part of this formation is composed of highly bioturbated deposits, such as sandy mudstone and muddy sandstone (Nanayama *et al*. 2016). The uppermost horizon of nannofossil datum examined by Sato *et al*. (1988) is in the middle part of the Kasamori Formation, which is considered to be below the last appearance datum of *Pseudoemiliania lacunosa* (410 ka, Sato *et al*. 1999; 433 ± 20 ka in the Ontong Java Plateau, Berger *et al*. 1994; 440 ka in the eastern equatorial Pacific, Gradstein *et al*. 2012). Many fall-out tephras, in the Kasamori Formation are named Ks1 (uppermost) to Ks23.5 (lowermost) (Kawai 1952; Tokuhashi and Endo 1984). As shown below, four widespread tephras (Ks18, 11, 10, and 5), which has been pointed out to be related to PFDs in southern Kyushu caldera region, are intercalated in the Kasamori Formation. Figure 5 shows the correlations of the distal ash fall deposits in the Kasamori Formation and proximal ignimbrites in the southern Kyushu by previous studies.

Kasamori 5 tephra (Ks5) and Kasamori 11 tephra (Ks11)

Ks5 tephra (Ks5; Machida *et al.* 1980; Tokuhashi and Endo 1984) in the Kasamori Formation was considered to be one of Middle Pleistocene widespread tephras derived from a certain caldera in Kyushu Island, SW Japan. Thus, Ks5 (400–450 ka; Machida 1999) was correlative to Oda distributed in the northwest area of the Kagoshima Bay (Fig. 3), based on the glass chemistry (Mizuno 1997; Suzuki and Fujiwara 1998). Ash fall deposits 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; Suzuki & Fijiwara 1998) and on the continental slope off

Shimokita Peninsura (Matsu’ura *et al*.; in press) (Fig. 5). However, these correlations are inconsistent with the stratigraphical relationship of Ks5 and another distal tephra in Boso Peninsula as mention below. According to Sato *et al*. (2000), the KKG is overlain by the Kb-Ks (PFD). Kikkawa *et al*. (1991) correlated the Kobayashi Pyroclastic Flow Deposit to Ks11 tephra (Ks11) in the Kasamori Formation, defined Kb-Ks (520–530 ka; Machida and Arai 2003) as one of the most important Middle Pleistocene marker tephras distributed from the southern Kyushu to eastern Honshu. However, Kb-Ks (Ks11) is positioning below Ks5 correlated to Oda in KKG. Moreover, other Middle Pleistocene distal vitric tephras petrographically similar to Ks5 are known, that is, the 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, both stratigrapically positioned above Ks5. OgA and Hg-7 are correlated to BT72 tephra in the lake sediments of Biwa Lake (Nakazato *et al.* 2005). The estimated age of BT72 is 349 ka (Nagahashi *et al.* 2004). Referring to their discrepancy, Nishizawa and Suzuki (2015) distinguished Nb and Oda by refractive indices of orthopyroxene and variation in the chemical composition of glass shards, and they concluded that Oda is not correlated to Ks5, OgA, and Hg-7. On the other hand, the proximal PFD of Ks5 most likely originated from Kyushu has not yet been reported.

Kasamori 18 tephra and Kasamori 10 tephra (Ks18 and Ks10)

Ks18 tephra (Ks18) was described by Kawai (1952) and Tokuhashi and Endo (1984). Machida and Arai (2003) correlated to Hiwaki PFD and Smkd with the Ks18, together with other distal volcanic ash layers in Central Japan, and proposed the Hiwaki tephra (Hwk) as unified name, which stratigraphically positioned below Kb-Ks. Distal ash fall deposits of Hwk (Ks18) have been detected from several terrestrial or marine sediments. Hwk, referred to as the Ashigakubo Volcanic Ash (A8 volcanic ash; Shiba *et al.* 1992), is interbedded in siltstone – the upper part of the Middle Pleistocene Numakubo Gravel and Silt Member (Yokoyama and Shiba 2013), in the Shizuoka Prefecture, in the Central Japan. Suganuma *et al*. (2003) correlated the Kume Volcanic

Ash intercalated in the Kume Formation of the Ina Group (Matsushima 1995), the Ina Basin, in the Central Japan. The tephras corresponded to Ks18 tephra are detected in western Japan. These are K1-285 Volcanic Ash (Yoshikawa *et al*. 2000) sandwiched in the upper part of the Osaka Group, and Sakawa I Volcanic Ash (Hayashi 1974; Yoshikawa 1984) in the Kobiwako Group (Nakazato and Nanayama 2013) (Fig. 5). The Osaka Group, composed of alternation of lacustrine, fluvial and marine beds, is another standard Early-Middle Pleistocene sequence that has been studied in detail. A vitric tephra referred to as K1-285 (Yoshikawa *et al*. 2000) in the upper part of the Osaka Group, is stratigraphically interbedded in Marine Clay Layers (Ma) named Ma 7. Also, according to Yoshikawa *et al*. (2000), the K1-223 tephra correlated with Ks5 was detected at the horizon 60 m above K1-285(=Ks18) (Fig. 5). In the Katata Hills, west Japan, Satoguchi and Hattori (2008) examined the correlation of vitric ash layers interbedded in the Kobiwako Group (Takaya 1963; Hayashi 1974) to Ks-series tephra based on detailed petrographic properties including the glass chemistry. They concluded that Kamiogi I, Kamiogi II and Ikadachi II are correlated with Ks11 (already correlated by Machida *et al*. 1980), Ks10 and Ks5, respectively. The closest area to southern Kyushu where Ks18, 11 and 10 have been detected is the northwest Shikoku. Kawamura and Shinohara (2008) examined the stratigraphy of the Uwa Formation and correlated three vitric ash layers of Uw-23, Uw-24 and Uw-25 with Ks18 (Hwk), Ks11 (Kb-Ks) and Ks10 (Fig. 5), respectively. In the eastern Boso Peninsula, the Kurahashi Formation of the Inubo Group (Sakai 1990) is another succession, which occures the three taphras together. According to Sato (2002), Kh3b, Kh5a and Kh5a tephras intercalated in the Kurahashi Formation, are correlated to Ks18, Ks10 and Ks5, respectively, based on their refractive indicies of glass shards, orthopyroxene and hornblend.

On the other hand, Ks10 tephra (Ks10; Machida *et al*. 1980) petrographically similar to Smkd exists above Ks18, is resulting in complication in widespread correlation of Smkd (Mizuno 1997). According to Machida and Arai (2003), the proximal tephra of Ks10 is supposed to be possibly correlated to Koseda Pyroclastic Flow (Ksd; Moriwaki *et al*. 2008), which is distributed in only Yaku Island, 60 km off

South Kyushu. The glass isothermal plateau fission-track age of 0.58 ± 0.08 Ma is obtained for Ksd (Moriwaki *et al*. 2008). Nishizawa and Suzuki (2013) argued the petrographic similarities among Smkd, Ks18 and Ks10. They indicated that the identification of Ks18 and Ks10 is possible by comparing the weight percentage ratio of K_2O, CaO, and Al_2O_3 in the chemical composition of the volcanic glass shards.

3 Methodology

3.1 Field observation for identification of pyroclastic deposits

In the study area, the author described details about thickness, grain size (matrix, pumice, and lithic fragment), bedding sets, grading, clast characteristics, flow features, welded or unwelded and pyroclast types. The thickness of pyroclastic units and the grain size of pumice are indicative of vent location. Even the locations where pyroclastic units are not fully exposed, maximum exposed thicknesses were measured. In addition, color, shape, phenocryst types, and variety of lithic clasts were visually described by naked-eye, for following identification of a specific formation or member.

3.2 Petrographic method

Each sample was washed several times by hand using tap water. Pumice clasts were crushed into coarse sand-size grains with a mortar and pestle. The crushed samples were cleaned using an ultrasonic bath until the clay and silt have been removed. Samples were then naturally dried and sieved through 0.25 and 0.063 mm pore size. The 0.25 to 0.063 mm grains were used for each analysis for fingerprinting. Dried samples were examined under stereoscopic microscopes for the description of the mineral composition. Refractive indices of volcanic glass shards, hornblende, cummingtonite and orthopyroxene were determined by the thermal immersion method (Danhara *et al.* 1992) using the Refractive Index Measuring System (RIMS) 2000 (Kyoto Fission-Track Co., Ltd.). Prior to measuring refractive indices of phenocrysts, the author picked up and crashed 20 grains (or more) to measure the highest refractive index of cleavage flakes of them.

In measurement of the refractive index for each sample, 30 grains were measured for volcanic glass shards and 30 observations using over 20 or more grains were measured for the phenocrysts. Moreover, major element compositions of volcanic glass shards from pyroclasts and resedimented tephras were determined by an energy dispersive X-ray spectrometer (EDAX GENESIS APEX2 and JEOL JSM-6930) according to the method shown by Suzuki *et al*. (2014). For the major chemical composition of volcanic glass shards, 16 grains were measured for each sample.

4 Stratigraphy and distribution of Middle Pleistocene pyroclastic flow deposits around the Kagoshima Bay

The author identified eight PFDs and one tuff in the study area (Fig. 3), including newly defined PFDs. They are Komiyaji, Sagise, Nabekura, Shimokado, Oda, Fumoto Tuff (as vitric tuff), Kobayashi, Takeyama and Hegawa PFDs in ascending order. For convenience of readers, it is desirable to show comprehensive stratigraphy before moving on to the contents of this chapter. The Figures 4a and 6 show that tephro-stratigraphy of the northwest coastal area of the Kagoshima Bay in Middle Pleistocene and correlations as Midlle Pleistocene widespread tephra. The stratigraphic position of Oda PFD which have been undetected in this study is referred from Sato *et al*. (2000) (Fig. 4a). The observation points around the coastal area of the Kagoshima Bay are shown in Figure 3. The geological columns are shown in Figures 7 and 8. In the central Boso Peninsula, Ks5, Ks10 and Ks18 were sampled at Uchihata, Manna, Senda, respectively (Fig. 9).

As mentioned above, several Middle Pleistocene tephras originated from southern Kyushu caldera region are compositionally similar to one another with respect to their major element compositions. Figure 10 shows the chemical composition of the volcanic glass shards of representative Quaternary PFDs, which were expected to distrubuted around the study area, in order to avoid erroneous identification of PFDs as far as possible. As shown in Figure 10, the PFDs described later can be mostly distinguished from each other. For comparison of Figure 10, samples of another Quatenary tephras possibly distributed in this region were collected at the following localities; Aira-Iwato tephra; A-Iw: (N31°46′24″, E130°46′25″), Kikai-Tozurahara tephra; K-Tz: (35°36′14″ 139°08′50″), Ata: (N31°14′10″, E130°47′54″), Imaizumi PFD (Im: Kawanabe and Sakaguchi 2005): (N31°17′10″, E130°36′48″), Ysn: (KH01; Fig. 3), Iso (KH01; Fig. 3). Moreover, samples of Keno (Suzuki *et al*. 1985), Kamogahara (Oki 1974) and Kogashira (Sasajima *et al*. 1980) PFDs were provided from Machida Hiroshi Collection which is stored in the Sagamihara City Museum.

In this chapter, the author presents the definition, type locality, stratigraphic relationships, lithological characteristics and petrographic properties of the pyroclasts such as thickness, maximum grain size of pumice clasts and lithic fragments, mineral assemblages and their refractive index, and the chemical compositions of glass shards.

4.1 Definition and description of the pyroclastic flow deposits

4.1.1 Komiyaji Pyroclastic Flow Deposits (Kmj)

Komiyaji Tuff Member is firstly described by Hase (1978) (Fig. 4a). The type localities were defined, the riverbed of Usonoki River along Takeyama to Komiyaji village section, and the road from Komiyaji to Sakeduru, the north of Kajiki Town. Afterward, Otsuka and Nishiinoue (1980) recognized this deposit as a pyroclastic flow deposit, and named Nabekura Pyroclastic Flow Deposits (Nb), setting the type locality at the cliff of Tempuku-ji (Fig. 3). Sato *et al*. (2000) referred to this deposit as the Komiyaji Tuff Breccia Member. Subsequently, Komiyaji Tuff has been recognized as Nabekura Pyroclastic Flow Deposits which stratigraphically positioned in the bottom of Kokubu Group (Hase *et al*. 1987; Otsuka and Furukawa 1988; Sato *et al*. 2000; Kagawa and Otsuka 2000). However, in this study, the author found out that Komiyaji Tuff Breccia (Nabekura Pyroclastic Flow Deposits) at several locations has different petrographic features. Specifically, the Nabekura Pyroclastic Flow Deposits (Otsuka and Nishiinoue 1980) at its type locality is not correlated to Komiyaji Tuff Breccia at its type locality. Therefore, this study distinguishes Komiyaji Tuff Breccia from Nabekura Pyroclastic Flow Deposits, and describes Komiyaji Tuff Brecia as Komiyaji Pyroclastic Flow Deposits (Kmj). A Zr-FT age of 0.96 ± 0.17 Ma is obtained for Kmj (Hase and Danhara 1985). Kmj exposed at 500 m west of Shimomyo, Aira city, retains the normal magnetic polarities (Hase and Danhara 1985). Source caldera of Kmj has not yet been identified.

Kmj corresponds to part of Komiyaji Tuff (Hase 1978; Hase *et al*. 1987) along the Usonoki River, and Nabekura Pyroclastic Flow Deposits (Otsuka and Nishiinoue

1980) except its type locality (Fig. 3). It is considered to be the lowest pyroclastic flow deposit distributed in this study area (Fig. 3). It crops out mainly north of the Kagoshima Bay, particularly along the valley of the Usonoki River (Fig. 3) not well exposed in the western part of the study area. In this area (Fig. 3), its stratigraphic contact with the underlying Kajiki Formation is uncertain. At location IS08 Kmj with a maximum thickness of 10 m (Fig. 8), is a tuff breccia composed of non-sorted pumice clasts and a purple to dark grey colored matrix without no internal stratification. Features of pumice clastts are white or yellow in color, rounded to subangular, poorly vesiculated, mainly 1-2 cm, up to 10 cm in diameter. The matrix and pumice are heavily weathered. The samples obtained from locations of IS05 and IS10 to IS12 (Figs. 3, 8 and 11) were not adequate to determine the glass chemistry (Table 1). However, refractive indices of orthopyroxene (γ: 1.702-1.710), confirm that these ignimbrites are correlated to Kmj.

Kmj obtained from locations of IS08 and IS09 (Figs. 3 and 8) contains orthopyroxene and clinopyroxene, and small numbers of hornblende. The average grain size of phenocrysts is smaller than 2 mm. The refractive indices of orthopyroxene and hornblende are γ: 1.703-1.709 and n_2: 1.668-1.677, respectively (Table 1). Moreover, Kmj is characterized by sponge type of volcanic glass shards whose refractive indices, major-element composition are n: 1.495-1.502, SiO_2: 77.3-78.5 wt.%, Al_2O_3: 12.3-12.9 wt.%, FeO*: 1.3-1.7 wt.%, CaO: 1.1-1.6 wt.%, K_2O: 4.4-5.3 wt.%, and Na_2O: 0.9-2.1 wt.% (Table1 and Fig. 12a).

Glass shards in Kmj are characterized by higher SiO_2, K_2O and FeO* contents, and lower Na_2O contents than those of Nb (Table 1 and Fig. 12a). The difference in glass chemistry between Kmj and Nb is clear as shown in the SiO_2-K_2O and SiO_2-Na_2O diagrams (Fig. 12a). Kmj glass shards show 0.6 wt.% higher mean SiO_2 content (77.8 wt.%) than those in Nb (77.2 wt.%) (Table 1). Thus, the major oxide compositions of the Kmj are different from those of Nb obtained from that type locality beyond analytical uncertainties. In conclusion, Nb is not correlated to Kmj in this area.

In the Keage village section of Kajiki Town (Fig. 3: IS12), it has been regarded as another main distribution area of Nb (Hase *et al*. 1987; Otsuka and Nishiinoue 1980). However, the sample collected from PFD, which have been recognized as Nb in the location IS12, has different glass chemistry from that of Nb. For example, a PFD with the thickness of 8 m, exposed at IS12 (Figs. 3 and 8), petrographically similar to Kmj rather than Nb (Fig. 12a).This deposit is a tuff breccia dominated by lapillis of 30-70 mm within a matrix of medium-coarse ash. This PFD is composed of massive, light brown colored deposit without internal stratification. The basal part of this PFD is fine sand tuff, which sharply covers the sheeted tuffacoeus sandy silt of the Kajiki Formation. The pumice clasts of this PFD are poorly to moderately vesiculated, angular to subangular, mainly 1~2 cm (up to 6 cm) in diameter. The weathered pumice clasts of this deposit show yellow colored. This deposit is petrographically similar to Kmj containing orthopyroxene and small numbers of hornblende (Table 1). However, comparison among the glass chemistries, Kmj glass shards have higher K_2O content, and lower Na_2O content than those of this deposit (Table1 and Fig. 12a). Considering that similar features such as the mineral composition and the weight percentage of SiO_2, this difference may be due to the weathering of the Kmj volcanic glass shards. However, since there is a possibility that it is another PFD related to the Kmj eruption, it is described separately in this study as Kmj (Keage-typed).

4.1.2 Sagise Pyroclastic Flow Deposits (Sgs)

Sagise Pyroclastic Flow Deposits (Sgs) was firstly described by Kino *et al*. (1984) as Sagise Pumice Flow Deposits. Sgs is intercalated in the bottom of the Kariya Formation of the Morokata Group in Miyazaki Plain (Nagaoka *et al*. 2010). This PFD is stratigraphically positioned below the Smkd, and was dated at 0.64 ± 0.17 Ma (Zr-FT) (Nagaoka *et al*. 2010). Magnetic polarity of this ignimbrite has not been examined and its source caldera was not identified.

At the type locality in Miyazaki prefecture (Fig. 2), Sgs exposes with a thickness of > 8 m, and the contact with the underlying massive silt of Miyazaki group appears quite sharp. The pumice clasts are moderately vesiculated, angular to subangular, mainly 1-5 cm, up to 15 cm in diameter.

In this study, it is turned out for the first time that Sgs distributed around the Kagoshima Bay. Sgs crops out mainly to northwest area of the study area, Higashifumoto-kami and Ryugayama (Fig. 3; WM14 to WM16, KM07 and IS05). Its stratigraphic contact of Sgs with the underlying Kmj is detected at Takeyama (IS05) shown in Figs. 3 and 11. Blocky lithic fragments originated from the highly oxidized Kmj with a maximum diameter of 100 cm are also found at IS05 (Figs. 3 and 11). At Ryugayama (Figs. 3 and 13; KM07), Sgs with maximum thickness reaching to 10 m as non-welded tuff, is composed of an unsorted mix of pumice clasts, abundant lithic lapillis and pseudo conglomerate in silt-sand matrix with many small-scale slump structures. All these components are set in a brown-yellow colored ash matrix. Pumice clasts are white in color, angular to subangular and moderately vesiculated mainly 1< cm, up to 3 cm in diameter. The matrix is fine, middle to coarse sized volcanic sand. Lithic fragments are abundant, and are composed mainly of altered andesites and sand stones.

In Higashisata town (Figs. 3 and 7; WM15 and 16), another distribution of Sgs in the west part of study area, Sgs presents various lithofacies. At WM16 site, Sgs is massive, brown-yellow colored deposit containing abundant lithic fragments composed of volcanic rocks, up to 10 cm in diameter. The average diameter of pumice clast is 3 cm, and the maximum is 10 cm in diameter. On the other hand, at the locality of WM15 (Figs. 3 and 7), Sgs is exposed with a thickness of 2 > m, as ash tuff with the aggregation of pumice lapillis. The average diameter of the pumice aggregation structure is 20 cm, consisting of poorly vesiculated pumice lapillis up to 1 cm. This lithofacies gradually change to tuff breccia laterally.

The Sample collected from its type locality of Sgs characteristically contains an abundance of cummingtonite and small numbers of orthopyroxene and clinopyroxene. Also, the containing of quartz is a fundamental feature of Sgs, but depending on the location, some samples are not containing quartz in abundance. The average grain size of phenocrysts is smaller than 2.5 mm. The refractive indices of orthopyroxene and cummingtonite are γ: 1.706-1.710 and n_2: 1.659-1.667 (Table 1), respectively. Sgs is characterized by bubble-wall type of volcanic glass shards whose refractive indices, and major-element composition are n: 1.498-1.500, SiO_2: 77.5-78.7 wt.%, Al_2O_3: 12.5-12.9 wt.%, FeO*: 0.7-1.0 wt.%, CaO: 0.7-1.0 wt.%, K_2O: 3.2-3.8 wt.%, and Na_2O: 3.4-3.8 wt.% (Table 1 and Fig. 14a).

Sgs were recognized at another 5 localities (Fig. 3; WM14 to WM16, KM07 and IS05). The refractive indices of orthopyroxene, and cummingtonite are γ: 1.707-1.710 and n_2: 1.659-1.666 (Table 1), respectively. The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs are n: 1.499, SiO_2: 77.4-78.7 wt.%, Al_2O_3: 12.3-12.9 wt.%, FeO*: 0.8-1.1 wt.%, CaO: 0.6-1.3 wt.%, K_2O: 3.0-4.0 wt.%, and Na_2O: 2.8-3.9 wt.% (Table 1 and Fig. 14a).

Comparing in the chemical composition of the volcanic glass shards among Sgs and the pumice sample collected from WM15 (Fig. 3), only the geochemical plots of the latter shows different populations (Fig. 14a). Especially, the difference is clear as shown in the SiO_2-FeO* and SiO_2-CaO diagrams (Fig. 14a). Geochemical plots of the glass shards consisting pumice aggregation structure show 0.4 wt.% higher mean FeO* content (1.3 wt.%) than Sgs glass (0.9 wt.%), (Table 1). Thus, the pumice clasts that exhibit aggregation structures are not essential fragments of Sgs.

4.1.3 Nabekura Pyroclastic Flow Deposits (Nb)

Nabekura Pyroclastic Flow Deposits (Nb) is firstly defined by Otsuka and Nishiinoue (1980). They recognized that this deposit is correspond to Kmj which described by Hase (1978). The type locality is the cliff of Tenpukuji in the Aira city (Fig. 3). According to Otsuka and Nishiinoue (1980) and Hase *et al*. (1987), Nb has the broadest distribution among all PFDs around the coastal area of the Kagoshima Bay. In spite of this broad distribution, the author detected Nb at only one location (5.5 km southwest of type locality) except its type locality. The distribution of Nb confirmed by similar chemical compositions of volcanic glass shards of the type locality, is not spatially continuous. Nb is unconformably underlain by the Kajiki Formation around the type locality (Otsuka and Nishiinoue 1980). Zr-FT ages of 0.9 ± 0.3 Ma (Miyachi 1983) and 0.96 ± 0.17 Ma (Hase and Hatanaka 1984) were obtained for Nb, suggesting that its eruption age possibly in Early Pleistocene. However, Nb shows the normal magnetic polarities corresponded to Brunhes Chron by Suzuki *et al*. 1985.

At the type locality (Figs. 3 and 8), Nb is exposed as non-welded pyroclastic flow deposit with a thickness of > 60 m. The base of the PFD could not be observed. This lithofacies is massive, light to dark grey colored deposit with no internal structure. The basal part of Nb is a tuff breccia dominated by 10-50 mm lapillis 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 diameter. The accessory fragments of andesite are angular with diameters of several centimeters.

The Sample collected from its type locality of Nb contains abundant orthopyroxene, and small numbers of clinopyroxene and hornblende. The amount of these phenocrysts is smaller than that of Oda as described below. The average grain size of phenocrysts is smaller than 1 mm. The refractive indices of orthopyroxene and hornblende are γ: 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 indices, major-element composition are n: 1.499-1.506 (1.505), SiO_2: 76.9-77.6 wt.%, Al_2O_3: 12.6-12.9 wt.%, FeO*: 1.2-1.6 wt.%, CaO: 1.2-1.5 wt.%, K_2O: 3.2-3.6 wt.%, and Na_2O: 2.7-3.4 wt.% (Table 1 and Fig. 12b).

Except type locality, Nb is detected only at the locality WM13 (Fig. 3). At this site, Nb is exposed as tuff treccia with a thickness of 1 m (Photo. C; Fig. 15). The matrix of this deposit is composed of fine to coarse-sized vitric ash. The lithic fragments are angular to subangular, up to 5 cm. The average diameter of the pumice is 3 cm (max 10 cm). As mineral assemblage, this deposit contains only orthopyroxene (γ: 1.704-1.709). The chemical composition of volcanic glass shards of the pumice is similar to that of Nb. At WM13 (Fig. 3), the mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.502-1.504, SiO_2: 76.8-77.3 wt.%, Al_2O_3: 12.6-12.9 wt.%, FeO*: 1.3-1.4 wt.%, CaO: 1.2-1.4 wt.%, K_2O: 3.4-3.7 wt.%, and Na_2O: 3.1-3.4 wt.% (Table 1 and Fig. 12b).

At this site, 2 m below Nb, a tuffaceous silty sandstone petrographically similar to Nb is exposed with a thickness of 10 m, accompanying a structure of aggregation of pumice lapillis (Photo. D; Fig. 15). This tuffaceous silty sandstone is composed of silt to fine-sized vitric ash with lamina structure. The lithic fragments are not detected. The average diameter of a pumice aggregation structure is 80 cm, consisting with the poorly vesiculated pumice lapillis up to 5 cm (Fig. 15). Due to the difference in the chemical composition and refractive indices of orthopyroxene between the pumice in aggregation structure (Fig. 15 and Table 1; WM13-2) and volcanic ash composing of tuffaceous silty sandstone (Fig. 15 and Table 1; WM13-1) as described below, it is inferred that this deposit is a pyroclasts formed during an eruption occurred before Nb eruption in subaqueous environment.

The chemical composition of volcanic glass shards of the pumice (WM13-2) is similar to that of Nb. The mode of refractive indices and chemical composition of the volcanic glass shards in the pumice aggregation structure (WM13-2 in Fig. 15), are n: 1.500-1.502 (1.501), SiO_2: 76.8-77.6 wt.%, Al_2O_3: 12.5-12.9 wt.%, FeO*: 1.1-1.5 wt.%, CaO: 1.2-1.4 wt.%, K_2O: 3.4-3.7 wt.%, and Na_2O: 3.2-3.3 wt.% (Table 1 and Fig.12b). On the other hand, those in a tuffaceous silty sandstone (WM13-1 in Fig. 10), the mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.501-1.507 (1.505), SiO_2: 76.2-77.3 wt.%, Al_2O_3: 12.7-13.1 wt.%, FeO*: 1.2-1.8 wt.%, CaO: 1.2-1.5 wt.%, K_2O: 3.4-3.7 wt.%, and Na_2O: 3.2-3.4 wt.% (Table 1 and Fig.12b). Although WM13-1 is petrographically similar to Nb, the range of weight percentage of SiO_2 (76.8 wt.%) is lower than those of Nb (77.2 wt.%) and pumice aggregation part (WM13-2; 77.3 wt.%) (Fig. 12b). On the other hand, compared with each refractive indices of orthopyroxine between Nb and WM13-2, Nb is clearly distinguished from WM13-2 (Table 1).Therefore, the author considered that this deposits, which composes of tuffaceous sandstone accompanying the aggregation structure of pumice clasts, is not to the essential pyroclaststs of Nb. The chemical composition of volcanic glass shards obtained from WM13, existing 2 m above this deposit as thinbedded tuff breccia, shows similar geochemical signature to those of Nb

(Fig. 12b). As mentioned above, in this study, the author considers this deposit (Photo. C; Fig. 15; WM13) corresponds to the Nb.

4.1.4 Shimokado Pyroclastic Flow Deposits (Smkd)

Oki and Hayasaka (1970) described Shimokado Pyroclastic Flow Deposits (Smkd) as a pumice flow deposit in the cliff of Ryugamizu the western margin of the Aira caldera. Afterward, Smkd is correlated with the Kuwanomaru Tuff Breccia Member (Sato *et al*. 2000) and the Yoshidaji Pyroclastic Flow Deposits (Kagawa and Otsuka 2000) in the Aira City. As widespread marker tephra, Machida and Arai (2003) proposed the unified name Hiwaki tephra, which stratigraphically positioned below the Kb-Ks tephra in the Kasamori Formation, in Boso Peninsula. Smkd from the Kogashira at the Aira city shows the normal magnetic polarities (Suzuki *et al*. 1985). A Zr-FT age of 0.61 ± 0.08 Ma was obtained for Smkd (Imura *et al*. 2001).

At the type locality shown by Oki and Hayasaka (1970), at the cliff in the Kogashira Water Purification Plant, the Kagoshima city, Smkd was exposed as welded pyroclastic flow deposit with a thickness of > 10 m (Oki and Hayasaka 1970). However, this outcrop has disappeared. For this reason, the author defined new type locality at the quarry 1500 m northwest distant from previous location (Figs. 2 and 3). Although it cannot be detected the contact with the Kogashira Formation of a marine deposit (Oki and Hayasaka 1970) below Smkd in this outcrop, Smkd is exposed with a thickness of > 10 m. The non-welded part less than 1 m in thickness exists in the bottom as vitric ash flow deposit. The upper welded part has developed eutaxitic structures up to 10 cm in length. Kkt with a thickness of 5 m covers the upper part, interposing a weathered tuffaceous sand layer with a thickness of 5 m. The pumice clasts of the non-welded part of Smkd are scattering, well vesiculated, subangular, mainly 3-5 cm, up to 10 cm in diameter.

The Sample collected from its type locality of Smkd contains abundant hornblende, orthopyroxene, and quartz, and small numbers of clinopyroxene. The amount of these phenocrysts is larger than that of Oda as described below. The average grain size of phenocrysts is smaller than 2.5 mm. The refractive indices of orthopyroxene and hornblende are γ: 1.706-1.710 and n_2: 1.669-1.674 (Table 1), respectively. Smkd is characterized by fiber type and sponge type of volcanic glass shards whose refractive indices and major-element composition are n: 1.499-1.500, SiO_2: 77.8-78.5 wt.%, Al_2O_3: 12.0-12.5 wt.%, FeO*: 0.9-1.3 wt.%, CaO: 1.0-1.2 wt.%, K_2O: 3.1-3.4 wt.%, and Na_2O: 3.4-3.7 wt.% (Table 1 and Fig. 16a).

In another outcrop of Smkd, at the Amagahana in Aira City (WM13; Fig. 3), the Smkd is exposed with a thickness of > 50 m. In this location, Smkd is dived into two units. The upper part is exposed as welded PFD with a thickness of > 40 m (Photo. A; Fig. 15). The lower part is as non-welded pyroclastic flow deposit with a thickness of 2 m (Photo. B; Fig. 15). This deposit is massive, light grey to pinkish colored PFD. It is poorly sorted, matrix-supported and consists of well vesiculated white pumice clasts up to 3 cm in diameter (Table 1). Smkd overlies the alternation of silty sand layers, without Plinian pumice fall deposits (Fig. 15).

Smkd were recognized at three localities (Figs. 3 and 7; WM12, WM13, KH02) except its type locality. The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs are n: 1.499, SiO_2: 77.8-78.8 wt.%, Al_2O_3: 12.0-12.6 wt.%, FeO*: 0.9-1.2 wt.%, CaO: 0.9-1.2 wt.%, K_2O: 3.0-3.5 wt.%, and Na_2O: 3.3-3.7 wt.% (Table 1 and Fig. 19a).

The Hiwaki PFD (Aramaki and Ui 1976) is distributed in Tonohara, the Satsuma-Sendai City (Fig. 2; location 5). The name "Hiwaki PFD" was firstly used by Aramaki and Ui (1976). However, although Aramaki (1976) showed the location of three outcrops of this deposit, the definition and lithofacies of "Hiwaki PFD" have not been presented (e.g. Aramaki 1977; Miyachi 1983; Miyachi 1987). In this study, the author use the name "Hiwaki PFD" only for the deposit distributed at the point presented by Aramaki & Ui (1976). The sample for the analysis was collected from the outcrop (Fig. 2; location 5), where is corresponded to the locality of “SA72081114” shown in Aramaki and Ui (1976).

The Hiwaki PFD is exposed as non-welded pyroclastic flow deposit with a thickness of 9 m. It is composed of massive, light brown colored pyroclastic flow deposit with no internal structure. The pumice clasts of this deposit are well vesiculated, angular, mainly 3-5 cm, up to 20 cm in diameter. The lateral exposure of this deposit is extremely poor. In addition, stratigraphic relationships between Hiwaki PFD and any other strata cannot be confirmed around the location 2 (Fig. 2). The Hiwaki PFD contains abundant hornblende, orthopyroxene, and quartz, and small numbers of clinopyroxene. The refractive indices of orthopyroxene and hornblende are γ: 1.706-1.710 and n_2: 1.668-1.674 (Table 1), respectively. Hiwaki PFD is characterized by fiber type, bubble-wall type and sponge type of volcanic glass shards whose refractive indices and major-element composition are n: 1.498-1.500 (1.499-1.500), SiO_2: 77.6-78.4 wt.%, Al_2O_3: 11.9-12.4 wt.%, FeO*: 1.0-1.2 wt.%, CaO: 1.0-1.2 wt.%, K_2O: 3.3-3.4 wt.%, and Na_2O: 3.5-3.6 wt.% (Table 1 and Fig. 19a). This deposit is petrographically similar to Smkd containing hornblende, orthopyroxene and quartz (Table 1). In addition, the Hiwaki PFD and Smkd are difficult to distinguish based on the comparioson of their mean oxide contents (wt.%). On the other hand, confident correlations require a multiple criterion approach to tephra characterization, not only the petrological features but also stratigraphic, paleomagnetic and radiometric age relations. Thus, in this study, the author considered that the Hiwaki PFD is excluded from Smkd, considering to the lack of its stratigraphy and age determination poor exposure of the Hiwaki PFD. The difference between Hiwaki PFD and Smkd is shown in the SiO_2- K_2O and SiO_2- Al_2O_3 diagrams (Fig. 16a). Geochemical plots of the glass shards sampled from Hiwaki PFD show different population from those of Smkd; the Hiwaki PFD has glass shards characterized by higher K_2O content, and lower SiO_2 and Al_2O_3 content than those of Smkd (Fig. 16a).

4.1.5 Oda Pyroclastic Flow Deposits (Oda)

At the type locality of Oda, the Forestry Road in Odanishi, the northwest of the Hayato Town (Fig. 3), Oda is exposed, as non-welded pyroclastic flow deposit with a thickness of > 70 m (Fig. 8). Oda is overlain by a grey colored silt layer of the Hayato Formation. Its stratigraphic contact with the other PFDs is uncertain, although it has the widest distribution in this study area. Oda is composed of massive, light brown colored pyroclastic flow deposit with no internal structure. The basal part of Oda is a tuff breccia dominated by pumice lapillis (10-30 mm) within a matrix of medium-coarse to fine ash. Oda is poorly sorted, matrix-supported, and consisting with white pumice clasts. The pumice clasts are poorly to moderately vesiculated, angular to subangular, mainly 3 cm, up to 15 cm in diameter. The accidental fragments are subangular, composed of andesite, up to 10 cm in diameter. A Zr-FT age of 0.97 ± 0.22 Ma was obtained for Oda at 1500 m west from Shimomyo, Aira city (Hase and Danhara 1985). Magnetic polarity of this ignimbrite has not been determined.

The Sample collected from its type locality of Oda contains abundant orthopyroxene, and relatively few hornblende and clinopyroxene. The average grain size of phenocrysts is smallar than 2 mm in diamater, however hornblende are rarely larger 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 (Table 2). Oda is characterized by abundant fiber type and stripe type of volcanic glass shards whose refractive indices, major-element composition are n: 1.501-1.504 (1.503-1.504), SiO_2: 76.3-77.3 wt.%, Al_2O_3: 12.6-12.9 wt.%, FeO*: 1.4-1.7 wt.%, CaO: 1.4-1.6 wt.%, K_2O: 3.0-3.2 wt.%, and Na_2O: 3.3-3.7 wt.% (Table 2 and Fig. 17a).

Oda were recognized at another 12 localities (Fig. 3; WM05 to WM08, KM05, KM06, KJ02 to KJ06 and IS06). The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs are n: 1.503-1.505, SiO_2: 75.9-77.5 wt.%, Al_2O_3: 12.4-13.0 wt.%, FeO*: 1.3-1.9 wt.%, CaO: 1.3-1.7 wt.%, K_2O: 2.7-3.5wt.%, and Na_2O: 3.0-3.9 wt.% (Table 2 and Fig. 17a).

4.1.6 Fumoto Tuff

The Fumoto Tuff firstly defined by Otsuka and Nishiinoue (1980). Afterword, Nakano and Oki (2013) concluded that this deposit is corresponded to the Hayato Formation of the Kokubu Group as the Fumoto Tuff Member. They divided this deposit into three part based on lithofacis and grain size. The thickness of this member is about 10 m (Nakano and Oki 2013). Based on the lithofacies shown by Nakano and Oki (2013), the upper and lower part of the Fumoto Tuff Member were observed at locality WM10 and WM011, respectively.

The upper part of this deposit is composed of vitric fine sized sand to silt. The author observed the upper part of the Fumoto Tuff at locality WM10. In this site, Fumoto Tuff is overlain by a fluvial gravel bed and Ata (PFD). This lithofacies is massive, white colored deposit with no internal structure.

At locality WM11 (Figs. 3 and 7), the lower part of this deposit is exposed as ash tuff with the aggregation of pumice lapillis with a thickness of 4 m. The basal part of this deposit could not be observed. This aggregation structure is similar to that of Sgs observed at locality WM15 (Figs. 3 and 7). The average diameter of the pumice aggregation part is 30 cm. This structure is composed by the poorly vesiculated pumice lapillis up to 1 cm in diameter. A few centimeters of charcoals are observed in both ash tuff matrix and pumice aggregation structure.

The upper part of Fumoto Tuff contains quit few hornblende. The average grain size of phenocrysts such as hornblende is smallar than 0.063 mm in diameter, and the refractive index of hornblende could not be determined. The upper part of Fumoto Tuff is characterized by abundant bubble-wall type and sponge type of volcanic glass shards whose refractive indices, major-element composition are n: 1.502-1.505 (1.503-1.505), SiO_2: 76.4-77.3 wt.%, Al_2O_3: 12.9-13.2 wt.%, FeO*: 1.3-1.7 wt.%, CaO: 1.4-1.8 wt.%, K_2O: 2.7-3.2 wt.%, and Na_2O: 3.3-3.8 wt.% (Table 2 and Fig. 18a).

The lower part of Fumoto Tuff composed of fine vitric tuff contains few hornblende and orthopyroxene. The average grain size of phenocrysts is smallar than 0.063 mm in diameter, causing difficulties in measuring for the refractive index of phenocrysts. On the other hand, the refractive index of orthopyroxene, obtained from pumice aggregation structure, is γ: 1.703-1.710 (1.705-1.710) (Table 2). The lower part of Fumoto Tuff is characterized by abundant bubble-wall type and sponge type of volcanic glass shards whose refractive indices, major-element composition are n: 1.503-1.506 (1.504-1.505), SiO_2: 76.4-78.1 wt.%, Al_2O_3: 12.1-13.0 wt.%, FeO*: 1.3-1.7 wt.%, CaO: 1.4-1.5 wt.%, K_2O: 2.7-3.4 wt.%, and Na_2O: 3.3-3.9 wt.% (Table 2 and Fig. 18a).

Glass shards in the Fumoto Tuff (including upper and lower parts) has higher Na_2O contents and lower K_2O contents than those of Oda (Table 2 and Fig. 18a), showing evident difference shown in the SiO_2-K_2O and SiO_2- Na_2O diagrams (Fig. 18a).

At locality WM02 (Figs. 3 and 19), three taffaceous sand layers with the thickness of 40 – 60 cm are intercalated in the alternation of silty sandstone of the Hayato Formation, which is overlain by Kb-Ks. Based on the variation of the major chemical composition of the volcanic glass, collected from WM02-1, WM02-2 and WM02-3, it is indicated that these tuffaceous sand layers (Fig. 19) contain volcanic glass shards derived from the Fumoto Tuff (Fig. 18b) with contents more than 50 %. That is harmonious with the stratigraphy of Sato *et al*. (2000) and Nakano and Oki (2013), which Kb-Ks is stratigraphically above the Fumoto Tuff Member of the Hayato Formation.

4.1.7 Kobayashi Pyroclastic Flow Deposits (Kb-Ks)

Kobayashi Pyroclastic Deposits is firstly defined by Kino and Ota (1976) as Kobayashi pumice flow deposit. Since there are few PFDs characterized by containing biotite in southern Kyushu, this PFD is effective as a Middle Pleistocene key bed (Nagamine 1987). Its source caldera was considered to be Kakuto Caldera or Kobayashi Caldera (Machida and Arai, 2003). This deposit is correlated to Ks11 in the Kasamori Formation of the Kazusa Group by Yoshikawa *et al*. (1991), and then redefined together with the another distal ash fall deposits as Kobayashi Kasamori tephra (Kb-Ks) by Machida and Arai (2003). In the Hitoyoshi Basin, 60 km north of the study area, it has been referred as the Fukada Pyroclastic Flow Deposit, with the thickness of 4 to 7 m, stratigraphically positioned below the Kkt (PFD) (Nagamine 1987).

Sample of Kb-Ks used for analysis in this study was collected at the cliff along the road of Kukino, Takaoka Town, Miyazaki Prefecture (Machida 1996) (Fig. 2;

Location 3). At this locality, Kb-Ks is exposed as non-welded pyroclastic flow deposit with a thickness of > 10 m. In the western part of this study area, this deposit referred to as the Honjo Pyroclastic Flow Deposits, unconformably covers the Kokubu Group by Sato *et al*. (2000). Its stratigraphic contact with the underlying Shimokado PFD is uncertain. Kb-Ks is badly exposed in central part of study area.

Kb-Ks contains abundant hornblende and biotite, characterized by absence of quartz. The average grain size of phenocrysts is smallar than 2 mm in diamater, however hornblende are rarely larger than 2 mm in diameter. The refractive indices of hornblende are n_2: 1.677-1.685 (Table 3). Kb-Ks is characterized by abundant fiber-type and stripe-type of volcanic glass shards whose refractive indices and major-element composition are n: 1.503-1.506 (1.504-1.506), SiO_2: 74.2-75.6 wt.%, Al_2O_3: 13.5-14.3 wt.%, FeO*: 1.1-1.7 wt.%, CaO: 0.9-1.3 wt.%, K_2O: 4.1-4.5 wt.%, and Na_2O: 3.3-3.9 wt.% (Table 3 and Fig. 20).

Kb-Ks were recognized at another three localities (Fig. 3; WM02, WM04 and KM04). This lithofacies is massive, pinkish to light brown colored deposit with no internal structure. At the locality KM04 (Figs 3 and 7), Kb-Ks is exposed with the thickness of 20 m as burring the valley composed by the alternation of silt and sand layers of the Kokubu Group. In addition, the maximum grain size of the pumice clasts observed at KM04 is 30 cm.

The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs (samples collected from WM02, WM04 and KM04) are n: 1.503-1.506, SiO_2: 74.0-75.4 wt.%, Al_2O_3: 13.7-14.3 wt.%, FeO*: 1.1-1.6 wt.%, CaO: 1.0-1.3 wt.%, K_2O: 4.1-4.4wt.%, and Na_2O: 3.6-4.1 wt.% (Table 3 and Fig. 20).

4.1.8 Takeyama Pyroclastic Flow Deposits (Tkym)

At three points in the study area (Fig. 3; WM02, WM03, and IS05), the author observed an undescribed PFD and newly named it as Takeyama Pyroclastic Flow Deposits. Although exposure of this deposit at the type locality is limited, those petrographic features are different from those of reported PFDs as described below.

The type locality of Takeyama PFD is the cliff along the road connecting between Takeyama Village and Takeyama Dam (Figs. 3 and 11; IS05). At the type locality, this is exposed as non-welded pyroclastic flow deposit with a thickness of > 1.5 m. The upper limit of this deposit cannot be observed because it is covered with thick talus deposits. Its stratigraphic contact with the underlying horizontally laminated silt layer with the thickness of 50 cm is quite sharp. Under the silt layer, Sgs with the thickness of 2 m is exposed, containing blocky lithic fragments composed by the highly oxidized Kmj volcanic block with diameters of 100 cm at a maximum. This lithofacies is massive, light grey colored deposit with no internal structure. The sketch of this point is shown in Figure 11.

At locality WM02 (Figs. 3 and 7), Takeyama PFD is exposed as non-welded pyroclastic flow deposit with a thickness of > 1.5 m. The upper limit of this deposit cannot be observed. Nevertheless, the author observed that Kb-Ks is overlain by Takeyama PFD (Fig. 19). In addition, taffaceous sand layers containing glass shards of the Fumoto Tuff is intercalated in the alternation of silty sandstone of the Hayato Formation, which is overlain by Kb-Ks directly (see section 4.1.6). Therefore, Takeyama PFD is stratigraphically above Kb-Ks and the Fumoto Tuff. The geological column and sketch of this point are shown in Figures 7 and 19.

The Sample collected from its type locality of Takeyama PFD contains abundant hornblende, biotite, orthopyroxene and quartz, and relatively few clinopyroxene. The average grain size of phenocrysts is smallar than 2.5 mm in diamater, however those of hornblende and quartz are often larger than 2 mm in diameter. The refractive indices of orthopyroxene and hornblende are γ: 1.704-1.711 (1.706-1.709) and n_2: 1.669-1.676 (Table 3), respectively. TakeyamaPFD is characterized by abundant stripe-type and fiber-type of volcanic glass shards whose refractive indices, major-element composition are n: 1.498-1.501 (1.499-1.500), SiO_2: 78.2-79.3 wt.%, Al_2O_3: 12.2-12.5 wt.%, FeO*: 0.9-1.3 wt.%, CaO: 1.0-1.2 wt.%, K_2O: 2.8-3.1 wt.%, and Na_2O: 3.1-3.6 wt.% (Table 3 and Fig. 21a).

Tkym were recognized at another 2 localities (Fig. 3; WM02, WM03). The mode of refractive indices and chemical composition of the volcanic glass shards determined for samples collected from Locs. WM02 and WM03 are n: 1.499-1.500, SiO_2: 78.0-79.0 wt.%, Al_2O_3: 12.1-12.4 wt.%, FeO*: 0.9-1.2 wt.%, CaO: 1.0-1.2 wt.%, K_2O: 2.8-3.2 wt.%, and Na_2O: 3.3-3.6 wt.% (Table 3 and Fig. 21a), confirming that are correlative to Takeyama PFD.

4.1.9 Hegawa Pyroclastic Flow Deposits (Hgw)

The author detected a new pyroclastic flow deposit in the distribution area of the Komiyaji Tuff Breccia (Hase 1978), which has not yet been reported. In this study, the author we named this deposit Hegawa (Hgw) PFD and set the type locality as the tributary of the western side of the Usonoki River at an altitude of 140 to 160 m (Figs. 3 and 22; IS01). Hgw is mainly distributed along the Usonogi River. In the type locality are, it is distributed along the ridges of hills, which are composed of an alternation of silt and sand, the Kajiki Formation, and along the river bed from the Dofu to the Tsurubaru villages. The distribution is fragmented on the western side of the study area, although it is exposed with a thickness of > 50 m in Shiroshita of Aira Town (Figs. 3 and 7; WM01). The area including location WM01 is one of the main distribution areas of the Nb (Otsuka and Nishiinoue 1980). Similarly, Hgw was detected at several points (Fig. 3; KM01 and KM02) in the geological map of Hase *et al*. (1987), where Nb was supposed to be distributed. From this, the author concluded that Hgw was probably identified as Nb or Kmj in previous studies (Fig. 4b). An idealized geological cross section along the Usonoki River is shown in Figure 23.

At the type locality, Hgw is exposed as non-welded PFD with a thickness of > 5 m (Figs. 3 and 22; IS01). Hgw is overlain by fluvial gravel beds with a thickness of 2 m. The geological column and sketch of this point are shown in Figures 8 and 22. Hgw covers a tuffaceous sandstone with a thickness of 8 m, interposing a massive silt layer with a thickness of 1.5 m. This taffaceous sandstone is composed of a mixture of rounded to sub-angular gravels, pseudo conglomerate in silty sand matrix, and few pumice clasts up to 1 cm in diameter, with sand-sized matrix. It is noteworthy that this deposit includes the volcanic glass shards derived from Kb-Ks (Fig. 24a). Contrary to this, those derived from Hgw are not included (Fig. 24a), suggesting that Hgw is stratigraphically above Kb-Ks.

The lithofacies of Hgw at the type locality is dived into two parts. The upper part of Hgw has a thickness of 5 m and is massive, light grey colored PFD with no internal stratification. It is poorly sorted, matrix-supported and consists of white pumice clasts and an abundant accretionary lappili up to 1 cm. The pumice clasts are moderately vesiculated, angular to subangular, mainly 1 cm, up to 5 cm in diameter. On the other hand, the basal part of Hgw with the thickness of < 2 m, which is fragmentally exposed along the riverbed of the valley of the type locality, is a tuff breccia dominated by lithic fragments (10 cm in diameters) within a matrix of medium-coarse to fine sand. In addition, there is a gap between the upper and lower parts (Fig. 22).

In another outcrop of Hgw, around the Tsurubaru Village (IS03; Fig. 3 and 8), the upper part of Hgw is exposed as non-welded PFD with a thickness of < 4 m. In this location, Hgw unconformably overlies the lower bluish grey massive siltstone of the Kajiki Formation. A pseudo conglomerate exceeding 2 m is vertically distributed in the matrix. The maximum grain size of the pumice clasts with well vesiculation is 20 cm.

The sample collected from the type locality of Hgw contains abundant orthopyroxene and clinopyroxene and relatively few hornblende and quartz. The average grain size of phenocrysts is smallar than 2 mm in diamater, however hornblende rarely larger than 2 mm in diameter. The refractive indices of orthopyroxene and hornblende are γ: 1.706-1.711 (1.707-1.708) and n_2: 1.669-1.683, respectively (Table 3). Hgw is characterized by abundant bubble wall-type and stripe-type of volcanic glass shards whose refractive indices, major-element composition are n: 1.502-1.505, SiO_2: 77.0-77.6 wt.%, Al_2O_3: 12.5-12.8 wt.%, FeO*: 1.3-1.5 wt.%, CaO: 1.3-1.5 wt.%, K_2O: 2.9-3.0 wt.%, and Na_2O: 3.3-3.8 wt.% (Table 3 and Fig. 25a), respectively.

Hgw were recognized at nine other localities (Fig. 3; WM01, KM01 to KM03, KJ01, and IS01 to IS04). The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs are n: 1.502-1.505, SiO_2: 76.6-78.0 wt.%,

Al_2O_3: 12.3-13.0 wt.%, FeO*: 1.2-1.7 wt.%, CaO: 1.0-1.5 wt.%, K_2O: 2.8-3.4wt.%, and Na_2O: 3.0-4.0 wt.% (Table 3 and Fig. 25b) , respectively. Based on the variation of the major chemical composition of the volcanic glass, it is evident that Hgw observed at KM01, KM02, and KJ01 (Fig. 3) contains volcanic glass shards derived from Kb-Ks (Fig. 24b) with contents below 25 %. This indicates that Hgw entrained glass shards of Kb-Ks during its flow and deposition, suggesting that Hgw is stratigraphically located above Kb-Ks. Figure 24b shows the chemical composition of the volcanic glass shards in the tuffaceous sandstone below Hgw in IS01 (Fig. 3). It is clear that 40 % of the analyzed glass shards are derived from Kb-Ks (Fig. 24b). This is more evidence, which suggests that Hgw is stratigraphically located above Kb-Ks.

4.2 Resedimented volcaniclastic deposits distributed in the Ryugayama area

At the Ryugayama area (Figs. 3 and 13a), in the northwestern part of the study area, sand and alternation of sand and silt layers of the Kamo Formation are exposed to the altitude of 20 to 90 m (Fig. 13b) (Otsuka and Nishiinoue 1980). As already mentioned in section 4.1.2 and 4.1.5, at locations KM06 and KM07, PFDs, which are correlated with Oda and Sgs, are exposed, respectively (Figs. 3 and 13b). However, their stratigraphic relationship is unconfirmed. Thus, the author examined petrographic characteristics of resedimented volcaniclastic deposits, and attempted to identify PFDs which is the origin of minerals and volcanic grass shards composing of them. In this section, resedimented volcaniclastic deposits sandwiched in the Kamo Formation are described, in order to estimate the stratigraphy of Oda and Sgs.

Eleven resedimented volcaniclastic deposits (named Rgy-1 to Rgy-11, in ascending order) with a thickness of approximately 1 m (maximum 2 m) are sandwiched in the alternation of sand and silt layers distributed in this area (Fig. 13b). The lithofacies and outcrop conditions of 11 resedimented volcaniclastic deposits from Rgy-1 to Rgy-11 are shown in Photo 1 to 11. All of these 11 layers are non-welded pumicious conglomerate or tuffaceous sand. In this study the author does not discuss the transportation and sedimentation processes of these deposits. The author certified resedimented volcaniclastic deposits based on two lithological features: 1) it contains well vesculated rounded pumices, 2) it consist several units formed by inverse or reveres graded layers. Petrolographic properties of Rgy-1 to Rgy 11 are shown in Table 4. Except for Rgy-4, all resedimented volcaniclastic deposits from Rgy-1 to Rgy-11 are characterized by containing abundant cummingtonite (Table 4). From the results of the comparison of the major element composition of each volcanic glass as described below, it was found that seven resedimented volcaniclastic deposits of 11 were correlated with Sgs.

Rgy-1, Rgy-2, Rgy-3, Rgy-6, Rgy-7, Rgy-8 and Rgy-9 contain abundant cummingtonite, and relatively few hornblende and orthopyroxene. The range of refractive indices of volcanic glass and cummingtonite are within n: 1.496-1.500 and n_2: 1.660-1.666 (Table 4), respectively. Major-element composition of volcanic glass shards collected in these seven layers are SiO_2: 77.4-78.7 wt.%, Al_2O_3: 12.3-12.8 wt.%, FeO*: 0.7-1.1 wt.%, CaO: 0.8-1.0 wt.%, K_2O: 3.2-4.0 wt.%, and Na_2O: 3.2-3.8 wt.% (Table 4 and Fig. 26). These petrolographc properties are in good agreement with those of Sgs (n: 1.498-1.500, SiO_2: 77.5-78.7 wt.%, Al_2O_3: 12.5-12.9 wt.%, FeO*: 0.7-1.0 wt.%, CaO: 0.7-1.0 wt.%, K_2O: 3.2-3.8 wt.%, Na_2O: 3.4-3.8 wt.%) (Table 1 and Fig. 26). On the other hand, comparing in the chemical composition of the volcanic glass shards among the other four layers (Rgy-4, Rgy-5, Rgy-10 and Rgy-11) and Sgs, the geochemical plots are shown differently in each individual area (Fig. 26). Especially, the difference is clear as shown in the SiO_2-K_2O and SiO_2- Na_2O diagrams (Fig. 26). Glass shards in Rgy-5, Rgy-10 and Rgy-11 are characterized by higher SiO_2, K_2O contents, and lower Na_2O contents than those of Sgs (Tables 1, 4 and Fig. 26). Similarly, glass shards in Rgy-4 are characterized by higher K_2O content and lower Na_2O content than those of Sgs (Tables 1, 4 and Fig. 26). Despite the fact that Rgy-5, Rgy-10 and Rgy-11 share common features with Sgs including cummingtonite, the major element composition of volcanic glass are not similar to those of Sgs. The existance of Rgy-5, Rgy-10 and Rgs-11 suggests that eruptions had been occurre, originating tephras characterized by cummingtonites other than Sgs, around the period of the deposition of the Kamo Formation.

From the above, seven of the 11 resedimented volcaniclastic layers in the Ryugayama area are derived from Sgs. The positional relationship among Oda (Figs. 3 and 13; KM06) and Sgs (Figs. 3 and 13; KM07) and resedimented volcaniclastic layers is shown in the schematic cross section of Figure 27. As for the altitude, the location KM07 (H: 100 m) of Sgs is higher than that of Oda (H: 40 m). However, since Oda is deposited overlying the Kamo Fomation composed of resedimented volcaniclastic deposits of Sgs, it can be assumed that Oda is stratigraphically upper than Sgs.

4.3 Description of distal ash fall deposits

In this section, petrolographic properties of the Ks5, Ks10, and Ks18 in the Kasamori Formation of the Boso Peninsula are shown, including another distal ash fall deposits correlative to them, respectively.

4.3.1 Ks5 volcanic ash

At Funaki (Fig. 9; location 1) in the middle of Boso Peninsula, the Ks5 Volcanic Ash (Tokuhashi and Endo 1984) occurs as a white vitric ash fall deposit 8 cm thick in the Kasamori Formation of the Kazusa Group, and is overlain by 10 cm of stratified volcanic ash reflecting the subsequent local reworking of the tephra.

Ks5 contains abundant bubble-wall type glass shards with a small number of orthopyroxene and hornblende (Table 3). The mode of refractive indices and chemical composition of the volcanic 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.% (Table 3 and Fig. 25a), respectively.

4.3.2 Ks10-Kh5b-Tsuburano volcanic ash

At Manna (Fig. 9; location 2) in the middle of Boso Peninsula, the Ks10 Volcanic Ash (Tokuhashi and Endo 1984) occurs as a white vitric ash fall deposit 8 cm thick in the Kasamori Formation of the Kazusa Group, and is 2 m above the Ks11 Volcanic Ash. Ks10 is composed of bioturbated silt to fine sand-sized grey volcanic ash. Ks10 contains abundant bubble-wall type glass shards with a small number of hornblende and orhopyroxene (Table 3). The mode of refractive indices and chemical composition of the volcanic glass shards in Ks10 are n: 1.498-1.500 (1.499), SiO_2: 78.0-78.7 wt.%, Al_2O_3: 12.3-12.5 wt.%, FeO*: 0.9-1.2 wt.%, CaO: 1.1-1.2 wt.%, K_2O: 2.8-3.1 wt.%, and Na_2O: 3.3-3.7 wt.% (Table 3 and Fig. 21), respectively.

At Asahi (Fig. 9; Location 4) in Choshi, the Ks10 referred to as Kh5b Volcanic Ash (Sakai 1990) occurs as a white vitric ash fall deposit 5 cm thick in the Kurahashi Formation of the Inubo Group (Sakai 1990). Here, the Ks11 is also observed 80 cm below the Kh5b as the Kh5a Volcanic Ash (Sakai, 1990). Kh5b is silt to fine sand-sized grey volcanic ash. Kh5b contains abundant bubble-wall, fiber, and sponge type glass shards with a small number of hornblende, biotite, and orthopyroxene (Table 3). The mode of refractive indices and chemical composition of the volcanic glass shards in these PFDs are n: 1.499-1.501 (1.499-1.500), SiO_2: 77.9-79.0 wt.%, Al_2O_3: 12.2-12.7 wt.%, FeO*: 0.8-1.3 wt.%, CaO: 1.0-1.2 wt.%, K_2O: 2.7-3.1 wt.%, and Na_2O: 3.2-3.7 wt.% (Table 3 and Fig. 21b) , respectively.

The Saginota Gravels (Konno and Otuka 1933) are fluvial fan deposits with thickness of 200 m distributed in the western half of Kambara Hills and in the southern Habuna Hills (Yamazaki 1992). The age of the Saginota Gravels is estimated to be 0.4 to 0.5 Ma on the basis of *Stegodon Orientals* and the occurrence of widespread vitric ash which is potentially correlated to Ks10 ash (Machida *et al*. 1980). To examine petrographic properties of this vitric ash, the author collected it along the road of Tsuburano-Ashigakubo village section in Shizuoka Prefecture. This vitric ash, with a thickness of 10 cm, is interbedded in the massive siltstone underlain by the Saginota Gravels. The author named this vitric ash as the Tsuburano Volcanic Ash.

The Tsuburano Volcanic Ash contains abundant bubble-wall, fiber, stripe, fiber, and sponge type glass shards with a small number of hornblende and orhopyroxine (Table 3). The mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.500-1.501, SiO_2: 78.2-79.1 wt.%, Al_2O_3: 12.0-12.4 wt.%, FeO*:

0.8-1.2 wt.%, CaO: 1.0-1.3 wt.%, K_2O: 2.8-3.1 wt.%, and Na_2O: 3.2-3.7 wt.% (Table 3 and Fig.21b), respectively.

4.3.3 Ks18-Kume-Ashigakubo volcanic ash

At Senda (Fig. 9; location 3), in the middle of Boso Peninsula, the Ks18 Volcanic Ash (Tokuhashi and Endo 1984) occurs as a white to pink colored vitric ash fall deposit 12 cm thick in the Kasamori Formation of the Kazusa Group. Its lower part with a thickness of 7 cm is silt to fine sized volcanic ash unit, and upper part with a thickness of 5 cm is fine to medium sand sized pink colored volcanic ash unit. Ks18 contains abundant bubble-wall, fiber, and sponge type glass shards with a small number of hornblende and orthopyroxene (Table 1). The mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.500-1.501 (1.500), SiO_2: 77.9-78.6 wt.%, Al_2O_3: 11.9-12.4 wt.%, FeO*: 0.9-1.2 wt.%, CaO: 1.1-1.2 wt.%, K_2O: 3.0-3.3 wt.%, and Na_2O: 3.3-3.6 wt.% (Table 1 and Fig. 16b) , respectively.

The Kume Volcanic Ash (Suganuma *et al*. 2003) was collected at Kume in the Iida City, Nagano Prefecture. It occurs as a white to pink colored vitric ash fall deposit 15 cm thick in the Kume Formation of the Ina Group. Its lower part with a thickness of 7 cm is silt to fine sized volcanic ash unit, and upper part with a thickness of 8 cm is fine to medium sand sized volcanic ash unit. The Kume Volcanic Ash contains abundant bubble-wall, fiber, stripe, and sponge type glass shards with a small number of hornblende orthopyroxene, and clinopyroxene (Table 1). The mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.499-1.501 (1.500), SiO_2: 78.0-79.2 wt.%, Al_2O_3: 12.0-12.4 wt.%, FeO*: 1.0-1.2 wt.%, CaO: 1.1-1.2 wt.%, K_2O: 2.9-3.2 wt.%, and Na_2O: 3.3-3.7 wt.% (Table 1 and Fig. 16b) , respectively.

The Middle Pleistocene Numakubo Gravel and Silt Member distributed around Numakubo in Fujinomiya City (Shiba *et al.* 1992) are consist of meandering fluvial, coastal plain incised valley, estuary, meandering fluvial, braided fluvial system, in ascending order (Yokoyama and Shiba 2013). The age is estimated to be 0.5 to 0.7 Ma

(Mizuno *et al*. 1992). The Ashigakubo Aolcanic Ash (A8 volcanic ash layer; Shiba *et al*. 1992), which interbedded in the upper part of the Numakubo Gravel and Silt Member, is correlated to Hwk by Mizuno *et al*. (1992). To examine petrographic properties of this vitric ash, the author collected it along the riverbed of Fuji River.

The Ashigakubo Volcanic Ash, with a thickness of 15 cm, is also divided to two units. Lower part with a thickness of 5 cm is silt to fine sized volcanic ash unit, and the upper part with a thickness of 10 cm is fine to medium sand sized volcanic ash unit. The Ashigakubo Volcanic Ash contains abundant bubble-wall, fiber, stripe, and sponge type glass shards with a small number of hornblende orhopyroxine, and clinopyroxine (Table 1). The mode of refractive indices and chemical composition of the volcanic glass shards are n: 1.499-1.501 (1.500), SiO_2: 78.0-79.2 wt.%, Al_2O_3: 12.0-12.4 wt.%, FeO*: 1.0-1.2 wt.%, CaO: 1.1-1.2 wt.%, K_2O: 2.9-3.2 wt.%, and Na_2O: 3.3-3.7 wt.% (Table 1 and Fig. 16b) , respectively.

5 Proposal of new widespread correlation of Middle Pleistocene pyroclastic flow deposits derived from southern Kyushu

In this chapter, we propose three tephras as widespread tephras originating from the large PFDs described in Chapter 4. In descending order, they are Hgw-Ks5, Tkym-Ks10, and Smkd-Ks18 (Fig. 6). The former two of reflect new proposals; the latter one is a redefinition. For each widespread correlation, we compare the petrographic characteristics of the Ks-series tephras as distal ash fall deposits with the petrographic characteristics of proximal PFDs and present the stratigraphic order. Each widespread correlation is discussed, comparing samples collected from both type localities of the proximal southern Kyushu and distal Boso Peninsula.

5.1 Hegawa-Ks5 tephra (Hgw-Ks5)

The sample collected from the type locality of Hgw contains abundant orthopyroxene and clinopyroxene and relatively few hornblende and quartz (Table 3). The samples from Ks5 on the Boso Peninsula were examined for their heavy mineral content; similar results were obtained (Table 3). Although clinopyroxene was not found in the sample of Ks5, it contains the characteristic minerals found in Hgw, such as orthopyroxene and hornblende, which indicated that the Ks5 tephra is derived from the same eruption. Orthopyroxene is the dominant heavy mineral of Hgw and Ks5. However, we could not determine the refractive indices of orthopyroxene and hornblende in Ks5 because the size of the phenocrysts is too small. Comparing in the refractive indices of the volcanic glass shards, there is a similarity that both Hgw and Ks5 have volcanic glass shards showing n: 1.505. Although those of Ks5 show higher range values (n: 1.505-1.506), comparing in the major element chemical compositions of volcanic glass shards, both samples contain homogeneous volcanic glass shards as indicated by low standerd deviations of oxide means (e.g. 0.1-0.2 wt.% for SiO_2, 0.0-0.1 wt.% for CaO and 0.0-0.1 wt.% for K_2O) (Table 3 and Fig. 25a). Although Ks5 shows a higher range value (n: 1.505-1.506) in refractive indices of volcanic glass shards than those of Hgw (n: 1.502-1.505), not completely match together, the glass chemistry of their volcanic glass supports this correlation. In addition, the glass compositions are similar to those of Yoshino PFD (Ysn). However, the analyses allow Hgw-Ks5 to be easily distinguished from the Ysn as shown in the SiO_2-K_2O Harker diagram (Fig. 25a). The relatively high K_2O and low SiO_2 contents of the glass shards from the Ysn are distinct from those of Hgw-Ks5. In this study, only parts of the major chemical composition of the Ysn glasses can be used to indicate such characteristics; it cannot be considered comprehensively and we only mention the fact that they are very similar to Hgw-Ks5. Based on these properties, the fine vitric ash fall deposits of Hgw-Ks5 were identified in Oga and the Pacific Ocean 1,500 km northeast of southern Kyushu (Matsu'ura, in press).

As already mentioned in section 4.1.9, the stratigraphic position of Hgw is above Kb-Ks in the southern Kyushu (Figs. 22 and 24). In addition, there is no stratigraphic contradiction with respect to the correlation of Hgw and Ks5 because Kb-Ks correlates with Ks11 interbedded in the Kasamori Formation of the Boso Peninsula (Machida and Arai 2003) and Ks5 is above Ks11 (Figs. 4a and 6). Figure 28 summarizes the distal ash fall deposits that have been correlated with Ks18, 10 and 5 or that have been pointed out for similarities in previous studies.

5.2 Takeyama-Ks10 tephra (Tkym-Ks10)

The sample collected from the type locality of Tkym contains abundant hornblende, biotite, orthopyroxene and quartz, and relatively few clinopyroxene (Table 3). The samples from Ks10 on the Boso Peninsula were examined for their heavy mineral content; similar results were obtained (Table 3). Although, biotite and clinopyroxene were not found in the Ks10 sample, it contains the characteristic minerals found in the Takeyama PFD, such as hornblende and orthopyroxene, which indicates that those deposits are derived from the same eruption. Hornblende is the dominant heavy mineral of Tkym and Ks10, comprising approximately one quarter of the total heavy minerals. The range of refractive indices of the volcanic glass shards and hornblende of both samples overlaps, with n = 1.498-1.500 and n_2 = 1.669-1.674. These features support the correlation of Tkym with Ks10 in proximal and distal areas. The similaries of the glass chemistry of Tkym and Ks10 also supports this correlation. Both samples contain a homogeneous major element composition, as indicated by low standard deviations of the oxide means (e.g. 0.2-0.3 wt.% for SiO_2, 0.1 wt.% for Al_2O_3 and 0.1 wt.% for K_2O; Table 3 and Fig. 21b). In addition, the major chemical compositions of the Tkym and those of the distal ash fall deposits are identical within the analytical uncertainties, correlating with Ks10, Kh5b, and the Tsuburano volcanic ash. Based on these results, the Tkym correlates with Ks10. In addition, the glass compositions are similar to those of Smkd. However, Tkym-Ks10 can easily be distinguished from Smkd, as shown in the SiO_2- K_2O harker diagram (Fig. 21a). The high K_2O contents and low SiO_2 contents of glass shards from the Smkd are distinct from those of Tkym-Ks10.

With respect to the proximal stratigraphy, Tkym, as the proximal PFD of Tkym-Ks10, is positioned above Kb-Ks (see Section 4.1.9 and Fig. 19). In this study, the author could not detect the stratigraphic relationship between the Tkym and newer PFDs. However, similar to the correlation of Hgw-Ks5 mentioned above, the correlation of Tkym-Ks10 is consistent with the stratigraphic order between Ks10 (upper) and Ks11 (lower) on the Boso Peninsula (Fig. 6). Therefore, the author concluded that Tkym-Ks10 is newer than Kb-Ks and older than Hgw-Ks5, depending on the stratigraphic order of Kb-Ks and Hgw-Ks5 in the Kasamori Formation of the Boso Peninsula.

5.3 Shimokado-Ks18 tephra (Smkd-Ks18)

Among the tephras correlated with the previous Hiwaki tephra proposed by Machida and Arai (2003), the author concluded that the Hiwaki PFD is not correlated with Smkd and Ks18 (see section 4.1.4). For this reason, the author proposes the redefined widespread tephra. It is referred to here as the Smkd-Ks18 tephra.

The sample collected from its type locality of Smkd contains abundant hornblende, orthopyroxene, and quartz, and small numbers of clinopyroxene (Table 1). Samples from Ks18 at the Boso Peninsula were examined for their heavy mineral content, and gave similar results (Table 1). Although there is variation for several mineral species (e.g. clinopyroxene), the similarity of the samples was consistent with their derivation from the same eruption. Hornblende was the dominant heavy mineral of Smkd and Ks18, comprising approximately half of the total heavy minerals. In refractive indices of hornblende, both samples had the range overlapping from n_2: 1.669 to 1.674. In refractive indices of orthopyroxene, both samples fall within the range from γ: 1.705 to 1.710. These features support the correlation of Smkd with Ks18 in proximal and distal areas. The similarities in glass chemistry between Smkd and Ks18 also support this correlation. Both samples contain homogeneous population, as indicated by low standerd deviations of oxide means (e.g. 0.2 wt.% for SiO_2, 0.1 wt.% for CaO and 0.1 wt.% for K_2O) (Table 1 and Fig.16b). In addition, the major chemical compositions of the Smkd are identical within analytical uncertainties to those of distal ash fall deposits correlated to Ks18 such as the Kume and Ashigakubo Volcanic Ash. From the above, Smkd was correlated with Ks18.

In the source caldera area, it was confirmed that the Smkd is positioned at least upper than Nb. Moreover, according to the stratigraphy of Sato *et al*. (2000), Smkd is considered to be positioned below Kb-Ks. This stratigraphic relationship is consistent with the stratigraphic order of Ks18 (lower) and Ks11 (upper) in the Kasamori Formation, in Boso Peninsula.

6 Middle Pleistocene eruptive history around the Kagoshima Graben

The author comprehensively discussed the eruptive ages of proximal PFDs and co-ignimbrite ash fall deposits referring to radiometric datings and stratigraphic positions determined in several areas such as Kagoshima Graben and Kanto area, and so on. Afterward, based on their eruptive ages, the author considers the frequency of explosive caldera-forming eruption in Middle Pleistocene. Figure 28 shows the distribution of Middle Pleistocene widespread tephras along with the proximal tephrostratigraphy.

6.1 Eruptive ages

There are four Middle Pleistocene widespread tephras originated from southern Kyushu caldera area before the Kakuto pyroclastic flow eruption, that is, Hgw-Ks5, Tkym-Ks10, Kb-Ks and Smkd-Ks18 in descending order. As it is concluded that eruptive ages of the Hgw-Ks5, Tkym-Ks10, Kb-Ks and Smkd-Ks18 are 430–450 ka (Marine oxygen Isotope Stage: MIS 12), 480–530 ka (MIS13), 520–530 (MIS is discussed below) ka and 570–580 ka (MIS 15), respectively. Discussions after this section are based on these ages. The age of each tephra estimated by previous researches are consistent with their stratigraphic relationship in the Kasamori Formation.

The eruptive age of Kb-Ks is controversial, broadly estimated from MIS 13 to MIS 15 by several researchers, and the view of the age has not been unified among researchers (Satoguchi and Hattori 2008). One of the important data to consider the eruptive age of Kb-Ks is its stratigraphic position in the Osaka Group. The Sakura Volcanic Ash (Ichihara *et al*. 1966; Yoshikawa 1984), which is correlated with Kb-Ks in the Osaka Group (Machida *et al*. 1980), is intercalated in the lower part or in the immediately below the Marine Clay Beds (Ma) Ma 7 (Yoshikawa *et al*. 2000). According to Yashikawa and Mitamura (1999), the Ma 7 is corresponded to MIS 15.1 (612 ka, Bassinot *et al*. 1994). On the other hand, Machida and Arai (2003) estimated eruptive age of Kb-Ks as MIS 13, although they recognized that Kb-Ks was stratigraphically below the Ma 7 in the Osaka Group. Thus, Machida and Arai (2003) considered to eruptive age of Kb-Ks to be 520–530 ka, referrting that Shirai (2000) estimated eruptive age of Kb-Ks as MIS 13.5 in the deep marine sediment core (ODP 794 and 797) of the Sea of Japan. Based on the sequence stratigraphy of the Kazusa Group (Ito 1994), eruptive age of Kb-Ks is estimated to be MIS 12 to MIS 13 (470 ka). Okuda *et al*. (2006) correlated the Kh5a intercalated in the Choshi core of the Inubo Group with Ks11. This correlation and the chronology constructed by pollen analysis for the same core, suggest that Kh5a (Kb-Ks) was deposited in MIS 15. Their interpretation is consistent with the stratigraphic position of the Sakura Volcanic Ash (Kb-Ks) (Yoshikawa *et al*. 2000) in the Osaka Group interbedded immediately below the Ma 7, and also is harmonious with the idea of Mitamura (1999), which positioned the Ma 7 at MIS 15.1. On the other hand, based on the oxygen isotopic curve obtained from the Choshi core of Kameo *et al*. (2006), it was referred that the stratigraphic position of Kh5a correlative to Ks 11 (Kb-Ks) is near the peak of MIS 14 (Nakazawa *et al*. 2009).

The author concludes that Ks11 is correlated to Kobayashi PFD. However, concerning the stratigraphic position of Ks11 in the Osaka Group, the author points out its problem in identification. Machida *et al*. (1980) correlated the Sakura Volcanic Ash to Ks11. However, in recent research, the Guminoki Volcanic Ash (Ichihara *et al*. 1966), which is petrographically similar to Sakura-Ks11 volcanic ash, was identified in the Osaka Group (Nagahashi *et al*. 2004). According to Nagahashi *et al*. (2004), the Guminoki and Sakura-Ks11 volcanic ash were difficult to distinguish, since the petrographic properties such as types of volcanic glass shards, mineral assemblage and glass chemistry are similar to each other. In the Osaka Group, the Guminoki Volcanic Ash is intercalated between the Ma 8 and Ma 7, and its stratigraphic position is corresponded to MIS 13 (Yoshikawa and Mitamura 1999). Although the author does not discuss this problem in this study, the author points out the necessity to study identification of Kb-Ks in the future.

In this study, the author does not refer to the older estimated age of Kb-Ks

Yoshikawa and Mitamura (1999) in the Osaka Group because the author does not directly compare the Sakura Volcanic Ash with Ks11. The age estimation of Shirai (2000) was based on the horizon of Kb-Ks in the ODP core which showed by Tada and Irino (1994; 1996) as detailed correlation of diatom abundance curve with the SPECMAP oxygen isotopic curve (Bassinot et al. 1994). Machida and Arai (2003) considered Shirai's (2000) age, and confirmed the stratigraphy in several areas. Thus, this study adopted 520–530 ka for the eruptive age of Kb-Ks based on the estimation by Machida and Arai (2003).

Suzuki and Fujiwara (1998) concluded that a volcanic ash layer (Oga-Wakimoto tephra: Suzuki and Fujiwara; Wkm: Machida and Arai 2003) intercalated in the basal part of the Shibikawa Formation at Oga Peninsula was correlative to Ks5. According to Shirai *et al*. (1997), the age of the horizon of this tephra is corresponded to ages before 440 ka (MIS 12). Machida and Arai (2003) was estimated the eruptive age of Ks5 (=Wkm) to 430–450 ka (MIS 12) in the Shibikawa Formation, based on a radiometric age of Oga-pumice-tuff (Ar-Ar: 421 ± 14 ka) (Kano *et al*. 1999), which is stratigraphically above the Wkm. Satoguchi and Hattori (2008) employed 450 ka (MIS 12) as the eruption age of Ikadachi II correlative to Hgw-Ks5. This age was determined both in the subsurface stratigraphy along the coast of Osaka bay (Yoshikawa and Miyakawa 1997) and the sequence stratigraphy in the Kazusa Group (Ito 1994). According to Yoshikawa *et al*. (2000), in the Osaka Group, K1-223 correlated with Hgw-Ks5 is interbedded in stratigraphically between the Ma 9 and Ma 8 (MIS 12; Yoshikawa and Mitamura 1999). Also, Yoshikawa (2012) shown the eruptive age of Minatojima I, which was correlated to Ks5, was positioned at 430 ka (MIS 12). The author adopted the eruptive age of Ks5 as 430–450 ka (MIS 12), accepting the age shown by Machida and Arai (2003) since their estimation was consistent with all ages noted above.

The volcanic ash layer correlated with Tkym-Ks10 has not yet been reported in the Osaka Group. However, since Tkym-Ks10 is exposed immediately above Kb-Ks in the southern Kyushu, the Kobiwako Group, and the Kasamori Formation (e.g. Satoguch and Hattori 2008; Tokuhashi and Endo 1984), it was estimated that

Tkym-Ks10 erupted in MIS 13 as the same as Kb-Ks eruption. In this study, the eruptive age of Tkym-Ks10 was assumed to be 480–530 ka (MIS 13) according to the age of MIS 13 corresponding to the LR04 oxygen isotopic curve indicated by the Liesckie and Raymo (2005). The estimated eruptive ages of the two tephras are partially overlapped, but in stratigraphically the Tkym-Ks10 eruption occurred after Kb-Ks eruption.

In this study, the eruptive age of Smkd-Ks18 was estimated to be 570-580 (MIS 15), based on ages of Hwk previously determined by Machida and Arai (2003). Machida and Arai (2003) proposed the age of Smkd-Ks18 (previous Hiwaki tephra) to 570–580 ka, assuming the Ks18 stratigraphically positioned at MIS 15 estimated from the oxygen isotopic stratigraphy of the Kazusa Group. As the stratigraphic position of Smkd-Ks18 in the Osaka Group, BK-173 volcanic ash layer, which is correlative to Smkd, intercalated in the Ma 6 layer (Kitani and Ka 2010). According to Yoshikawa and Mitamura (1999), the Ma 6 was corresponded to MIS 15.5, suggesting a concordance with the age of Machida and Arai (2003). In addition, several radiometric ages, confirming this estimated age, have been obtained for Smkd in the proximal caldera region, such as 0.58 ± 0.03 Ma, 0.57 ± 0.03 Ma (K-Ar; Machida and Arai 2003), and 0.61 ± 0.08 Ma (Zr-FT; Imura *et al*. 2001), respectively.

6.2 Eruptive volume of co-ignimbrite ash fall deposits of Smkd-Ks18, Tkym-Ks10 and Hgw-Ks5 tephra

In this study, the volumes of these widespread tephras were calculated from thickness of these co-ignimbrite ash fall deposits (CAFD) in their distributed area. The bulk volume was calculated by multiplying the area of a circle whose radius is the distance from the Aira caldera to the farthest detected point of each tephra and their mean thickness assumed that smaller than those in the Kasamori Formation, in Boso Peninsula. The farthest distribution points of Smkd-Ks18 and Tkym-Ks10 are located in the Boso Peninsula (the Kasamori and Kurahashi Formation) approximately 1,000 km northeast from the center of Aira caldera. Among the three newly defined widespread tephras, Hgw-Ks5 is the only tephra found in the Tohoku region, northeast Japan. The distance from the Aira caldera to its distribution point is 1,250 km at the Oga Peninsula (Wkm; Suzuki and Fijiwara 1998) and 1,450 km at the east off Shimokita Peninsula (Matsu'ura *et al.*; in press). To convert the bulk volumes to dense-rock equivalent (DRE; 2.5 g/cm^3), the density of co-ignimbrite ash fall deposits were adopted as 1.0 g/cm^3 (Table 5).

As a result, volumes of co-ignimbrite ash fall deposits of Smkd-Ks18, Tkym-Ks10, and Hgw-Ks5 are estimated as 330, 217, and 217 km^3, respectively (Table 5). The total volume in DRE of Smkd-Ks18, Tkym-Ks10, and Hgw-Ks5 are calculated to be 132, 87 and 87 km^3, respectively (Table 5). In addition, Eruption Magnitudes (Hayakawa 1993) are 7.5 to 7.3 (Table 5). Regarding to the volume of these widespread tephras, the volume of each one is on the order of 100 km^3 (Table 5). Therefore, it is considered that these eruptions are assigned to VEI 7, although each amount of PFD (not yet estimated) is excluded.

Comparing the volume by previous studies, Kb-Ks (including pfa, pfl, and afa) was estimated more than 200 km^3 in bulk volume and 150 km^3 in DRE volume (Nagaoka and Okuno 2011), suggesting that newly proposed widespread tephras has a possibility to reach these values. Futhermore, Nagaoka and Okuno (2011) discussed the total DRE volume of magma discharge in Kirishima volcano over the last 600 ka is 244.8 km^3, of which 85 % is tephra, reflecting that Kb-Ks (150 km^3) and Kkt (50 km^3) occupy 83 % of the total volume. Assuming that Smkd-Ks18, Tkym-Ks10 and Hgw-Ks5 are originated from the Aira Caldera, this caldera is presumed to have more than twice the amount of eruptive volume as compared with other calderas in southern Kyushu as well as the Kobayashi caldera.

6.3 Frequency of large caldera-forming eruptions

The eruptive ages of Smkd-Ks18, Tkym-Ks10 and Hgw-Ks5, which were proposed as a new widespread tephra, were concluded to be 570–580 ka, 480–530 ka and 430–450 ka. The following shows the frequency of large caldera-forming eruption as the whole Kagoshima Graben in the past 600 ka on the basis of the eruptive age and stratigraphy established in this study and previous studies. Time space diagram (Fig. 29) allows an estimate of the average frequency of large-scale eruption of the Kagoshima Graben, showing the eruption of VEI 5 or more in the Middle Pleistocene to Holocene derived from the five calderas comprising the Kagoshima Graben. The North and South Ata caldera was shown together as the Ata Caldera. Tephras and VEI, volume, and eruptive age were in accordance with Machida and Arai (2003), Nagaoka and Okuno (2011). In Figure 29, Sgs distributed in the Miyazaki plain was assumed to be VEI 6, since the A-Iw tephra originated from the Aira caldera and distributed in the Miyazaki plain was estimated to be VEI 6 (Machida and Arai 2003). Ii is difficult to estimate volumes of Kmj, Oda and Nb, however, since distribution in Miyazaki has not yet been reported, it was supposed to be smaller than Sgs and assumed to be VEI 5. The Figure 28 also includes tephras that composed of only Plinian pumice fall deposits without PFDs (e.g. A-Fk; Aira-Fukuyama, Kr-Iw; Kirishima-Iwaokoshi, Sz-S; Sakurazima-Satsuma: Machida and Arai 2003) to compare VEI to these explosive eruptions.

Previously well studied eight widespread tephras derived from the southern Kyushu caldera region during the last 600 ka, Smkd-Ks18 (part of former Hwk), Kb-Ks, Kkt, Ata-Th, Ata, K-Tz, AT and K-Ah tephras, in ascending order, had been reported (Fig. 29). This indicates that eruptions accompaning huge pyroclastic flow deposits (VEI 7) occurred at an average interval of about 75 kry as the whole Kagoshima Graben. However, considering two widespread tephras Tkym-Ks10 and Hgw-Ks5, newly defined positioned between 530 to 340 ka from Kb-Ks to Kkt eruptions, the frequency of large caldera eruption (VEI 7) through the past 600 ka was revised to once in 60 kyr on average. In addition, focusing on the eruption interval in detail, the interval has changed at Hgw-Ks5 eruption (Fig. 29). During the period of 500 kyr from Smkd-Ks18 eruption to Ata eruption (105 ka), the average interval of large-scale eruption in the Kagoshima Graben had become longer from 40 to about 100 kyr after the Hgw-Ks5 eruption.

On the other hand, occurrence of the eruptions of VEI = 5 to 6, no eruption of these intensity has been recognized in about 300 kyrs from Hgw-Ks5 to Ata eruption (Fig. 29). It is unsure that this suggests the presence of dormant interval of explosive volcanic activity in the southern Kyushu caldera region. However, according to the tephrostratigraphy constructed by Nagaoka *et al*. (2010), tephras less than VEI 7 have not yet been detected in the Miyazaki Plain. In addition, the occurrence of tephras derived from other than Kirishima volcanic region is only the Aso-3 tephra derived from the Aso Caldera (Machida and Arai 2003). In order to establish a more detailed tephrostratigraphy, it is necessary to detect tephras in continuous marine sedimentary succession such as ocean cores off the Hyuga-Nada coast, together with adopting field survey approaches. In this study, the author indicated that as the explosive volcanic activity in the southern Kyushu caldera region in the past 600 ka, the large-scale pyroclastic flow eruption was dominant over the period of 580 to 450 ka of the Middle Pleistocene, comparing in the occurrence of those in the subsequent 300 kyr.

7 Conclusions

To reconstruct the stratigraphy and distribution of the Middle Pleistocene large-scale PFDs formed by caldera-forming eruptions in the southern Kyushu Caldera Region, we identified and correlated the tephras using petrographic methods including the glass chemistry and refractive indices of glass, hornblende, and orthopyroxene. Consequently, we comprehensively delineated the explosive eruptive history of the Middle Pleistocene in southern Kyushu with respect to the eruptive ages, stratigraphic position obtained from the proximal and distal areas, and precise volume of tephra. We conclude that the sequence of the large-scale Middle Pleistocene PFDs in this region is Komiyaji, Sagise, Nabekura, Shimokado, Oda, Kobayashi, Takeyama, and Hegawa, in ascending order. The stratigraphic position of the Oda PFD and Fumoto tuff remain unclear; however, the former is located above Sagise and the latter is positioned below Kobayashi, respectively. In addition, as a result of the examination of the widespread correlation among the proximal PFDs and distal vitric ash layers in the Kasamori Formation of the Kazusa Group in central Japan, three new widespread tephras are proposed: Shimokado-Ks18 (Smkd-Ks18), Takeyama-Ks10 (Tkym-Ks10), and Hegawa-Ks5 (Hgw-Ks5), in ascending order.

Based on the stratigraphic location of the distal vitric ash layer in previous stratigraphy studies of MIS, the eruptive ages of Smkd-Ks18, Tkym-Ks10, and Hgw-Ks5 are 570–580 ka (MIS15), 480–530 ka (MIS13), and 430–450 ka (MIS12). These eruptive ages are consistent with the tephrostratigraphy in the proximal caldera region based on the field observation and analytical work in this study.

The co-ignimbrite volumes (DRE) of Smkd-Ks18, Tkym-Ks10, and Hgw-Ks5 estimated from the distribution area of co-ignimbrite ash fall deposits (CAFD) are 132, 87, and 87 km3, respectively, assuming that the CAFD is distributed concentrically around the Aira Caldera of their source. Therefore, these eruptions can be assigned to a Volcanic Explosivity Index (VEI) of 7, ignoring the volume of their proximal PFDs.

The large-volume eruptions forming CAFDs occurred once every ~40 ka during the Middle Pleistocene from 450–580 ka. The interval between the large-volume eruptions increased after the Hgw-Ks5 eruption (430–450 ka). Eruptions occurred in intervals of 100 ka after the Hegawa-Ks5 eruption, whereas they occurred at an interval of ~50 ka before that, after Smkd-Ks18. The volcanic activity of the Middle Pleistocene in the southern Kyushu Caldera Region was higher between the Sgs and Hgw-Ks5 eruptions, approximately 600 to 400 ka.

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