The role of tephras in developing a high-precision chronostratigraphy for palaeoenvironmental reconstruction and archaeology in southern Kyushu, Japan, since 30,000 cal. BP: an integration

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Abstract

Tephras are important for the chronostratigraphy of palaeoenvironmental and archaeological records in southern Kyushu because numerous tephra beds enable these records to be connected and dated precisely using tephrochronology. A regional tephra-based framework or lattice for the past 30,000 calendar (cal.) years is proposed in the style of recent INTIMATE projects elsewhere. We review stratigraphic, compositional, age, and distributional data for a range of tephras, and comment on the relationship of several marker tephras to distinct palaeoenvironmental and cultural events in the southern Kyushu region since 30,000 cal. BP. More than 90 visible tephra beds are recorded, deriving from Kakuto, Aira, Ata, and Kikai volcanic centres, which incorporate large calderas, and the Tokara volcanic islands. The tephra record is underpinned by two widespread tephras, Aira-Tn tephra (AT; ca. 30,000 cal. BP), and Kikai-Akahoya tephra (K-Ah; ca. 7,300 cal. BP). In addition to AT and K-Ah, locally-distributed marker tephra beds are related to the chronostratigraphy of terrestrial and marine palaeoenvironments including sea-level and coastal environments, vegetation, and culture. Some tephras, notably AT, K-Ah, and Sakurajima-Satsuma tephra (Sz-S, ca. 12,800 cal. BP), have been recognized in marine and laminated lake sediments and hence dated with high precision, thereby facilitating correlation of those records to global high-resolution ice, marine, and terrestrial stratotypes. Sz-S is a useful isochron for the last deglaciation in southern Kyushu. Our integrated regional chronostratigraphic model for southern Kyushu, founded by tephras (and with further potential via systematic identification of cryptotephras), will enable change in regional palaeoenvironments and culture to

be evaluated in national and global contexts.

1. Introduction

The past 30,000 calendar (cal.) years are notable for the occurrence of marked and abrupt environmental change during the deglaciation from the last glacial to postglacial period. Collective research efforts to integrate ice core, marine, and terrestrial records for this period have been undertaken in the North Atlantic and Australasian INTIMATE projects (INTegration of Ice-core, MArine, and TErrestrial records) to determine the nature, timing, and regional to global extent of abrupt climatic and environmental change with high precision (Alloway et al., 2007; Lowe, J. et al., 2008; Blockley et al., 2012, 2014; Davies et al., 2012; Barrell et al., 2013; Bourne et al., 2015). In Japan, such integration has not yet been conducted formally, although numerous palaeoenvironmental and archaeological records, and high-resolution records, have been accumulated (e.g. Japan Association for Quaternary Research, 2009). Such records spanning the past 30,000 cal. years have been also obtained in southern Kyushu and the surrounding area, notably the East China Sea and western Pacific Ocean (e.g. Matsushita, 2002; Moriwaki et al., 2002, 2010a, 2011; Ijiri et al., 2005). Developing high-precision palaeoenvironmental and archaeological records on a regional scale, such as in the southern Kyushu area, is a critical step towards constructing an integrated national Japanese stratotype.

Tephras have played an important role for high-precision integration of regional and national-scale records in northwestern Europe (Blockley et al., 2014; Davies et al., 2014), New

Zealand (Lowe, D. et al., 2008; Lowe et al., 2013; Vandergoes et al., 2013), and elsewhere (e.g. see Lowe et al., 2011), because tephra layers (and cryptotephra deposits, which are glass shard and/or crystal concentrations not visible as layers in the field) provide time-parallel stratigraphic marker beds or isochrons (Lowe, 2011; Matsu‟ura et al., 2011a, 2011b; Davies, 2015). Such a comprehensive framework of volcanic events is sometimes referred to as a lattice, which combines mineralogical and geochemical signatures with well-constrained age estimates (Bourne et al., 2015).

Numerous Quaternary tephra beds in southern Kyushu have provided a stratigraphic, compositional, and chronological framework or lattice for developing a high-precision chronology of both past environments and archaeological records (Moriwaki and Lowe, 2010). Nearly 100 tephra beds have been documented for the past~ 30,000 cal. years in southern Kyushu. The tephras include those erupted as part of extremely voluminous ignimbrite-generating eruptions, the Aira-Tn tephra (AT) and the Kikai-Akahoya tephra (K-Ah).

In this review, we document the key tephra beds, and their compositional character, that are essential for establishing the chronostratigraphy of palaeoenviromental and archaeological records for the past 30,000 cal. years in southern Kyushu, and develop a chronology for these records incorporating tephra-based age models. In addition, we include a summary diagram that combines the tephrostratigraphic records with marine oxygen isotope changes (recorded from cores obtained from the East China Sea and western Pacific near Kyushu) with sea-level change and coastal palaeoenvironmental change, vegetation records, and archaeological records. We also integrate this tephra-based chronostratigraphic model with benchmark records from the NGRIP core and its associated age model (GICC05), a coral-based sea-level curve, and a terrestrial pollen record from central Japan.

2. Tephra-based chronostratigraphic framework in southern Kyushu

In southern Kyushu, which lies on a subduction zone between the Philippine Sea Plate and the Eurasian Plate, numerous Quaternary volcanoes occur aligned north to south (Fig. 1). In the northern part of this region, the volcanoes lie in and around four gigantic calderas, namely Kakuto, Aira, Ata, and Kikai calderas, forming complex volcanic centres. Tokara volcanic islands, associated with smaller calderas and stratovolcanoes, occur south of the Kikai volcanic centre (Fig. 1). These volcanoes and volcanic centres (including calderas) have produced numerous tephras in the Quaternary period, and more than 90 tephras have been erupted in the past ~30,000 cal. years (Table 1; Moriwaki, 2010).

A tephrostratigraphic framework for the past ca. 30, 000 cal. years has been erected for these tephras, which provide generally high-precision markers for the stratigraphy and chronology of palaeoenvironmental and cultural events, although age and compositional data are not yet available for some of tephra beds (Fig. 2; Machida and Arai, 2003; Moriwaki and Lowe, 2010). We document below data on selected tephras for this framework including their sources, composition, age, stratigraphic relationships, and distribution. We emphasise tephras that are related to distinct events or changes in environments and culture in antiquity.

The stratigraphy of the tephras can be constructed in the proximal areas near each volcanic centre, although relationships of some thin tephras with respect to the other, much thicker, eruptives can be obscure at present, particularly the thin tephras of Tokara volcanic islands (Fig. 2). The tephras generally are distributed mainly eastward from their sources because of prevailing westerlies. Several widespread tephras such as AT, K-Ah, and Sz-S help constrain the stratigraphic positions of the more locally-distributed tephras (Figs. 2 & 3). AT and K-Ah provide exceptional isochronous markers for palaeoenvironmental and cultural events in and around Japan, as well as for southern Kyushu (Machida, 2010). In addition to AT and K-Ah, many of the smaller-scale tephras provide useful markers for the palaeoenvironmental records of southern Kyushu, which, partly because of its comprehensive tephrostratigraphy, is one of the key regions in Japan for developing a high-precision, synchronised chronology for the past ca. 30,000 cal. years.

Essentially, the ages of the tephras (Table 1) are based on ^{14}C ages obtained using mainly organic material including charcoal derived from buried soils (e.g. Okuno, 2002; Okuno and Nakamura, 2003), peat and shell fragments. Known stratigraphical and archaeological relations help provide a cross-reference on the veracity of the tephra-based ages, although deposits on Tokara volcanic islands are not yet fully analysed chronologically. Ages with high accuracy and precision have been acquired for some widespread tephras, including AT and K-Ah, partly because many ^{14}C dates have been obtained for them, and partly because the marine-based oxygen isotope chronology (Machida and Arai, 2003), and the high-resolution varve chronology from Lake Suigetsu, central Japan, have enabled them to be dated very precisely through correlation (Staff et al., 2013; Smith et al., 2013). Improved chronologies based on stratigraphic positions relating to the oxygen isotope chronology of deep-sea cores have been acquired for some of the less widespread tephras such as Sz-S (e.g. Moriwaki et al., 2012b).

Fingerprinting tephras using mineral compositions are generally not so effective in southern Kyushu because the dominant ferromagnesian silicate mineral compositions are similar for many of the tephras, which commonly contain orthopyroxene and clinopyroxene in the heavy mineral fractions. Two exceptions are Ikeda tephra, which contains hornblende (and quartz in the light mineral fraction), and Miike tephra, which contains minor amounts of hornblende (Machida and Arai, 2003). Refractive indices of glass and ferromagnesian silicate minerals, in addition to the stratigraphic superpositions and physical properties of the tephras in the field, have therefore been employed to correlate and identify the tephras in southern Kyushu (e.g. Machida and Arai, 2003).

Geochemical data are important for characterizing and thus mapping tephras of mid- to small-scale eruptions in southern Kyushu, because this area lies in western parts of Japan and thus they have potential to be found as cryptotephras more extensively in Japan (e.g. see Matsu’ura et al., 2011a, 2012), which is situated in the mid-latitude zone of westerlies. Because low-density volcanic glass shards disperse farther than other tephra constituents, their geochemical analysis by electron probe microanalysis (EMPA) and laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) (e.g. Hayward, 2012; Hall and Hayward (2014); Pearce, 2014; Pearce et al., 2014) provide the most useful means for improving further the tephrostratigraphic (and potentially cryptotephrostratigraphic) frameworks for Japanese sedimentary sequences and hence enable enhanced high-precision correlations to be obtained for palaeoenvironmental and human cultural changes in and around Japan.

AT and K-Ah ash fall deposits, derived from voluminous associated ignimbrite eruptions, have been identified extensively in Japan by refractive indices of glass and phenocrysts, and by EPMA-derived glass major element compositions (Machida and Arai, 2003). Recently, these tephras were identified using such compositions in high-resolution deposits of Lake Suigetsu, central Japan (Smith et al., 2013), from which high-precision ages of the two tephras were derived, therefore improving the precision of palaeoenvironmental and archaeological chronologies.

As well, geochemical analyses of major element compositions of glass shards using EPMA have been acquired for some tephras from mid- to small volume tephras (Table 1, Fig.4; Moriwaki et al., 2008, 2011). The EMPA analyses of glass enable Sakurajima-derived tephras to be distinguished even where they are close together stratigraphically and broadly similar compositionally.

In the following sections (2.1 to 2.5), the tephras most important chronostratigraphically are recorded and briefly described, and their relationships to palaeoenvironmental changes or cultural events, or both, are noted.

2.1 Kakuto volcanic centre

All of the tephras associated with this centre are derived from Kirishima volcano complex on the southern side of the Kakuto caldera, in which occur several stratovolcanoes and vents, constructed after the caldera-forming eruption of Kakuto at ca. 330 ka (Imura, 1994; Imura and Kobayashi, 2001). Those volcanoes produced numerous tephras since the Kakuto 330-ka eruption, including ~20 prominent tephras for the past 30,000 cal. years (Imura, 1992; Nagaoka et al., 2009; Nagaoka and Okuno, 2011; Tajima et al., 2014). These post-30 cal ka tephras are composed predominantly of pumice and scoria fall deposits. In terms of their importance in marking palaeoenvironmental changes and cultural events, as well as volume, the Miike and Kobayashi tephras are noteworthy (Fig. 2).

Kirishima-Miike (Kr-M) This tephra consists of pumice fall and base surge deposits sourced from Miike maar on the southern edge of the Kirishima volcano. The tephra, with a bulk volume of 3.1 km^3 , is the most voluminous of Kirishima tephras erupted since 30,000 cal. BP (Nagaoka and Okuno, 2011). Its age is ca. 4600 cal. BP (Nagasako et al., 1999; Okuno, 2002). Kr-M characteristically contains hornblende. The fallout pumice is widely dispersed south to southeast from the source (Fig. 3) and the distribution overlaps that of Sakurajima tephras, which together provide a more reliable chronological framework than individual eruptives. Miike tephra provides an isochron for the chronology of mid-late Holocene human remains (Kuwahata and Higashi, 1997).

Krishima-Kobayashi (Kr-Kb) This tephra, comprising mainly pumice fallout deposits, is aged ca. 16,700 cal. BP and was sourced from Karakunidake volcano in the northern part of the Kirishima volcano complex (Table 1, Fig. 2; Imura and Kobayashi, 2001). With a bulk volume of 0.91 km^3, this tephra is the second largest volumetrically for the past 30,000 cal. years from Kakuto volcanic centre (Imura and Kobayashi, 2001). It was dispersed mainly northeast of the source volcano (Fig. 3).

2.2 Aira volcanic centre

This centre incorporates Aira caldera, with several associated volcanoes in and around the caldera. The three tephras mentioned below are very extensive and provide key isochrons for palaeoenvironments of the last glaciation and deglaciation and for epoch-making human or cultural remains.

Aira-Tn tephra (AT) This tephra, sourced from Aira caldera, provides the outstanding isochron for the last part of the last glacial (Machida and Arai, 1976, 2003). The ^{14}C-based age for it is ca. 29,000 cal. BP (Okuno, 2002), consistent with an age of 30,009 ± 189 $SG06_{2012}$ year BP derived from the Lake Suigetsu record (Smith et al., 2013), which corresponds to the stage shortly before the Last Glacial Maximum, i.e. it lies near the transition from MIS 3 to MIS 2. The total volume (bulk) of AT tephra amounts to >450 km^3 (Machida and Arai, 2003). The AT ash associated with the eruption of the Ito ignimbrite produced in the last phase of the Aira-Tn eruption cycle occurs extensively in and around Japan and has provided a tie point for the correlation of various marine and terrestrial palaeoenvironments, and human cultures (Machida and Arai, 2003). In southern Kyushu, the AT tephra exists as an extensive ignimbrite deposit which occurs over an area with a radius >100 km from Aira caldera (Fig. 3). From the chronological point of view, the surface of the Ito ignimbrite, as well as the constituent deposits it encompasses, provides a visible landform (geomorphic) datum.

The ferromagnesian mineral composition of AT tephra is predominantly ortho- and clinopyroxene, and it additionally contains minor amounts of quartz. The AT glass has a distinctly high amount of SiO_2 (ca. 78 wt%; normalized, anhydrous basis) compared with that of other eruptives (Fig. 4).

Sakurajima-Satsuma (Sz-S) This tephra, ~11 km^3 in bulk volume, is the most voluminous of ~17 tephras erupted from Sakurajima volcano (Kobayashi and Tameike, 2002). Sz-S comprises ~13 units, most of which are pumice fall deposits including base surge and ashfall deposits of phreatomagmatic origin (Fig. 5). The Sz-S tephra occurs on Satsuma Peninsula as well as Osumi Peninsula, and thus presents a generally circular distribution pattern around the source (Fig. 2), because each fall unit was dispersed in different azimuths away from the vent (Moriwaki, 1992).

Sz-S tephra was widely dispersed over southern Kyushu and the East China Sea. Its age is ca. 12,800 cal. BP (Okuno, 2002), and it provides an excellent isochron for late deglaciation just prior to the start of the Holocene. It contains ortho- and clinopyroxene, the same assemblage that characterizes other Sakurajima tephras. Glass chemical compositions of this tephra show no variations between units, and a moderately high silica content (SiO_2, 75.6 wt %; normalized, anhydrous basis) (Moriwaki et al., 2011).

Sakurajima-Takatoge 3 (Sz-Tk3/P13) This tephra, with a bulk volume of 1.3 km^3 (Okuno et al., 1999), is thus much smaller in volume than Sz-S, but occurs over northern Osumi Peninsula. The tephra, ca. 10,600 cal. BP in age (Okuno, 2002), is a useful isochron marking a point ca. 1000 years after the boundary between the Pleistocene and Holocene, which in Japan is defined at 11, 552 ± 88 cal. BP in Lake Suigetsu, one of five global auxiliary stratoypes (Walker et al., 2009). Sz-Tk3/P13, and Sz-S mentioned above, together help constrain the stratigraphic position of the Younger Dryas, GS-I, event. Sz-Tk3/P13 was dispersed northeast and east of the source vent.

Glass major element compositions for tephras deposited stratigraphically close together in the Aira volcanic centre are distinctly different, with differences between AT and Sakurajima tephras, Sz-S, Sz-Tk3, and Sz-Ub, evident in oxide bivariate plots (Fig. 4). There is a sufficient variation for the Sakurajima tephras to show that glass-based major-element compositions are useful for differentiating them.

2.3 Ata volcanic centre

Ata volcanic centre consists of Ata caldera and many associated volcanoes. Most of the tephras spanning the past 30,000 cal. years were erupted from Ikeda caldera and Kaimondake volcano in the mid- to late Holocene.

Ikedako (Ik) Ikedako tephra, erupted from a caldera with a diameter of ~5 km and VEI 5, consists (from lower to upper units) of ash fall, surge, scoria fall, pumice fall, pyroclastic flow, surge and ashfall deposits (Naruo and Kobayashi, 1980; Naruo and Kobayashi, 1984; Okuno et al., 1996; Inakura et al., 2014). Its age is ca. 6400 cal. BP (Okuno, 2002). Of these units, pumice fall deposits (Ikeda pumice fall) and a pyroclastic flow deposit (Ikeda pyroclastic flow deposit) are important for connecting and dating palaeoenvironmental changes and ancient cultures because of their wide distribution. Ikeda pumice fall deposits are evident on middle and south Osumi Peninsula to the southeast and to northeast of the vent (Fig. 3). The tephra was possibly dispersed much farther from southern Kyushu. It contains quartz as a distinct felsic mineral. Ikedako tephra, together with K-Ah, is a useful marker of the mid-Holocene in southern Kyushu.

Kaimondake 12 (Km12) Kaimondake volcano, a stratovolcano on the southern tip of Ata caldera, produced 12 scoria fall deposits called Km 1 to 12 from ca. 4400 to 1100 cal. BP (Fujino and Kobayashi, 1997; Okuno, 2002). These scoria beds are not voluminous, but they nevertheless provide important isochrons for the archaeology of the southern part of southern Kyushu, particularly in historical periods (Fig. 3). Km12 comprises several fall units with an interval of nine years between eruptions in AD 885 and 874 (Fujino and Kobayasi, 1997). It is recorded in the old document called “Nihon Sandai Jitsuroku”, the sixth of the six classical Japanese history texts.

2.4 Kikai volcanic centre

The centre consists of Kikai caldera and associated volcanoes. Most of the volcanoes are under the sea, except for the islands on the north of which Satsuma-Iojima Island, on the northwestern rim of the caldera, is a post-caldera volcano. There was no major tephra dispersal to the surrounding terrestrial regions apart from that arising from the Kikai-Akahoya caldera-forming eruption.

Kikai-Akahoya (K-Ah) K-Ah tephra consists of four units (from lower to upper): a pumice fall deposit (Koya pumice fall deposit), a low-volume pyroclastic flow deposit (Funakura pyroclastic flow deposit), a large-volume pyroclastic flow deposit (Koya /Takeshima pyroclastic flow deposit), and co-ignimbrite ash fallout (K-Ah ash fall) (Machida and Arai, 1978; Ono et al., 1982). Of these units, K-Ah ash derived from the Koya pyroclastic flow was dispersed widely in and around Japan. The total bulk volume of this tephra is >150 km^3 (Machida, 2010). Machida and Arai (2003) estimated an age of ca. 7300 cal. BP for K-Ah on the basis of a varved age of 7280 years BP from the Lake Suigetsu record of Fukusawa (1995). A more recent age estimate for K-Ah identified at Lake Suigetsu suggested an age of 7234 (7165-7303) cal. BP (95% probability range) (Smith et al., 2013). Matching these high-resolution ages and archaeological data, Kuwahata (2013) suggested an age for K-Ah of ca. 7200 to 7300 cal. BP.

K-Ah is youngest of the tephras in Japan that have a (bulk) volume of more than 100 km^3. It is useful for correlating palaeoenvironments and cultural deposits at the time of the post-glacial (mid-Holocene) hypsithermal period in and around the Japan islands.

The K-Ah ash is dominated by bubble-wall glass shards with minor phenocrysts. Many analyses including glass-shard based major elements have been obtained for it. K-Ah is compositionally rhyolitic, and SiO_2 content is 74.3 wt% on average (normalized, anhydrous basis) (Moriwaki et al., 2008). On bivariate oxide plots, K-Ah glass analyses can be similar to plots of glass analyses for Sakurajima tephras (Fig. 4). According to Smith et al. (2013), however, K-Ah is compositionally heterogeneous with SiO_2 ranging from 70.4 to 77.8 wt% (normalized, anhydrous basis). The Koya pyroclastic flow reached the Kyushu mainland, travelling across the sea, over a distance of ~100 km from source. The pyroclastic flow deposit can be recognized in central Osumi and on Satsuma Peninsula.

2.5 Tokara volcanic islands

The Tokara volcanic islands, aligned north–south, lie to the south of Kikai volcanic centre. The islands comprise both calderas and stratovolcanoes. Younger volcanic islands erupted in the late Pleistocene and Holocene number seven islands in total, from Kuchinoerabujima in the north to Io-Torishima in the south.

Numerous tephra beds including pumice and scoria fall deposits, and pyroclastic flow deposits, were erupted from these seven volcanoes. The most voluminous tephra in the past 30,000 cal years, identified on other islands and in the sediments of the surrounding sea, is Noike-Yumugi tephra of Kuchinoerabujima Island (Figs. 2 & 3). The general stratigraphy and some ^{14}C dates on tephras have been obtained for deposits on each island, and the occurrences of both AT and K-Ah tephras as well have helped to constrain the stratigraphic positions of the local (Tokara-derived) tephras (Moriwaki et al., 2009). Apart from Bunka scoria in Suwanosejima Island, no distinct tephras occur after K-Ah (in contrast to other volcanic centres with large-scale calderas on mainland), which means no distinct explosive eruption occurred since the K-Ah eruption episode. This dearth may be the result of sea-level change (Moriwaki et al., 2009).

Noike-Yumugi (N-Ym) This tephra is derived from Noike vent of Kuchinoerabujima Island, ~30 km south of Kikai caldera (Geshi and Kobayashi, 2006). It consists of pumice fall and pyroclastic flow deposits (Moriwaki et al., 2008). Radiocarbon ages for charcoal in the bed suggest that the eruption occurred ca.14,900 to 14,500 cal. BP (Geshi and Kobayashi, 2006; Moriwaki et al., 2009). This tephra is compositionally variable from lower to upper units, ranging from 73.3 to 77.4 wt% SiO_2 (normalized, anhydrous basis) (Moriwaki et al., 2011). Isopachs suggest N-Ym was distributed on the island northward and eastward from the vent. On

Tanegashima Island and in the deep-sea core in the East China Sea, this tephra lies stratigraphically lower than Sz-S (Moriwaki et al., 2011). With Sz-S, N-Ym is useful for helping to define the chronology of marine palaeoenvironments during the last deglaciation, in particular the GS-2a stadial to GI-1 interstadial.

No other tephras have yet been found beyond each island.

3. Role of tephras for palaeoenvironmental recontruction and linking and dating cultural events in antiquity

In southern Kyushu, tephras have played a key role in connecting and dating environmental changes and cultural events spanning the past ca. 30,000 cal. BP. In particular, changes in terrestrial vegetation, coasts, and marine environments, along with palaeolithic and ceramic cultures associated with human activity, have been compared and dated using tephrochronology to synchronize timescales. The chronologies of these changes and events are integrated with other regional stratotypes in Fig. 6. A chronology of cultural events relating to ceramic and stone cultures, and epoch-making cultural events, is given in Fig. 7.

We examine below how the key tephra marker beds mentioned above relate stratigraphically to the palaeoenvironments and cultural events recorded since ca. 30,000 cal. years ago.

3.1 Last Glacial Maximum

Tane IV This tephra, aged ca. 33,000 cal. BP to 32,500 (Tabira, 2002; Okuno et al., 2012) is related to the onset of the palaeolithic culture in southern Kyushu, although it is recognised only on Tanegashima Island. Tane IV overlies a layer comprising knife blades and traces of traps on this island (Tabira, 2002; Kagoshima Prefectural Archaeological Center, 2009). These remains are the oldest known artefacts in southern Kyushu. Although palaeolithic stone tools older than these remains are reported below Kr-Iwk tephra (ca. 50 ka BP), their veracity (whether the artefacts are real or not) is debated (Fig. 7). The analysis of tephras in marine cores adjacent to Tanegashima Island should provide a more accurate assessment of the stratigraphic juxtapositions of these palaeolithic artefacts.

Aira-Tn (AT) This widespread tephra, deposited shortly before the Last Glacial Maximum, is an excellent isochron for various palaeoenvironmental changes and palaeolithic cultural events that characterize this period (Machida and Arai, 2003). In southern Kyushu, the AT tephra occurs in part as extensive ignimbrite plateaux and thick pyroclastic deposits (Ito ignimbrite). Accordingly, records younger than the ignimbrite are usually readily determined, but older deposits are more difficult to establish. In this region, the eruption of the AT tephra catastrophically changed the landforms. Yokoyama (2000) showed that rapid erosion occurred shortly after the deposition of the ignimbrite, and the modern dissected ignimbrite plateaux and valleys were essentially formed in a short time. The oldest Sakurajima tephra, Sz-Tk6/P17 (ca.

26,000 cal. BP), occurs on the dissected non-cyclic river terraces and in the small valleys and gullies buried by the post-eruption deposits on the ignimbrite plateaux, suggesting the erosion of the ignimbrite occurred in less than ca. 4000 years (Moriwaki et al., 2007), somewhat akin to the massive reworking and landscape instability following deposition of the voluminous Kawakawa (Oruanui) eruptives ca. 25,400 cal. BP in New Zealand (Manville and Wilson, 2004; Vandergoes et al., 2013). Palaeolithic stones such as knives and flake points are often excavated in the soil between Ito ignimbrite and Sz-Tk6/P17 (Fig. 5), hence constraining their ages to between ca. 30,000 and 26,000 cal. BP. In a marine core in the East China Sea, the AT tephra lies at the boundary between MIS 3 and MIS 2.

3.2 Last deglaciation

Kirishima-Kobayashi (Kr-Kb) and Iwamoto(Iw) These tephras are critical for determining the transition period, when a microlithic culture replaces the previous knife culture (Fig. 7). Although the extent of these tephras is limited, microlithic stones occur above the tephras.

Sakurajima-Satsuma (Sz-S), Noike-Yumugi (N-Ym) Sz-S has been widely identified in the marine and terrestrial area in and around southern Kyushu, and hence is most useful for the integration of marine and terrestrial records in the last deglaciation. On the basis of the age model of core MD982195 (Ijiri et al., 2005), this tephra has been ascribed an age of ca. 13,000 cal. BP, which is similar to a terrestrical ^{14}C age of 12,800 cal. BP (Okuno, 2002). In the $\delta^{18}O$-based chronology of MD982195 (Ijiri et al., 2005), this tephra lies on the transition stage from warm to cold, which correspond to the transition of GI-1a interstadial to GS-1 stadial, i.e. Allerød to Younger Dryas stages (Fig. 6; Moriwaki et al., 2011).

N-Ym, slightly older than Sz-S, lies in the stratigraphic position corresponding to the transition from GI-1b to GI-1a. It corresponds to a peak of rapid increase on arboreal pollen from non-arboreal pollen in the core. However, on-land ^{14}C ages for this tephra on its source island mentioned above suggest the tephra marks the transition from GS-2a to GI-1e.

For terrestrial records, Sz-S lies in an andic soil overlying a distinct tephric loess bed derived partly from re-worked Ito ignimbrite (Fig. 5). Quartz grains derived from continental China are also found in the tephric loess (Naruse et al., 1994). Judging from the relationship of tephra beds to cultural remains included in the loess, the loess (hence cultural remains) is aged ca. 17,000 to 15,000 cal. BP, likely corresponding to GI-2a to GI-1e. The tephric loess is widely distributed on the Ito ignimbrite plateaux of southern Kyushu.

The Sz-S tephra is recognized in cores from the coastal plain of Kagoshima Bay (Moriwaki et al., 2012a). It lies in deposits associated with rapid sea-level rise, corresponding to the end of the meltwater Pulse 1A event (Yokoyama et al., 2007) (Fig. 6). Sz-S lies at ~50 m below present sea-level in the Kagoshima Bay area (Moriwaki et al., 2012a).

Sz-S is also a critical time marker for cultural remains (Fig. 7). Remnants of houses and ceramics underlie the Sz-S, indicating that housing settlement and the ceramic culture began before ca. 13,000 cal. BP, likely in the GS-1 interstadial. Radiocarbon dates for the Jomon ceramics, notably the Iwamoto type immediately above the Sz-S layer (Shinto, 1997; Nakamura et al., 2010), may suggest that re-settlement to southern Kyushu occurred ~1500 years after the Sz-S eruption.

Sakurajima-Takatoge 3/P13 (Sz-Tk3) This tephra (aged ca. 10,600 cal. BP) was deposited soon after the onset of the Holocene, i.e. it occupies a stratigraphic position shortly after GS-1/Younger Dryas. Pollen analysis on the eastern plain of Osumi Peninsula shows that Sz-Tk3 tephra lies on the boundary of transition from deciduous broad-leaved forest to a mix of deciduous broad-leaved and broad-leaved evergreen forest, i.e. it marks the onset of broad-leaved evergreen forest (Fig. 7; Matsushita, 2002). Sz-Tk3 occurs in the marine deposits associated with a rapid rise of sea-level, likely meltwater pulse 1B, in the coastal plain (Fig. 6; Moriwaki et al., 2012a). Culturally, Sz-Tk3 marks the onset of markedly more houses in the archaeological record. Many house remains are often excavated immediately below or above the Sz-Tk3/P13, which is different from artefactual relationships recorded previously. The most extensive site, Uenohara, is located on the plateau east of the head of Kagoshima Bay and consists of 52 house remains identified thus far (Kurokawa, 2002).

3.3 Post glacial

Kikai-Akahoya (K-Ah) This widespread tephra (aged ca. 7300 cal. BP) has provided a critical chronostratigraphic deposit for Japanese environments and culture in the Holocene

(Machida and Arai, 2003; Machida, 2010), as noted earlier. We describe briefly some aspects relevant to southern Kyushu, i.e. the proximal region for the distribution of K-Ah tephra. K-Ah corresponds to a transition stage within the middle Holocene. Pollen analyses show broad-leaved evergreen forest was prevalent in central Osumi Peninsula (Matsushita, 2002), and arboreal vegetation was close to its peak development as shown in contemporaneous pollen assemblages in a core from the East China Sea (Kawahata et al., 2006). The tephra corresponds to the Holocene transgression characterized by attainment of a stable sea level similar to that of the present (Fig. 7; Moriwaki et al., 2002). As a result, the present coastal plain areas were inundated by the sea, forming deep bays at the time of K-Ah. K-Ah beds are widely recognised in the marine deposits of the coastal plain close to present sea level in southern Kyushu as in other regions (Moriwaki et al., 2002).

The K-Ah tephra provides a precise datum to enable shorelines and sea-levels to be deduced from the coastal landforms and deposits. The present elevations of sea level at the time of K-Ah deposition (ca. 7300 cal. BP) around the head of Kagoshima Bay formed by Aira caldera suggest a dome-like uplift was centred at the western central part of the caldera, likely because of volcanic activity of Aira caldera (Moriwaki et al., 2002).

As for impact on vegetation by K-Ah eruption, Sugiyama (2002) pointed out from phytolith analyses that the Koya pyroclastic flow resulted in a change of vegetation from evergreen forest to grass-land, and the recovery of lucidophyllous forest took ca. 900 years following the eruption.

Other areas experienced only minor impacts from K-Ah ash fall beyond the Koya pyroclastic flow deposits.

Archaeologists and anthropologists have discussed how the K-Ah pyroclastic flow deposits and associated widespread co-ignimbrite ash impacted on people at the end of the earliest Jomon period (e.g. Shinto, 1984; Kawaguchi, 1991; Kuwahata, 2002, 2013). The main data for discussion are ceramic types, of which a precise chronology has been erected in southern Kuyush as well as for greater Japan (Fig.7). Numerous archaeologic data have been obtained by excavations during public constructions. As a result, on the basis of a difference between ceramic types above and below K-Ah bed, Shinto (1984) suggested an important impact on the Jomon people by K-Ah eruption in Kyushu. Recent findings show that ceramics, of the Todoroki type, which are similar to ceramic types above K-Ah bed, occur below the ash in some sites in the northeastern part of southern Kyushu which lie beyond the area encompassed by the pyroclastic flow deposits (Fig.7, Kuwahata, 2013). These stratigraphic relationships indicate that the impact on the Jomon people may differ from region to region.

Kaimondake 4 (Km4) and Kaimondake 12 (Km12) It is an interesting issue as to when and how rice cultivation dispersed from the continent to the various regions of Japan. Botanical records from pollen and phytolith studies, as well as archaeological remains in southern Kyushu (Higashi, 2011; Nasu, 2014), provide the basis for such studies. Km4 (ca. 3400 cal. BP, Okuno, 2002) provides a marker for the timing of the introduction of rice to southern Kyushu.

Km12 is important for examining the relation between volcanological data and historical documents. The Km12 eruption occurred in the ancient (Nara) period (Fig. 7). This tephra eruption has been recorded on paper, one of the oldest paper documents in southern Kyushu, but the timing of the event is not known precisely. In Ibusuki district, on the southern part of Satsuma Peninsula, southern Kyushu, some house remains are overlain by this tephra (Takano, 2010).

4. Conclusion

Southern Kyushu has potential for a high-precision chronology on terrestrial and marine palaeoenvironments, and culture, to be developed because of the occurrence of numerous visible tephras, and potentially cryptotephras, as discussed above. In this review, we have examined the role of such tephras for erecting an integrated model of environmental and cultural changes over the past ca. 30,000 cal. years. The wide identification of smaller-scale, locally distributed tephras, as well as the very widespread AT and K-Ah marker tephras, especially through high-resolution records such as those of Lake Suigetsu, will help to erect a more robust and chronologically precise tephra framework. Such a framework or lattice will enable local and regional records to be connected more precisely and in turn to help synchronize them with national and global stratotypes. The construction of such frameworks in various regions also enables both chronologically and spatially precise diagrams to be constructed. These advances may provide fundamental data for global modelling of late Quaternary environmental change and their relationships to humans in the future.

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Captions to figures

Figure 1. Volcanic and geomorphologic settings in southern Kyushu.

Dotted circles and black triangles denote volcanic centres and volcanic islands, respectively.

Figure 2. Marker tephra beds in southern Kyushu in the past ~30,000 cal. years.

Tephra beds marked by red lines can be applied to the chronology of Kokubu lowland deposits. See Table 1 for the tephra names designated by abbreviation

*1) Lowe, J. et al. (2008), based on Moriwaki et al. (2011)

Figure 3. Extent of distribution of major marker tephras deposited in southern Kyushu in the past ~ 30,000 cal years.

N-Ym(u), Noike-Yumugi upper; N-Ym (m, l), Noike-Yumugi middle and lower. See Table 1 for the abbreviations of other tephra names.

Volcanoes: v.c., volcanic centre; Kr, Kirishima; S, Sakurajima; Kc, Kuchinoshima Island; Nk, Nakanoshima Island; Sw, Suwanosejima Island; Ak, Akusekijima Island.

Based on the data of Moriwaki (1992), Nagaoka et al. (2001), Machida and Arai (2003), and Moriwaki (2010) with additional information.

Figure 4. Some glass major element compositions (as oxides) for five important tephras.

Based on the EMPA-derived data of Moriwaki et al. (2008) and Moriwaki et al. (2011) with additional information (values reported on normalized basis). *After Smith et al. (2013) for the data on Lake Suigetsu

Figure 5. Tephra beds above the Ito ignimbrite in Satsuma Peninsula at the site of Kagoshima

University, 13 km southwest of Sakurajima volcano (photo: H. Moriwaki).

Location: the site of the Sakuragaoka campus of Kagoshima University, 13 km southwest of Sakurajima volcano, background: Sakurajima volcano, middle: Ito ignimbrite

Figure 6. Integration of ice, marine, and terrestrial records in southern Kyushu and their chronologies.

*1: Lowe, J. et al. (2008), *2: Ikehara et al. (2006), *3: Ijiri et al. (2005),

*4: Yokoyama et al. (2007), *5: Moriwaki et al. (2002), *6: Moriwaki et al. (2002, 2011),

*7: Nakagawa, et al. (2005), *8: Kawahata et al. (2006), *9: Matsushita (2002),

*10: Moriwaki et al. (2010b)

T.L.: Tephric loess. See Table 1 for the abbreviations of tephra names.

Figure 7. Archaeological chronology of southern Kyushu

Based on Nakamura (1987), Kuwahata and Higashi (1997), Nakazono (1997), Shimoyama (2002), Yamazaki and Matsuda (2004), Kobayashi (2008).

Figure 8. Occurrence of K-Ah in Holocene marine deposits constituting a marine terrace in the Aira lowland. Note that K-Ah is located at stratigraphic position close to the marine terrace

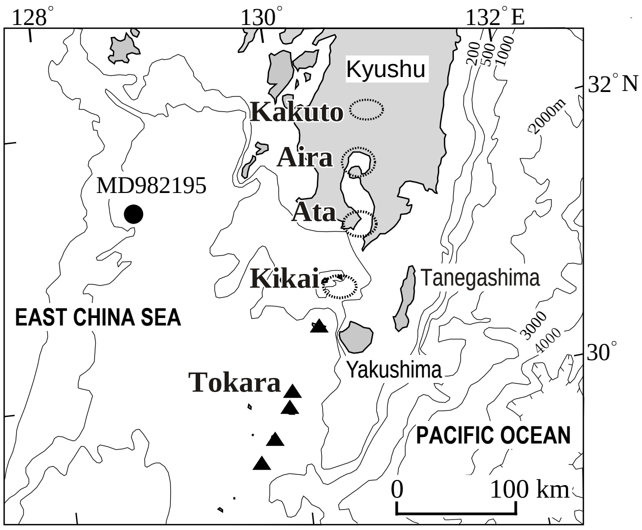
surface. After Moriwaki (2010)

Table 1. Data on the stratigraphy and ages of tephras deposited in the past ~30,000 cal. years in southern Kyushu

*, ** and # denote AD, $SG06_{2012}$ka BP and publications with data on glass chemical compositions respectively. c: century

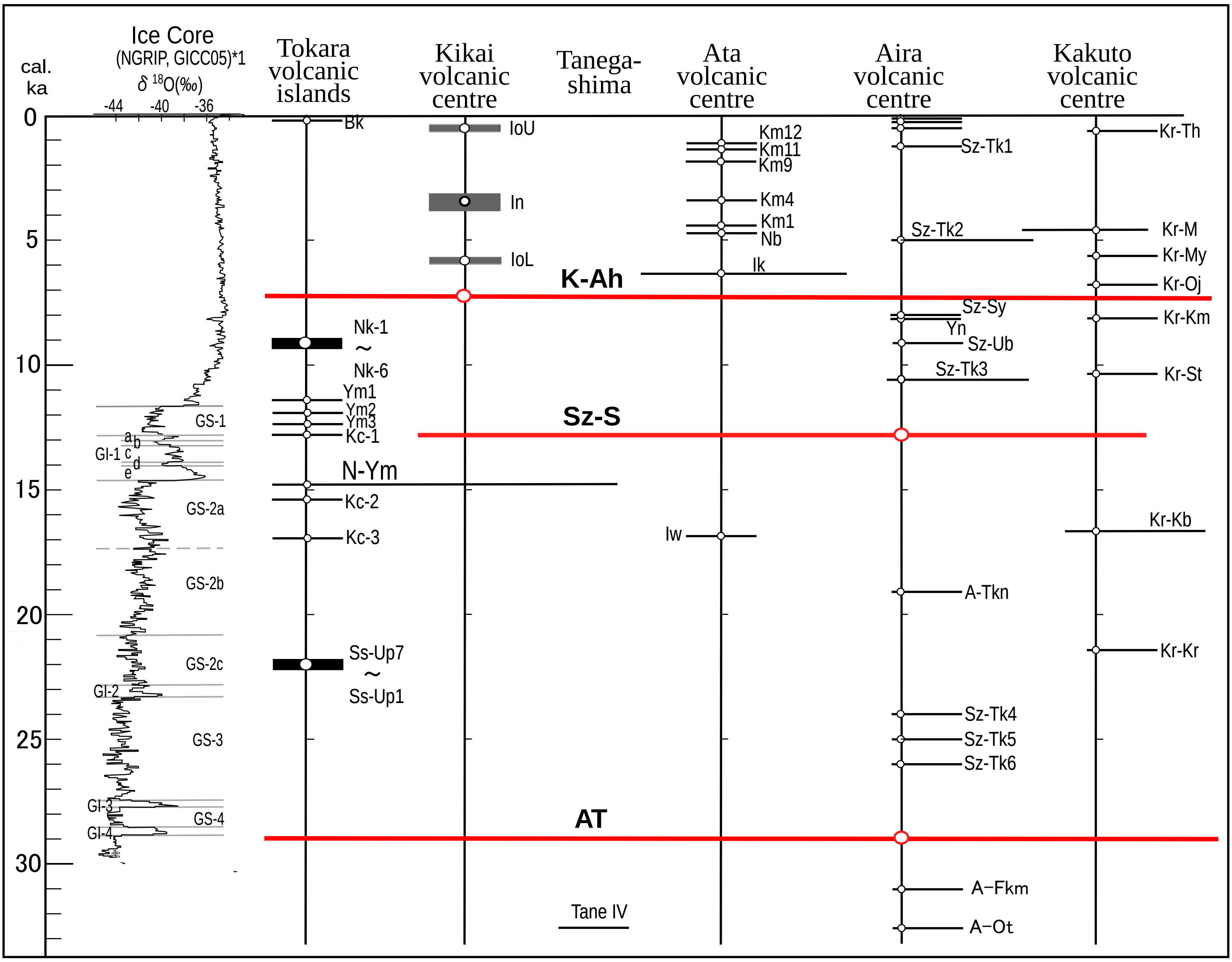
Figure

Figure 1



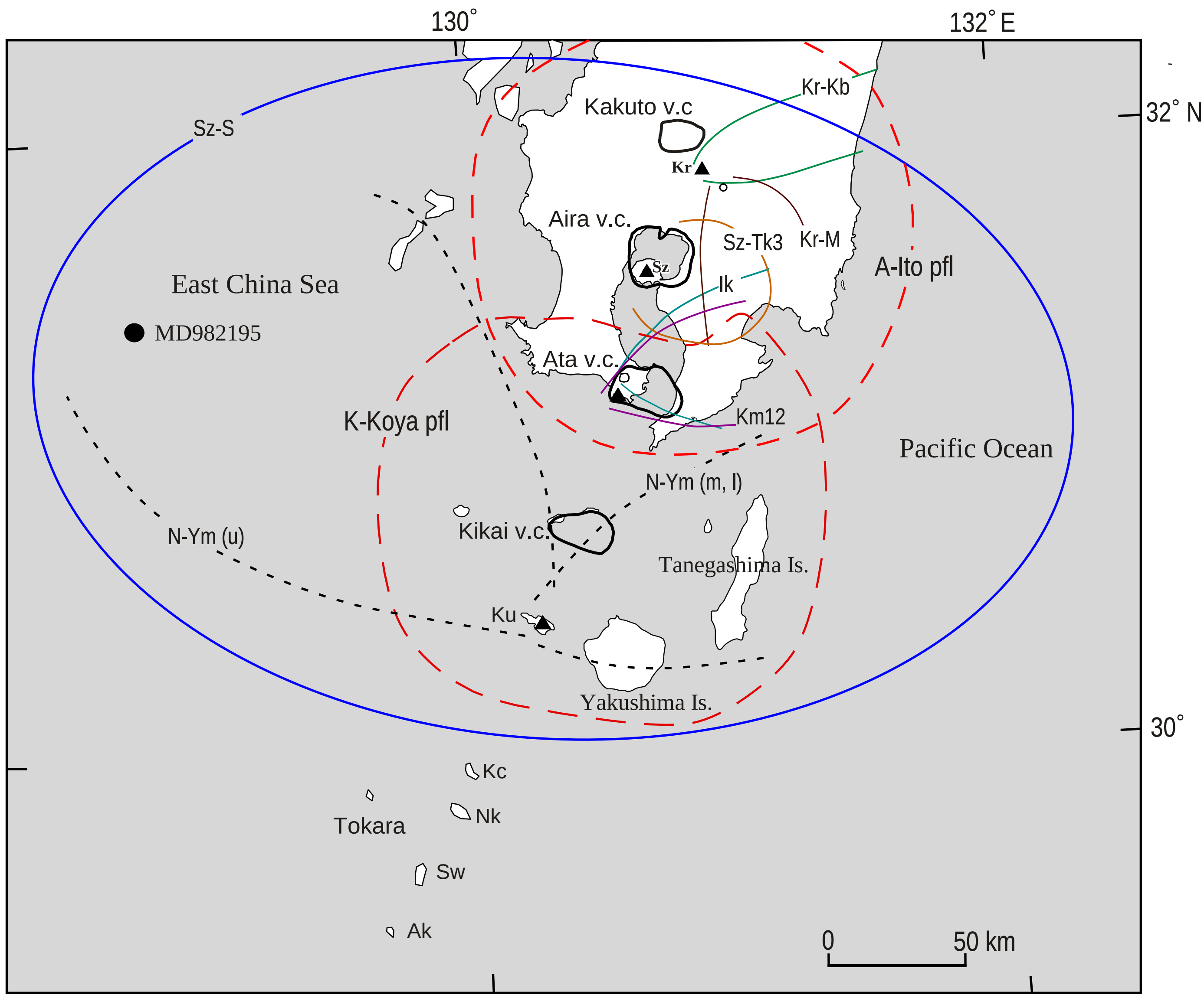
Figure

Figure 2



Figure

Figure 3



Figure

Figure 4

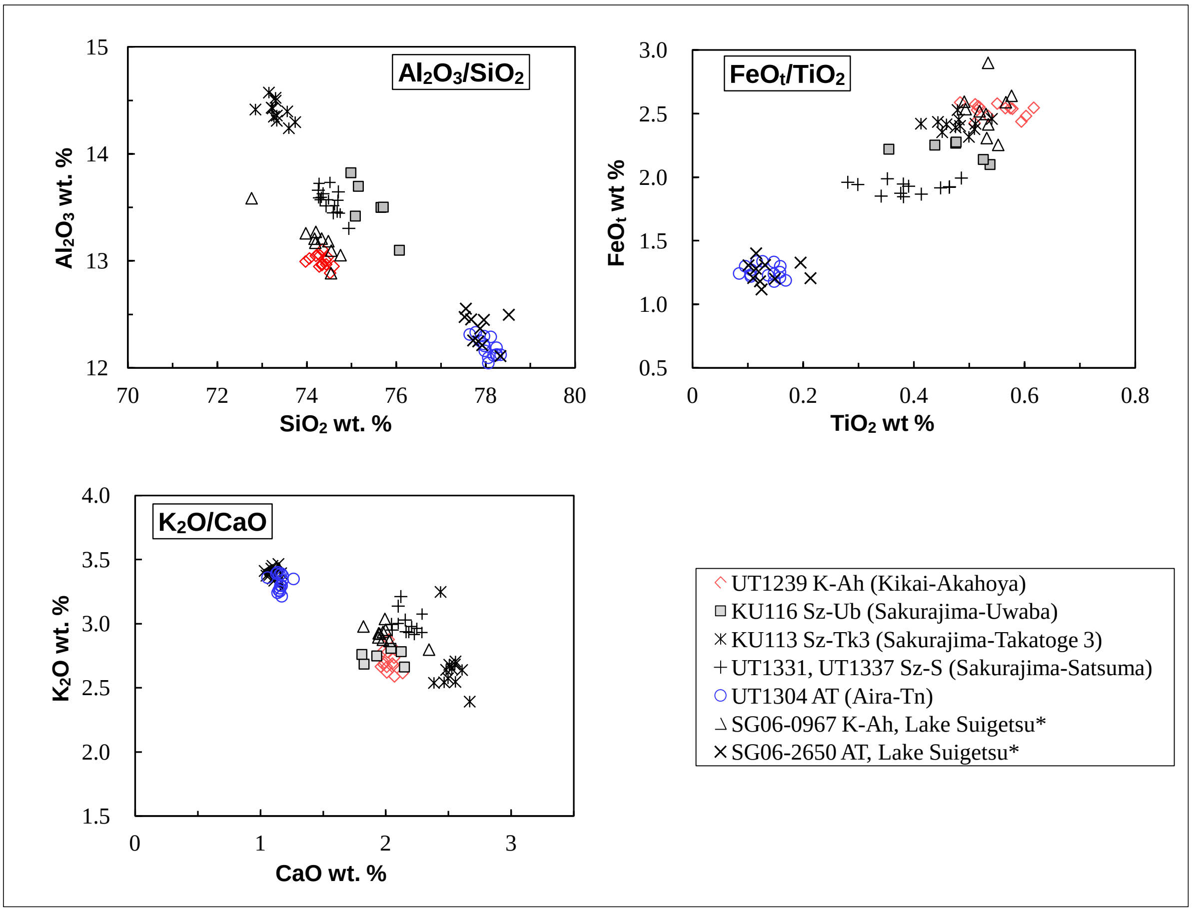


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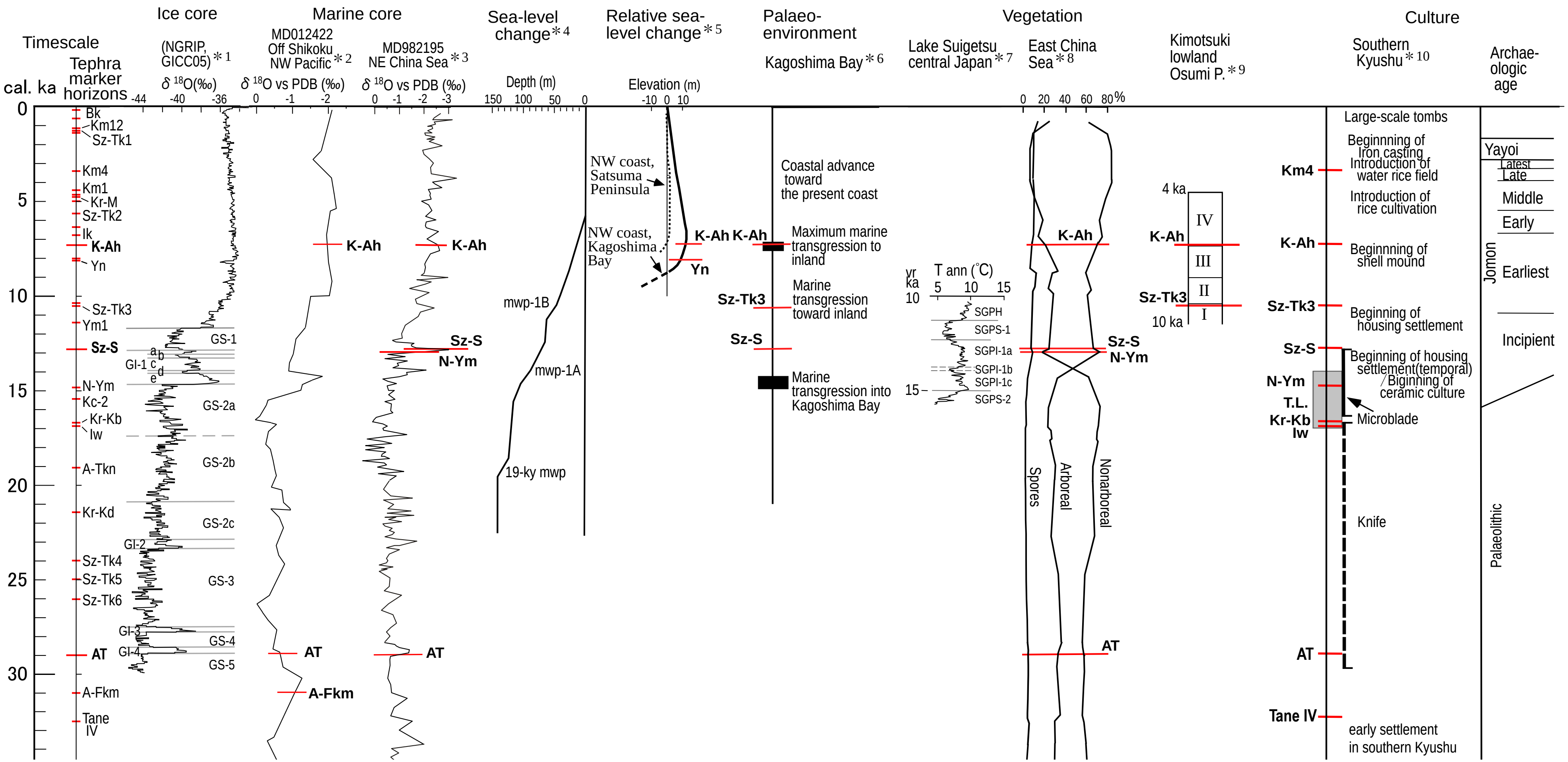
Figure 5

Figure

Figure 6



Figure

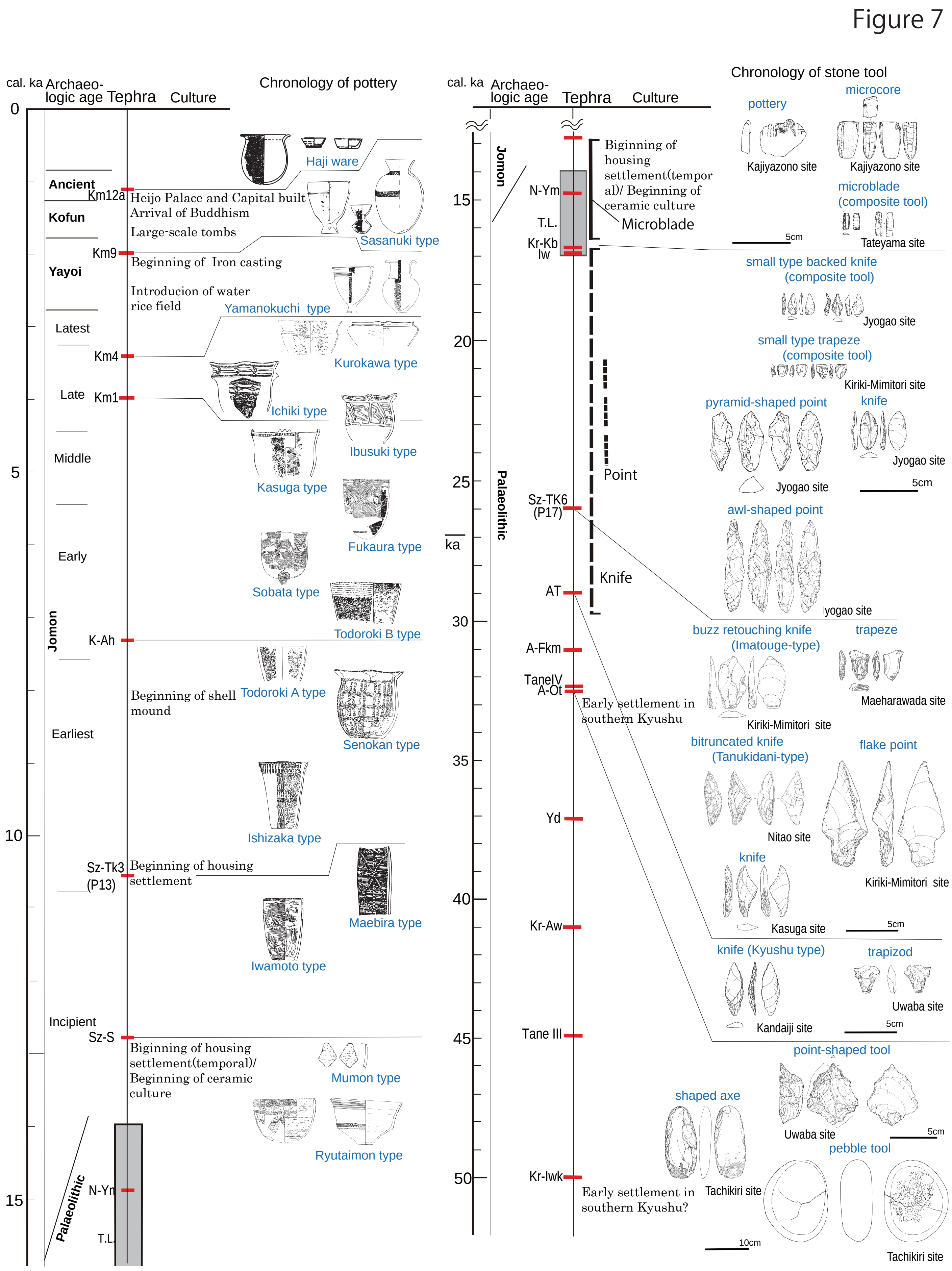


Figure 7
cal. ka
Archaeo-logic age
Tephra
Culture
Chronology of pottery
Ancient
Kofun
Yayoi
Latest
Late
Middle
Early
Jomon
Earliest
Incipient
Palaeolithic
Km12a
Km9
Km4
Km1
K-Ah
Sz-Tk3 (P13)
Sz-S
N-Ym
T.L.
Heijo Palace and Capital built
Arrival of Buddhism
Large-scale tombs
Beginning of Iron casting
Introducion of water rice field
Beginning of shell mound
Beginning of housing settlement
Biginning of housing settlement(temporal)/ Beginning of ceramic culture
Haji ware
Sasanuki type
Yamanokuchi type
Kurokawa type
Ichiki type
Ibusuki type
Kasuga type
Fukaura type
Sobata type
Todoroki B type
Todoroki A type
Senokan type
Ishizaka type
Maebira type
Iwamoto type
Mumon type
Ryutaimon type
Chronology of stone tool
Jomon
Palaeolithic
ka
N-Ym
T.L.
Kr-Kb
Iw
Sz-TK6 (P17)
AT
A-Fkm
TaneIV
A-Ot
Yd
Kr-Aw
Tane III
Kr-Iwk
Biginning of housing settlement(temporal)/ Beginning of ceramic culture
Microblade
Point
Knife
Early settlement in southern Kyushu
Early settlement in southern Kyushu?
pottery
microcore
Kajiyazono site
microblade (composite tool)
Tateyama site
5cm
small type backed knife (composite tool)
Jyogao site
small type trapeze (composite tool)
Kiriki-Mimitori site
pyramid-shaped point
knife
awl-shaped point
buzz retouching knife (Imatouge-type)
trapeze
Maeharawada site
bitruncated knife (Tanukidani-type)
flake point
Nitao site
Kasuga site
knife (Kyushu type)
trapizod
Kandaiji site
Uwaba site
point-shaped tool
shaped axe
pebble tool
Tachikiri site
10cm

Figure

Figure 8

Table

Table 1

Tephra name	Abbreviation	Volcano	^{14}C age (ka)	Cal. year (cal. ka)	Reference
Kakuto volcanic centre (Kirishima)					
Showa	Kr-SmS	Sh		1959*	8
Bunka	Kr-SmB	Sh		1822*	8
Meiwa	Kr-SmM	Sh		1771~1772*	8
Kyoho	Kr-SmK	Sh		1716~1717*	8
Takaharu	Kr-Th	Oh		788*, 1235*	2, 13, 14
Ohachi	Kr-Oh	Oh		9c~17c*,17c*	2, 9, 13
Miyasugi	Kr-Ms	Oh		742?*, 10c*	2, 9, 13
Katazoe	Kr-Kz	Oh	2	788*	2, 4, 13
Nakadake ash	Kr-Nkd	Na	2.3	2.4	10, 11, 15
Miike	Kr-M	Mi	4.2	4.6	10,11,15,16
Maeyama	Kr-My	Sh	4.5, 4.9	5.6	2, 11, 15
Oji scoria	Kr-Oj	Ta	5.0 6.0	6.8	2, 11, 15
Mohara ash	Kr-Mh	Ta	5.5	6.9	2, 4, 11
Ushinosune U	Kr-Us U	Kta	6.3~6.5	~7.1	2, 4, 11
Ushinosune L	Kr-Us L	Kta	6.5~6.8, 6.7 ~	7.6 ~	2, 11, 15
Kamamuta	Kr-Km	Kta	7.4, 7.5	8.1	2, 4, 11, 15
Setao	Kr-St	Sh	9, 9.2	10.4	2,8,11,15,18
Kobayashi	Kr-Kb	Kd	15, 14	16.7	4, 11, 15
Karakunidake	Kr-Kr	Kd	18	21.4	4, 7, 11
Aira volcanic centre					
Taisho /P1	Sz-Ts/P1	Sz		1914*	28, 60, 63
Anei /P2	Sz-An/P2	Sz		1779~1782*	61
Bunmei /P3	Sz-Bm/P3	Sz		1471~1476*	28, 61
Takatoge 1 / P4	Sz-Tk1/P4	Sz		764~766*	29, 61, 63
Minamidake ash	Sz-Mn	Sz	4.0 ~ 1.7	4.5 ~ 1.6	11, 30
P5	Sz-P5	Sz	4.9	5.6	11, 30, 61
P6	Sz-P6	Sz	3.5	3.8	19, 23,61
Takatoge 2 /P7	Sz-Tk2/P7	Sz	4.5	5	10, 16,61,63
Sueyoshi /P11	Sz-Sy/P11	Sz	7.2, 7.5	8	19, 32,61,63
Yonemaru	Yn	Yn	7.3	8.1	32
Sumiyoshiike	Sm	Sm		8.2	32
Uwaba /P12	Sz-Ub /P12	Sz	8	9	11, 19,61,63
Takatoge 3 /P13	Sz-Tk3 /P13	Sz	9.4	10.6	19, 21,61,63
Satsuma /P14	Sz-S/P14	Sz	11	12.8	19,22,61,63, 65[#]
Takano	A-Tkn	Ar	16	19.1	23,61
Takatoge 4 /P15	Sz-Tk4/P15	Sz	21	24	19,61
Takatoge 5/ P16	Sz-Tk5/P16	Sz	22	25	19,61
Takatoge 6 /P17	Sz-Tk6/P17	Sz	23	26	19,61
Aira-Tn	AT	Ar	24~25, 24.5, 25.12, 25.9, 27	29, 29.4, 26~29, 28.1~28.3, 30, 30.09**	6,11,24,25,26,27,46,56[#],57,58,64[#],65[#]
Kenashino	A-Kn	Ar	25.3	30	11, 27, 55
Fukaminato	A-Fkm	Ar	26.5	31	1,11,27,55,56
Otsuka	A-Ot	Ar	30	32.5	1, 11, 27, 55
Ata volcanic centre					
Kaimondake 12b	Km12b	Km		885*	33,34,35,36, 66[#]
Kaimondake 12a	Km12a	Km		874*	33,34,35,36, 66[#]
Kaimondake 11	Km11	Km	1.6	7c*	34,35,36,60, 62
Kaimondake 10	Km10	Km	1.8	1.7	11, 36, 60
Kaimondake 9	Km9	Km	2	1.9	11, 35, 36, 60
Kaimondake 8	Km8	Km	2.1	2	11, 36, 60
Kaimondake 7	Km7	Km	2.3	2.3	11, 36, 60, 62
Kaimondake 6	Km6	Km	2.5	2.5	11, 36, 60
Kaimondake 5	Km5	Km	2.9	3	11, 36, 60
Kaimondake 4	Km4	Km	3.1	3.4	11, 36, 60, 62
Kaimondake 3	Km3	Km	3.4	3.7	11, 36, 60
Kaimondake 2	Km2	Km	3.6	3.9	11, 36, 60
Kaimondake 1	Km1	Km	4	4.4	11,33,34,36, 37, 60, 62
Nabeshimadake	Nb	Nb	4.3	4.8	11, 38
Ikedako	Ik	Ik	5.6	6.4	11, 31
Iwamoto	Iw	Ata		19	39

Tephra name	Abbreviation	Volcano	^{14}C age (ka)	Cal. year (cal. ka)	Reference
Kikai volcanic centre					
Iodake upper	IoU	Id	~ 0.4	~ 0.35	40, 41,42
Inamuradake	In	In	3.6 ~ 3.0	3.9 ~ 3.2	40, 41,42
Iodake lower	IoL	Id	5.2 ~	6.0 ~	41
Akahoya	K-Ah	Kk	6.5	7.3, 7.2	6,12,17,20, 64
Komoriko	Km	Kk	13 ~ 8.0	16 ~ 9.0	41,43
Tokara volcanic islands					
Bunka scoria	Bk	Sw		1813*	51
Yumugi 1	Ym1	Ku		11.43	45, 44
Yumugi 2	Ym2	Ku			45
Yumugi 3	Ym3	Ku			45
Kuchinoshima 1	Kc-1	Kc	10.9		45, 48
Noike-Yumugi	N-Ym	Ku	12.6, 12.4	14.9, 14.53	44, 45[#], 47
Kuchinoshima 2	Kc-2	Kc	12.9		45, 48
Kuchinoshima 3	Kc-3	Kc			45
Nakanoshima 1	Nk-1	Nk			45
Nakanoshima 2	Nk-2	Nk			45
Nakanoshima 3	Nk-3	Nk			45
Nakanoshima 4	Nk-4	Nk			45
Nakanoshima 5	Nk-5	Nk			45
Nakanoshima 6	Nk-6	Nk			45
Suwanose S.U.7	Ss-Up7	Sw			50
Suwanose S.U.6	Ss-Up6	Sw			50
Suwanose S.U.5	Ss-Up5	Sw			50
Suwanose S.U.4	Ss-Up4	Sw			50
Suwanose S.U.3	Ss-Up3	Sw			50
Suwanose S.U.2	Ss-Up2	Sw			50
Suwanose S.U.1	Ss-Up1	Sw			50
Akuseki Y. 2	Ak-Y2	Ak			45
Akuseki Y. 3	Ak-Y3	Ak			45
Akuseki Y. 4	Ak-Y4	Ak			45
Akuseki Y. 5	Ak-Y5	Ak			45[#]

Sh:Shinmoedake, Oh:Ohachi, Na: Nakadake, Mi: Miike, Ta: Takachiho, Kta:Ko-Takachiho, Kd: Karakunidake, Sz: Sakurajima, Yn:Yonemaru, Sm:Sumiyoshiike, Ar: Aira caldera, Km: Kaimondake, Nb: Nabeshimadake, Ik:Ikeda cakdera, Id:Iodake, In:Inamuradake, Kk: Kikai caldera, Sw:Suwanosejima, Ku:Kuchierabujima, Kc:Kuchinoshima, Nk:Nakanoshima, Ak:Akusekijima

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