Volcanoes and Tephras in the Japan Area

Hiroshi MACHIDA

Professor emeritus, Tokyo Metropolitan University
machida@andes.metro-u.ac.jp/QYP04721@nifty.ne.jp

Abstract

Volcanic centres in and around Japan can be explained by the theory of plate tectonics. Large quantities of lava and tephra, mainly of rhyolitic and andesitic composition, have erupted throughout the Quaternary in thoses areas. Tephra layers, including not only fallout deposits but also flow deposits play an important role in characterising soils and landscapes as well as stratigraphic studies. A catalogue of tephras occurring there provides fundamental criteria for the establishment of a regional Quaternary chronostratigraphy. The basic tephra framework is reconstructed through recognition of widespread marker tephras. A detailed and regional chronology based on distal tephras has been improved with the aid of local, proximal tephras. The juxtaposition of dated marine and terrestrial tephras with paleoceanographic, terrestrial, sea-level and tectono-geomorphic (e.g., terrace) records has enabled a synthesis of event-associations that has improved significantly the understanding of Quaternary events.

Key words: Aira-Tn tephra, Aso-4 tephra, identification, Japan, Kikai-Akahoya tephra, Korea, Shikotsu-1 tephra, tephrochronology, Toya tephra, widespread tephra,

1. Regional Volcanic Framework

Volcanic centres in and around Japan occur in two zones accompanying plate subduction along the Japan island arcs and Korean areas west of the Sea of Japan (Fig. 1). The east Japan volcanic zone lies on the edge of the North American/Eurasian and the Philippine Sea Plates that are being underthrust by the subducting oceanic Pacific Plate. The west Japan volcanic zone has been formed by interaction between the Eurasian Plate and the Philippine Sea Plate. Therefore, large quantities of lava and tephra, mainly of rhyolitic and andesitic composition, have erupted throughout the Quaternary from about 200 volcanic centres, of which about 80 have continued their activity into the Holocene.

In the west Japan volcanic zone, central and southern Kyushu have been the foci of large-scale explosive volcanism producing a number of ignimbrite and widespread fallout tephra sheets from clusters of large caldera volcanoes. All of these deposits form important Quaternary isochrons in the Japan region as shown in a subsequent section.

In the east volcanic zone, considerable large-scale explosive volcanism has occurred, particularly from caldera volcanoes in Hokkaido and northern Honshu, producing extensive tephra sheets. Volcanic centres in central Honshu and the Izu-Ogasawara island arcs are characterised by many stratovolcanoes with or without calderas, producing a large quantity of tephra and lava of various compositions. Accordingly, a more or less continuous mantle of tephra exists over some 40 % of the four main islands of Japan, strongly influencing landforms and near-surface materials (Fig. 2).

Korean volcanoes occur in the three districts: Baegdusan (Baitoshan, Changbaishan) and adjacent volcanic fields on the border of North Korea and China; Ulreung-do and adjacent submarine volcanic fields; and Cheju-do volcano off the Korean Peninsula. The former two are characterised by an alkaline trachytic explosive volcanism that provides many distal tephra layers to the Sea of Japan and the Japan Island arcs. Cheju-do volcano, however, has produced mainly basaltic lava with no significant tephras. Each has been active throughout the Quaternary period.

2. Summaries on Development of Japanese Tephrochronology

Japanese tephrochronology has evolved under the influence of several discrete geoscientific disciplines and current tephra studies continue to reflect the framework of this historical development. This development can be viewed as a progression through four distinct phases:

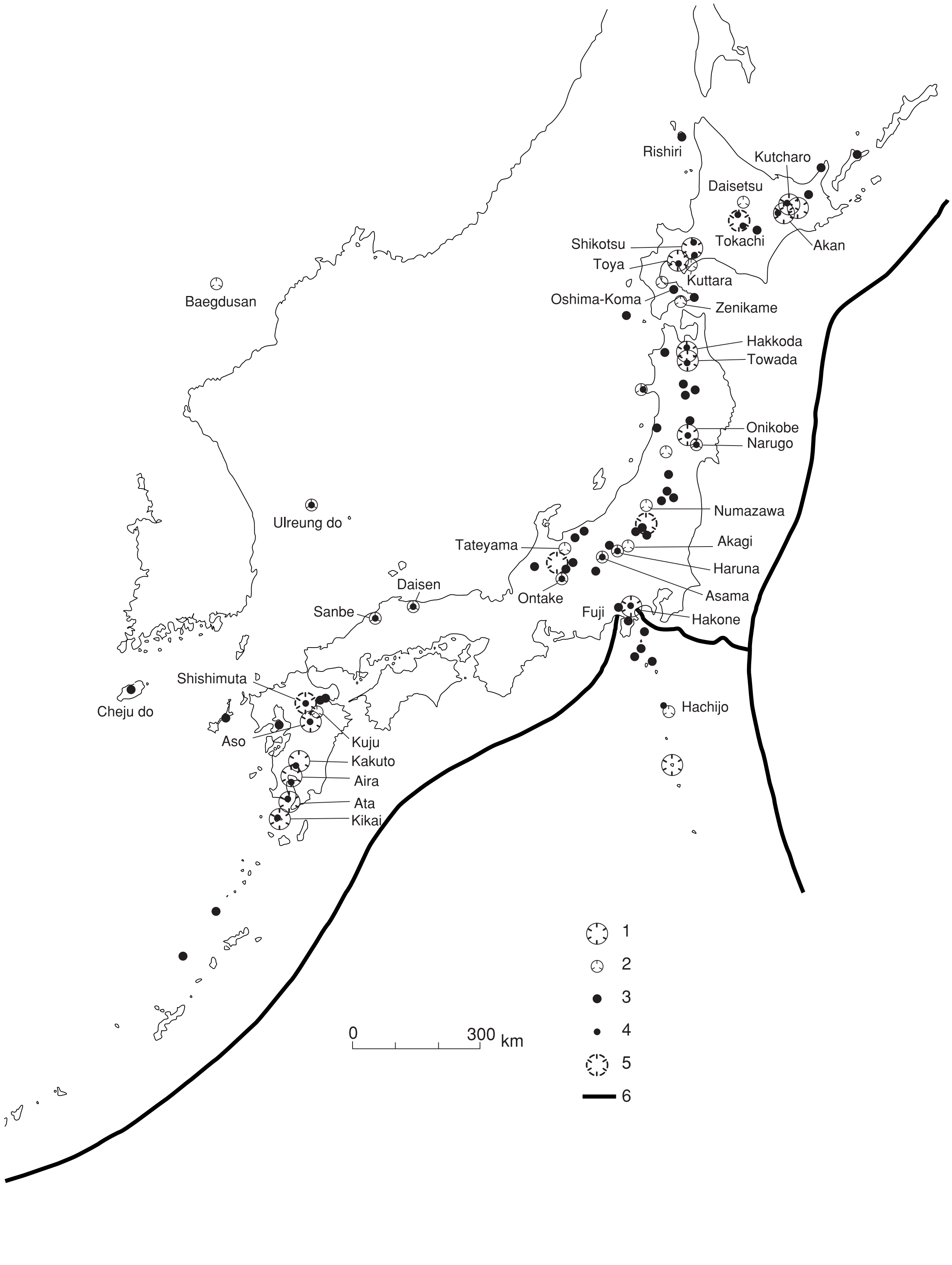

Fig. 1 Map showing localities of major source volcanoes of Quaternary tephras in and around Japan.
1, large caldera with diameter of more than 10 km; 2, caldera volcanoes with diameters of less than 10 km often associated with composite stratovolcanoes; 3, stratovolcanoes; 4, central cones within calderas; 5, buried calderas; 6, trench and trough axis (plate boundary).

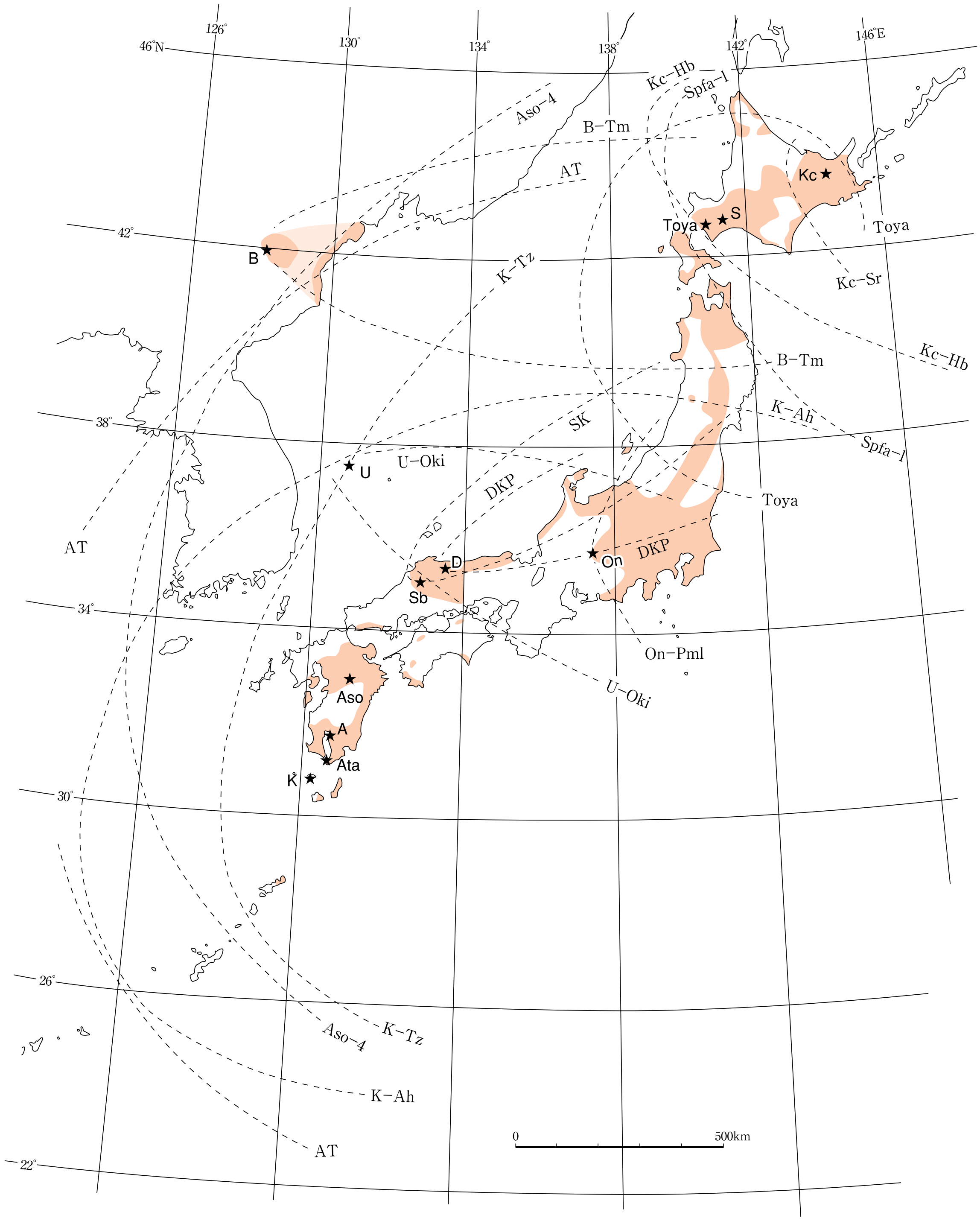

Fig. 2 Map showing general distribution of the representative marker-tephras of the Late Pleistocene and volcanic ash soil with total thickness of more than 2 m in Japan and adjacent areas (stipples).

1) The impact of other disciplines on the early stages of tephrochronological research. As early as the 1930s, pioneer studies on Holocene tephras were carried out in Hokkaido, northern Japan, in closely association with soil studies (Uragami *et al.*, 1933). In the 1940-1950's the discovery of Paleolithic cultural remains from volcanic ash soils in northern Kanto, central Japan, stimulated further the chrono-stratigraphic study of tephra (Kanto Loam Research Group, 1956). Developments in areas such as soil sciences, archeology, geomorphology, radiometric dating and general Quaternary research greatly stimulated development of a Japanese tephrochronology. Primary tephra sequences were studied in conjunction with geomorphic surfaces (Kanto Loam Research Group, 1965) and paleontological and geomagnetic studies (Itihara *et al.*, 1975), reflecting the prominence of tephras as correlative and relative-age stratigraphic tools in interdisciplinary group studies.

2) Volcanological studies of tephra followed from these pedological, stratigraphical and geomorphologic investigations. In their initial development, Japanese volcanological investigations focused on lavas rather than pyroclastic materials or tephra. However, since the early 1960s, eruptive histories of several active volcanoes have been developed on the basis of associated tephra deposits (Katsui, 1963; Aramaki, 1963; Nakamura, 1964; Machida, 1964). This was facilitated by the systematisation of tephrochronology through volcanological interpretations as introduced by Nakamura *et al.* (1963).

3) Land-based and local studies were predominant in comparison with marine tephra studies in the 1950-1960's. Because most of Japan is covered with Quaternary volcanic ash soils, early studies focused on proximal fallout tephra and the description of their megascopic features including phenocryst assemblages. As these assemblages are generally more abundant in proximal tephras, this approach was particularly fruitful in Hokkaido, Kanto and Kyushu, which are located near many active volcanoes. The first studies of marine tephras were associated with terrestrial exposures of sediments formed under higher relative sea levels. In the Kinki district (around Osaka and Kyoto) far from Quaternary volcanoes, early to middle Pleistocene distal tephras within the Osaka group, (cyclic sediments of marine and lacustrine origin) had already been studied as useful stratigraphic markers (e.g., Ishida *et al.*, 1969; Itihara *et al.*, 1975). The study of distal tephras preserved in the present marine realm around Japan began in the early 1970s (Furuta, 1974; Furuta *et al.*, 1986; Machida and Arai, 1988).

4) Since the early 1970s developments in characterisation techniques for tephra identification and dating methods have placed regional tephra stratigraphies on a more solid framework (Kobayashi, 1972; Arai, 1972; Machida and Suzuki, 1971). As a result, the long-distance correlation of tephra became possible in the mid 1970s (Machida and Arai, 1976), with tens of very widespread marker tephra now identified and greatly facilitating Quaternary studies over extensive areas, including the Japanese islands and adjacent seas (Machida and Arai, 1992; Machida, 1999).

The compilation of a tephra catalogue for the Japan area now provides fundamental data for land-sea correlation and establishment of a chrono-stratigraphic framework for Japanese Quaternary studies (Table 1). In addition the eruptive history of many volcanoes and periods of recurrent distal ash formation and large-scale explosive volcanism can be studied from these long-term tephra records (Machida, 1990).

3. Tephra Identification and Chronology

The characterisation of marker-tephra layers constitutes the basis of tephra studies and is carried out using a combination of parameters. Detailed descriptions have recently been given, not only of megascopic features and mineral assemblages of proximal tephras, but also of the refractive indices and chemical compositions of volcanic glass and specified minerals of both proximal and distal tephras. In particular, recent technical progress in rapid, high-precision determination of refractive indices and major and minor elements has provided fundamental data for tephra identification (Machida and Arai, 1992).

In general tephras occurring in distal areas, more than 800 km from their source volcano, are highly vitric in composition. High precision analysis of glass chemistry is therefore vital for their reliable characterisation and identification in addition to the aforementioned criteria. Major and minor element analyses of volcanic glass shards are usually carried out by electron microprobe (EPMA), INAA and inductively coupled plasma (ICP) methods. As a result, it has become possible not only to correlate tephras in remote districts with one another but also to address a variety of stratigraphical and volcanological problems as described later.

In most of Japan and Korea, the ages of tephra forming eruptions in the last 1,500 years have been determined mainly from historical documents. In general, however, eruptions older than the 10th century were documented too insufficiently to date reliably, and therefore archeology, varved chronology and dendrochronology have been applied for cross-checking to give a reliable calendar year estimate for specific eruptions.

The majority of tephras ejected between *ca.* 50 ka and 1.5 ka have been dated by radiocarbon methods. However, there are some problems in dating pre-20 ka tephra eruptions since the range of different age determinations for a discrete tephra of this antiquity frequently expands with the increase in the number of determinations! Also a calibration system to obtain calendar years from AMS ^{14}C dating has not yet been fully established. The use of additional dating techniques, including fission-track, uranium series, thermo-luminescence, electron spin resonance and K-Ar methods ensures that the tephrochronological approach can be employed both within and beyond the limit of radiocarbon dating. In addition, a number of ages obtained by various methods from the same tephra at different localities can be checked against each other, resulting in high-quality age control with the strictly identified tephra sequences playing an important role in revision and refinement of various radiometric ages.

Table 1 A list of the widespread Quaternary tephra layers in and around the Japan area.

Tephra name (symbol)	Source volcano	Age in ka method	Eruption sequence	Occurrence areas	Bulk vol. (km^3)	Rock type	Reference
Baegdusan-Tm (B-Tm)	Baegdusan (N. Korea/China)	1 A, C	p, i, c	NE Korea, N. Japan Sea, N. Japan	50	peralkaline rhyolite, trachyte	Machida *et al* (1990)
Kikai-Ah (K-Ah)	Kikai (S. Kyushu)	7.3 C, V	p, i, c	in and around Japan	>150	px. dacite	Machida & Arai (1978)
Ulreung-Oki (U-Oki)	Ulreung (Korea)	10.7 C, V	p, i	S. Japan Sea, C. Honshu	>10	trachyte	Machida & Arai (1983) Machida *et al* (1984)
Towada-H (To-H)	Towada (N. Honshu)	15 C, Ol	p, i, c	N. Honshu, NW. Pacific	50	hb. px. dacite	Hayakawa (1985) Arai *et al* (1986)
Aira-Tn (AT)	Aira (S. Kyushu)	26-29 C, Ol	p, i, c	in and around Japan	>450	px. rhyolite	Machida & Arai (1976)
Kutcharo-Shoro (Kc-Sr)	Kutcharo (E. Hokkaido)	35-40 C, ST	pp, i	E. Hokkaido, NW. Pacific	100	px. rhyodacite	Arai *et al* (1986)
Shikotsu-1 (Spfa-1, Spfl)	Shikotsu (C. Hokkaido)	40-45 C, Ol	p, i, c	Hokkaido, NW. Pacific	200	hb. px. rhyodacite	Katsui (1959) Arai *et al* (1986)
Daisen-Kurayoshi (DKP)	Daisen (W. Honshu)	≧55 ST, C, U	p, (i)	crossing Honshu	>20	px. dacite	Machida & Arai (1979)
Aso-4 (Aso-4)	Aso (C. Kyushu)	85-90 Ol, KA, ST	i, c	in and around Japan	>600	px. hb. dacite	Machida *et al* (1985) Ono *et al* (1977)
Kikai-Tz (K-Tz)	Kikai (S. Kyushu)	95 ST, TL	pp, i, c	in and around Japan	>150	px. rhyolite	Machida & Arai (1992)
Ontake-1 (On-Pm1)	Ontake (C. Honshu)	100 FT, KA, ST	p	C-N. Honshu	50	bt. px. hb. rhyodacite	Kobayashi (1968) Machida & Arai (1992)
Ata (Ata)	Ata (S. Kyushu)	105-110 KA, ST	pp, p, i, c	in and around Japan	>300	px. dacite	Machida & Arai (1992)
Sambe-Kisuki (SK)	Sambe (W. Honshu)	110-115 ST	p	crossing Honshu	20	bt. rhyolite	Toyokura *et al* (1991)
Toya (Toya)	Toya (C. Hokkaido)	112-115 Ol, ST	i, pp, i, c	N. Japan & surrounding Seas	>150	hb. px. rhyolite	Machida *et al* (1987)
Aso-3 (Aso-3)	Aso (C. Kyushu)	120?, 135? FT, KA, ST	p, i, c	C. Kyushu - C. Honshu	>100	px. dacite-andesite	Machida & Arai (1994)
Kutcharo-Hb (Kc-Hb)	Kutcharo (E. Hokkaido)	115-120 FT, ST	pp, p, i, c	Hokkaido, NW Pacific	≫150	px. dacite	Machida *et al* (1987) Okumura (1988)
Ata-Th (Th)	Ata (C. Kyushu)	230-250 Ol, FT, ST	p, i, c	in and around Japan	≫150	bt. px. hb. rhyolite	Machida & Arai (1992)
Aso-1 (Aso-1)	Aso (C. Kyushu)	255 Ol, KA, FT, ST	p, i, c	in and around Japan	≫50	px. dacite	Shirai *et al* (1997)
Takayama-Ng1 (Tky-Ng1)	Suien-dani (C. Honshu)	29-30 ST, FT	p, (i), (c)	C-W. Honshu & Shikoku	50	px. hb. bt. rhyolite	Mizuno & Kikkawa (1991) Tamura & Suzuki (2001)
Kakuto (Kkt)	Kakuto (S. Kyushu)	330-340 FT, ST	p, i, c	S. Kyushu - Honshu	>100	px. rhyodacite	Machida & Arai (1992)
Ksm5 (Ksm-5)	Aira (S. Kyushu)	430-450 ST	i, c	S. Kyushu - Honshu	>100	px. rhyodacite	Mizuno (1997) Suzuki & Fujiwara (1998)
Kobayashi-Ks (Kb-Ks)	Kobayashi (S. Kyushu)	520 Ol	i, p, i, c	in and around Japan	>100	px. rhyodacite	Machida & Arai (1992)
Hiwaki (Hwk)	? (S. Kyushu)	570-580 KA, Ol	i, c	S. Kyushu - Honshu	>100	px. hb. rhyolite	Machida & Arai (1992) This paper
Kamitakara (KMT)	Kaishio (C. Honshu)	600-620 Ol, FT	i, c	C. Honshu	≫50	bt. rhyolite	Suzuki (2000)
Seiganji-Toga (Se-Tg)	Hohi (C. Kyushu)	610-650 FT	p, (i), c	C. Kyushu – C. Honshu	≫50	hb. bt. rhyolite	Machida & Arai (1992)
Hakkoda-Ku1 (Hkd-Ku)	Hakkoda (N. Honshu)	760 Ol	p, i, c	N-C. Honshu	≫50	px. rhyodacite	Suzuki *et al.* (2001)
Shishimuta-Azuki (Ss-Az)	Shishimuta (C. Kyushu)	850-870 FT, Ol	p, i, c	C. Kyushu – C. Honshu	≫100	px. dacite	Kamata *et al* (1994)
Shishimuta-Pink (Ss-Pk)	Shishimuta (C. Kyushu)	1020 Ol, KA, MGN	p, i, c	C. Kyushu – C. Honshu	≫100	px. hb. rhyodacite	Danhara *et al* (1992)
Shikito (Skt)	Shishimuta? (C. Kyushu)	1200 ST, FT	i, c	C. Kyushu – C. Honshu	100?	px. bt. cgt. hb. rhyolite	Yoshioka *et al* (1997)
Omine (Omn)	N. Hida? (C. Honshu)	1600-1650 KA	i, c	C. Honshu	50	hb. bt. rhyolite	Machida *et al* (1997) Nagahashi (1998)
Ebisutoge-Fukuda (Ebs-Fkd)	Hodaka? (C. Honshu)	1700 KA, ST	p, i, c	C. Honshu	>100	bt. px. hb. rhyodacite	Yoshikawa *et al* (1996)

As many distal tephra layers occur in abyssal marine sediment cores around Japan, high resolution dating of tephra may find importance in provision of reliable age-estimates for marine oxygen isotope chronology. Such work has rapidly progressed in Japan as shown in Table 1 and Fig. 3.

4. Distal Tephras as Fundamental Quaternary Isochrons

Since 1976 two widespread tephra layers from gigantic explosive volcanism of southern Kyushu caldera volcanoes Aira and Kikai, have been identified over unusually extensive areas throughout Japan and the Sea of Japan as well as over the floor of the Pacific Ocean to the South of Honshu (Machida and Arai, 1976, 1978 & 1983). Both tephra layers, Aira-Tn tephra (AT) of *ca*. 26-29 ka and Kikai-Akahoya tephra (K-Ah) of *ca* 7.3 ka, provide distinct datum planes available for many applications of Quaternary sciences in the Japan region. These results have encouraged the identification of many other widespread tephra layers, including those of continental volcanic origin (B-Tm & U-Oki) and older tephras.

The petrographic characteristics of fine-grained tephras of the late Quaternary have been thoroughly investigated not only on land but also in cores from abyssal sediments around Japan. The most extensive Quaternary tephras are listed in Table 1 and approximate outer distribution limits of typical widespread Late Quaternary tephra layers are illustrated in Fig. 2. The abundance of widespread tephras of Quaternary age has contributed greatly to Quaternary studies and in particular in the interpretation of associated marine and terrestrial sequences from Kyushu to Hokkaido (Fig. 3).

The above-mentioned tephras can be classified into two types according to differences in their mode of ejection and distribution:

1) Co-ignimbrite fallout tephra: these deposits are predominantly fine-grained vitric ashes produced at the same time as unusually large-scale pyroclastic flows (Machida and Arai, 1976; Sparks and Walker, 1977). The volume of tephra from these events often approximates or exceeds that of the ignimbrite itself. These eruption-types are closely associated with gigantic caldera collapses which resulted in cataclysmic environmental impacts over extensive areas. Almost all tephras originating from the gigantic caldera volcanoes of Kyushu and Hokkaido are of this type. Distal deposits of these events are dominated by bubble walled types of glass shards. Co-ignimbrite tephras often mantle wide areas surrounding the vent (e.g., K-Ah, AT, Toya tephras). This occurrence may suggest that many secondary vents formed on the extensive, low aspect ratio ignimbrites, possibly associated with hydromagmatic eruptions. It is probable that the transport of tephra occurred by both stratospheric (dominantly westerly) and tropospheric winds.

2) Plinian tephra: a number of pumice fall layers of this type are found throughout Japan. These consist predominantly of pumiceous glass shards with abundant phenocrysts. An elongated fallout area is common with areal coverage not so extensive compared with that of the co-ignimbrite tephras. The Sambe Kisuki and Daisen Kurayoshi tephras are of this type and have been particularly useful in the correlation of associated strata and geomorphic surfaces from western to north-eastern Honshu. Eruptions of this type were often followed by extrusions of pyroclastic flow deposits.

5. Representative Late Quaternary Widespread Tephra Layers

Co-ignimbrite tephras are clearly the most important of the two types in Japan, because of their unusually extensive coverage (Figs. 2 and 3). Selected widespread tephras of particular stratigraphic importance are described below. Most tephras are named after their source volcano and the place-name of the type-section of the distal deposit (e.g., the Aira-Tanzawa tephra). In the event that the source volcano is uncertain, only the type-section place-name is adopted. However, there are some exceptions to the conventional nomenclature such as Shikotsu-1, Aso-4, etc. In all cases eruption sequences and petrographic properties for these tephras are presented in Table 1.

Kikai-Akahoya tephra (K-Ah)

This originated in Kikai, a major caldera largely submerged off southern Kyushu, and forms the most widespread Holocene tephra layer in the Japan region. The tephra occurs in marine and terrestrial deposits at various localities in southwestern and central Japan (Fig. 2) and forms a good marker for the hypsithermal stage, because it was deposited during the culmination of the Holocene transgression. It is of a critical age (*ca.* 7.3 ka) for understanding environmental changes associated with postglacial sea level changes and local tectonic movements.

Vertical changes in the foraminiferal and oxygen isotope characteristics of marine cores from the southern part of the Sea of Japan record the onset of the present abundant inflow of warm-current water from the Pacific Ocean and East China Sea into the Sea of Japan. The stratigraphic level of this circulation-shift lies between the Kikai-Akahoya tephra and the underlying Ulreung-Oki tephra (*ca.* 10.7 ka), clearly indicate that the present circulation pattern became established between the ages of these two tephrogenic eruptions (Arai *et al.*, 1981). This circulation change may have depended largely on strengthening of warm current and widening of the two straits, Tsushima and Tsugaru, as a result of the sea level rise.

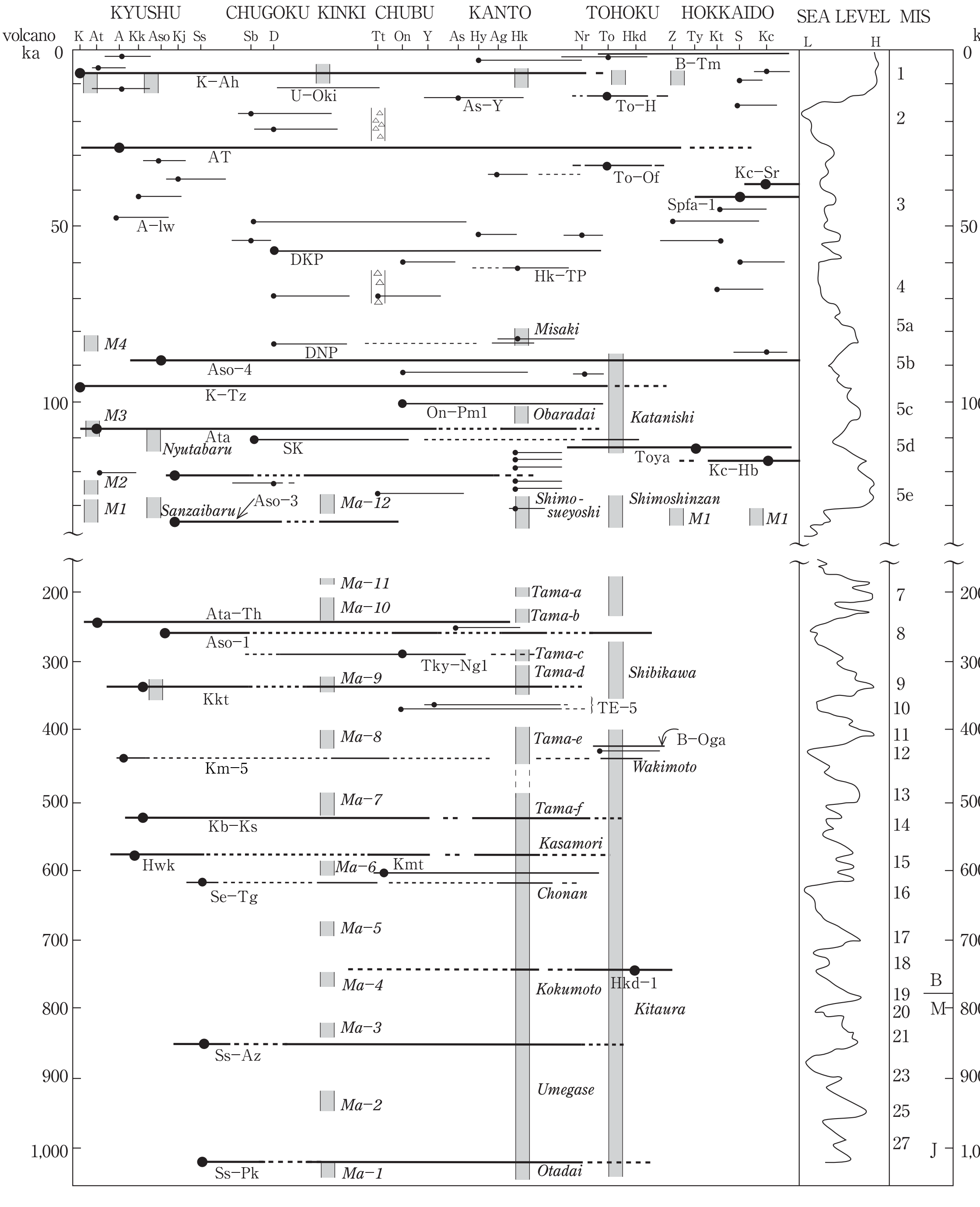

Fig. 3 Time-space diagram of marker-tephras with representative marine (stippled column) and glacial (open triangle) sequences in Japan for the last 1 Ma.

Ages in ka. Abbreviations of volcanoes: K, Kikai; At, Ata; A, Aira; Kk, Kakuto and Kirishima; Aso, Aso; Kj, Kuju; Ss, Shishimuta; Sb, Sambe; D, Daisen; Tt, Tateyama; On, Ontake Y, Yatsugatake; As, Asama; Hr, Haruna; Ag, Akagi; Hk, Kakone; Nr, Narugo; To, Towada; Hkd, Hakkoda; Z, Zenikame; Ty, Toya; Kt, Kuttara; S, Shikotsu; Kc, Kutcharo
Quaternary sea level curves derived mainly from marine oxygen isotope fluctuations by Chappell (1994) for the last 140 ky and Chen *et al*. (1995) for the earlier periods. A closed circle indicates the position of source area of each tephra, also indicating the size of eruption: large circle, >100 km^3; medium, 20-100 km^3; small, 5-20 km^3 in bulk volume.

This Kikai-Akahoya isochron also provides a definite datum plane in the Neolithic archeological sequence over an extensive area and indicates clearly that a great volcanic disaster occurred in prehistoric Kyushu (Machida, 1984). This will be mentioned in the other paper of this volume (p.65).

Chronological studies of laminated lake sediments have recently been carried out in the brackish lake of Suigetsu, north of Kyoto. A detailed counting of annual layers suggests that the K-Ah tephra was ejected at 7,324 cal. yr. BP (Fukusawa, 1995). If reliable, this proxy-calendrical age determination should play an important role in the application of radiocarbon calibration to associated ^{14}C assays.

Aira-Tanzawa tephra (AT)

This rhyolitic ash is the most prominent marker-tephra of the late Pleistocene, and occurs most extensively on land and in abyssal sediments around Japan (Machida and Arai, 1976; 1983; 1992; Fig. 2). More than one hundred radiocarbon dates hitherto obtained indicate that the cataclysmic eruption of the Aira caldera, southern Kyushu, occurred at around 22 to 25 ^{14}C ka. This tephra forms a valuable time-marker indicating the Paleolithic age and the last glaciation. Many deep sea cores around Japan indicate that this tephra was produced in a boundary period between marine isotope stages (MIS) 3 and 2 (Arai *et al.*, 1981; Yamane and Oba, 1999). The age of this boundary differs slightly from author to author, ranging widely from 2.5 ka to 2.9 ka, but recent ice core studies suggest that it should fall in the range between 2.6 ka and 3.2 ka. Recent studies on radiocarbon calibration indicate that such an age estimate would be conformable. In this paper an age estimate of 26 to 29 ka is adopted for this eruption.

Pollen analysis studies also suggest that a significant and abrupt vegetation change occurred at the time of this tephra forming event, with a shift from temperate deciduous forest to boreal conifer forest in the Kanto plain, central Japan (Tsuji and Kosugi, 1991). Stratigraphic evidence suggests that the coldest climate and lowest sea level occurred soon after this tephra forming eruption. In addition, a marked decrease in oxygen isotope values in planktonic foraminiferal tests occurs immediately below the eruption layer in the Sea of Japan indicating a continuous decrease in the salinity of the sea. The oceanographic change is thought to relate to a paleogeographic-controlled reduction of the inflow of water from the open sea at the Tsushima Straits between Korea and Kyushu at a time when the sea level was falling (Arai, *et al.*, 1981).

Shikotsu-l tephra (Spfa-l)

This rhyodacitic tephra derived from the plinian eruption of the Shikotsu caldera in Hokkaido, with tephra found in the Pacific Ocean off Hokkaido and the northeastern coast of Honshu (Fig. 2). The radiocarbon age of around 32 ka had long been regarded as reliable (Machida and Arai, 1992), however recent AMS radiocarbon dates and marine tephra chronology suggest the possibility of an older event (late to mid MIS3, 40-45 ka, Yamane and Oba, 1999; Aoki and Arai, 2000). Cryoturbated features and pollen assemblages associated with this tephra in Hokkaido suggest that the eruption occurred in a cold climate during MIS 3.

Aso-4 tephra

The Aso caldera in central Kyushu was the source of several major eruptions from the mid to late Pleistocene. This tephra is the youngest and largest of these caldera-related products and mantles extensive areas from Kyushu to Hokkaido. The tephra has also been identified in several piston cores from the Sea of Japan and the northwest Pacific Ocean as a co-ignimbrite ash of the Aso-4 ignimbrite (Fig. 2; Machida *et al.*, 1985; Machida and Arai, 1992). The fallout area is now known to approximate 4×10^6 km^2, the same order as that of the AT tephra. Distal Aso-4 tephra exhibits the coarsest grain size of the widespread ashes in Japan and can be distinguished by its dacitic glass chemistry with high alkali content together with characteristic phenocrysts and refractive indices of glass shards.

Six radiometric dates are available ranging from *ca.* 70 ka to 89 ka. The K-Ar age of 89±7 ka is the most probable age since the tephra is found in the Stage of 5b or at the 5a/5b boundary in marine isotope chronology (Oba, 1991; ODP site 792A, Oba *et al.*, in prep.). The marine terrace chronology of the southern Kanto district supports this age estimate because the tephra occurs after the Obaradai interstadial (MIS 5c) with high sea levels and before the Misaki interstadial (MIS5a). The widespread distribution and the association of the tephra with the marine isotope and terrace chronologies ensure that Aso-4 tephra provides a significant datum plane in the late Pleistocene sequence in and around Japan.

Toya tephra

The major eruption of the Toya caldera in Hokkaido started with ejection of a fine-grained pyroclastic flow and fall deposits suggesting a phreato-magmatic eruption, immediately followed by the cataclysmic eruption forming Toya pyroclastic flow IV. During this phase a fine-grained vitric ash layer of rhyolitic composition was produced as a co-ignimbrite ash fall, covering extensive areas of northern Japan and its adjacent seas (Machida *et al.*, 1987; Fig. 2). This tephra has been dated by various radiometric methods in a range from 130 ka to 103 ka BP. Marine stratigraphy based on diatom abundance patterns tuned to the standard oxygen isotopic curve from the Japan Sea cores suggests that the Toya tephra was produced during MIS 5d (Shirai *et al.*, 1997). In addition, its stratigraphic relation with other distal tephra layers of nearly the same age (Ata and SK) suggests a most possible age of 112-115 ka for Toya.

The Toya tephra is a useful tool for correlating marine terraces of MIS 5e and 5c in northern Japan. Its stratigraphic position in the type-section of Hachinohe, northern Japan, shows that it erupted after the culmination of the last interglacial period as represented by the Takadate marine terrace (MIS5e), and immediately after the Tagadai interstadial (post-MIS5e).

Recent progress in describing many Quaternary distal tephras results both from developments in the characterisation of their component phases and from enhanced knowledge of tephra distribution. A catalogue of tephras occurring in and around Japan provides fundamental criteria for the establishment of a regional Quaternary chronostratigraphy. The basic tephra framework is reconstructed through recognition of widespread marker tephras. A detailed and regional chronology based on distal deposits has been improved with the aid of local, proximal tephras. The juxtaposition of dated marine and terrestrial tephras with paleoceanographic, terrestrial, sea-level and tectono-geomorphic (e.g., terrace) records / features has enabled a synthesis of event-associations that has improved significantly the understanding of Quaternary events.

Acknowledgements

Special thanks go to Dr. F. Arai who has long been very helpful in characterization and identification of tephra since 1973.

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(Received 22 March 2002, Accepted 8 May 2002)