Quaternary Volcanoes and Widespread Tephras of the World

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Abstract

It is the two contrasting volcanic products, flood basalt and silicic ignimbrite, that represent the largest known volcanism in the earth history. The former is a product of effusive eruption at hot spots and divergent plate margins, forming extensive lava plains and shield volcanoes. On the other hand the ignimbrite is usually associated with large calderas on the conversion boundary and continental rift, forming ignimbrite sheets and co-ignimbrite volcanic tephras. Many extraordinarily large tephras have been recognized not only on land but also from abyssal sediments. This paper particularly focuses on the significance of Quaternary widespread tephras. A catalogue of the large volume tephras of the Quaternary around the world is tentatively listed, because they are very powerful tools for correlating stratigraphic sequences and landforms extensively, particularly for land-sea correlation. Continual revision and supplement action for compilation of the tephra catalogue will be a task for future studies.

Key words: co-ignimbrite ash, flood basalt, ignimbrite, plate tectonics, Quaternary, tephra catalogue, widespread tephra

1. Volcanoes of the World

The theory of plate tectonics is a well supported model and one which is able to describe the distribution of volcanoes of different types on the surface of the earth. Figure 1 shows the distribution of volcanoes in association with plate boundaries. The plate boundaries are classified into three types: divergent, transform and convergent. Divergent boundaries are mid-ocean ridges where new crust is being formed, and continental rifts like those of East Africa formed by active volcanism. Transform boundaries are typified by the San Andreas Fault in California and represent areas in which plates move past each other. They are not associated with volcanism but with devastating earthquakes. Convergent boundaries are complex areas forming linear mountain chains, metamorphic belts and volcanic chains. There are many distinct styles of plate collision and these produce various forms of volcanic activity and deposits.

1.1 Intra-plate volcanoes

Intra-plate volcanic activity is driven by mantle plumes that create volcanoes at hot spots on the Earth's surface. Activity occurs within both oceanic and continental plates.

Active and inactive volcanic islands and seamounts are features of intra-plate oceanic volcanoes in the Pacific, Indian and Atlantic Oceans. Examples include the Hawaiian islands, the Maldive Islands and others. Volcanic islands of this type are chielfly composed of basaltic lavas with small volumes of silica-rich materials. They form large shield volcanoes of the Hawaiian type. Therefore, tephras including scoria and hyaloclastic materials can be seen in very limited areas.

The principal expression of continental intra-plate volcanism is the eruption of extensive flood basalt in such regions as the Columbia plateau (USA), Deccan (India), South Africa, etc. Although volcanic activity is mainly effusive, producing lava flows with small tephra (pyroclastic and volcanic ash) layers, there sometimes occur explosive eruptions with voluminous silica-rich tephra deposits. Examples include the Baegdusan volcano on the border between China and North Korea and the Yellowstone volcanic complexes (USA). These suggest that silicic continental crust may have been melted by intrusion of basaltic magma.

1.2 Volcanism at divergent plate margins

Volcanic activity is associated with two categories of divergent plate boundary, mid-ocean ridge activity and continental rift ones. The former is generally characterized by effusive volcanic activity, producing large amounts of basaltic lava flows on the deep sea bottom. One exception occurs in Iceland where the Mid-Atlantic Ocean ridge has met a hot spot and,

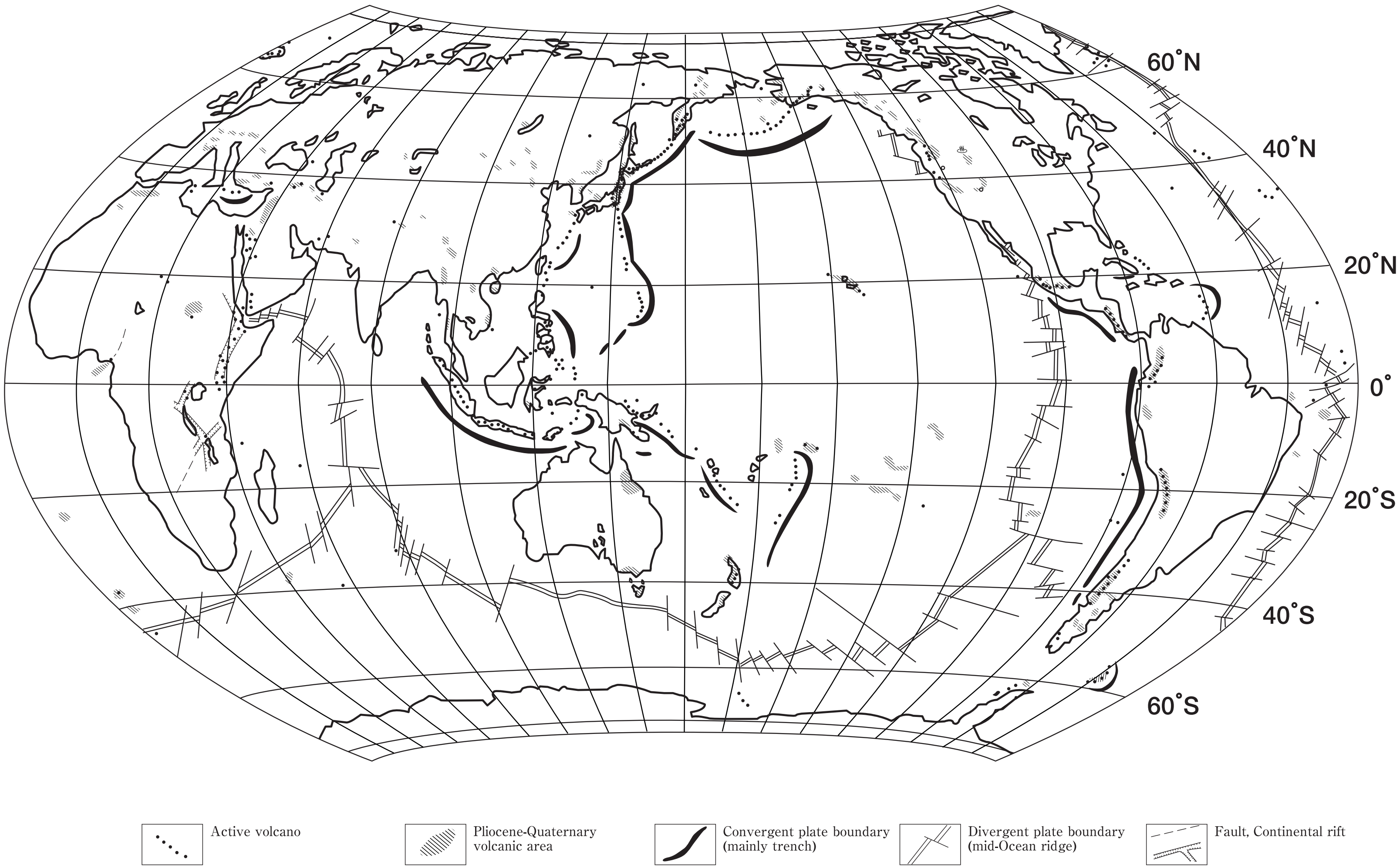

Fig. 1 Distribution of Quaternary volcanoes of the world. (Otsuka and Katsui (1976), revised)

therefore, extraordinarily large amounts of volcanic products are being produced. The volcanic products vary greatly from lava flows to pyroclastic ejecta, and, consequently, large amounts of tephra occur in Iceland and the adjacent seas.

Continental rift volcanism is well studied in the East African rifts and the Basin and Range region of the USA. The East African narrow rift is a place of swarms of volcanoes of many different types. Volcanic products generated in those rifts are much more variable than those of mid-ocean ridges. Lava flows and a variety of pyroclastic materials, including ignimbrites commonly occur. Compositions range from basalts to silica-rich trachytes and rhyolites and are generally more alkaline.

1.3 Volcanism at convergent plate margins

It is estimated that about 80% of the active volcanoes occur above subduction zones in the convergent plate margins. The circum-Pacific volcanic zone is known a place of high magnitude and frequent devastation wrought by eruptions. Magmas range from basalt to dacite and rhyolite. Consequently type of volcanic landforms and products vary from lava flows to ignimbrite plateaus around calderas, and from local ash soil to widespread sheet of ignimbrite and/or co-ignimbrite ash, respectively. These volcanic areas supply major tephra deposits extensively as shown in Fig. 2.

Volcanoes found in these convergent plate margins may be divided into two categories: 1) those occurring at continental margins such as the Andes, and 2) those related to island arcs.

The nature and style of volcanoes and their products may be controlled by many factors such as thickness of the crust, tectonic stress, geometry and age of plate subduction, etc. The Late Cenozoic volcanism of the Andes is characterized by infrequent but very large ignimbrite forming eruptions in central areas where thick continental crust evolved. On the other hand, frequent eruptions of lava and pyroclastic materials alternately occur forming stratovolcanoes and volcanic ash soil in southern areas with relatively thin and young continental crust.

The main difference between young arc volcanism and that found in areas of evolved island arcs such as Japan, Indonesia and New Zealand is related to the nature of the magmas produced. Whereas in the former case they are predominantly silica-poor and consequently effusive, in the latter, silica-rich andesites and dacites are associated with explosive volcanism together with eruptions of various types.

2. Major Widespread Tephras of the World

In highly volcanic areas, thick volcanic sequences comprising tephra and soil layers commonly occur at the foot of andesitic or/and basaltic volcanoes and adjacent areas. Most of them are the products of plinian and sub-plinian eruptions and commonly occur in elongated fallout areas. Volcanic ash soil or andosol is usually a product of tephra of this kind.

Many tephra layers play important roles as time markers in establishing a chronology for the Quaternary, because they occur within very short intervals of time over wide areas. Individual tephras, however, vary significantly and are restricted spatially by such factors as the magnitude and direction of prevailing wind, particle size of the tephra, etc. Consequently it had been said that tephra is only useful for local and regional stratigraphy.

Progress in characterization techniques for identification and dating methods has made possible a long-distance correlation between tephras and, therefore, placed local tephra studies on a more solid framework since the early 1970s. Details in Japan will be described in the next chapter, “Volcanoes and Tephras in the Japan Area”.

The discovery of the co-ignimbrite ash is one of the major results of recent tephra studies. They are predominantly fine-grained vitric fallout tephras ejected at the same time as large-scale pyroclastic flows (Machida and Arai, 1976; Sparks and Walker, 1977). The volume of co-ignimbrite tephra often approximates or exceeds that of the ignimbrite itself. These eruption-types are closely associated with gigantic caldera collapses.

Many extraordinarily large tephras have been recognized not only on land but also from abyssal sediments. They are very powerful tools for correlating stratigraphic sequences and landforms extensively, particularly for land-sea correlation. In addition, such large-scale eruptions have a serious impact on human societies as well as ecosystems over wide areas and consequently have been recognized as one of the triggers for global changes, as will be discussed in the other papers of this volume.

Such widespread co-ignimbrite and large plinian tephra layers occurring in various places of the world clearly indicate extraordinary explosive eruptions with Volcanic Explosivity Indices of 7 or 8 (total volume on the order of 10^2~10^3 km^3; Newhall and Self, 1982) in those regions. Examples include the Aira-Tn ash, Aso-4 ash and other tephras in Japan as shown in the next chapter. Studies in North America disclosed the widespread Mazama tephra, product of the ~7,600 cal.yBP Mt. Mazama volcano (Crater Lake caldera) first described about 60 years ago (e.g., Williams, 1942). The volume of the eruptive product was about 78 km^3, and has been identified about 1,700 km from the source. In addition, the three on-land Yellowstone tephras, the Lava Creek, Mesa Falls, and Huckleberry Ridge Tuffs (e.g., Christiansen and Blank, 1979) and the Bishop Tuff erupted from Long Valley (e.g., Izett *et al.*, 1970) have been identified extensively in North America. They are far larger in volume than the Mazama tephra.

Studies of deep-sea cores have helped to describe

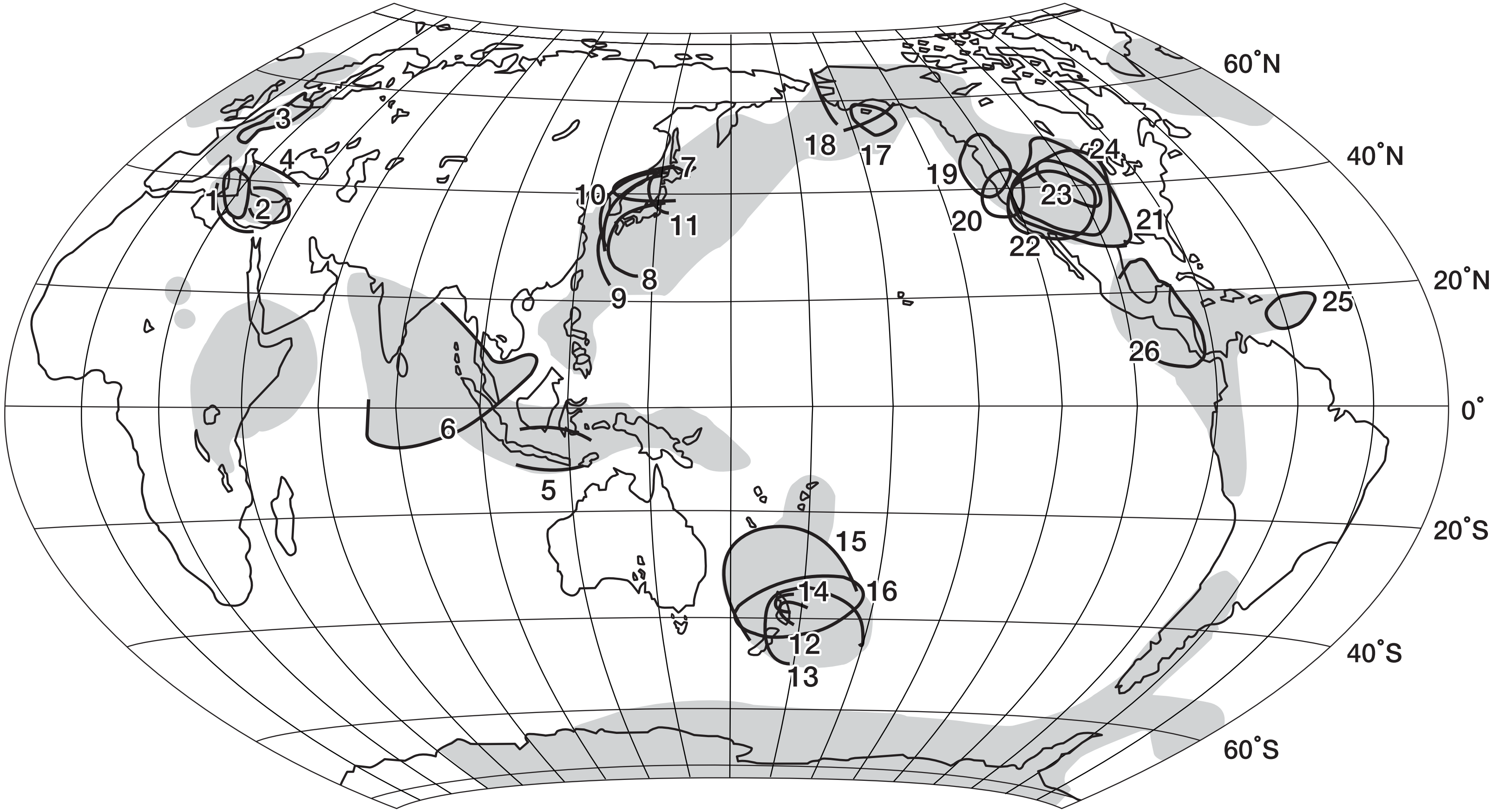

Fig. 2 Main regions of remarkable tephra layers around the world and approximate outer limits of identified marker-tephras.

1. Avellino (Z-1, Vesuvius); 2. Minoan (Santorini); 3. Laacher See; 4. Campanian (Campi Fregrei); 5. Tambora 1815; 6. Youngest Toba; 7. Baegudusan-Tm (Baegudusan); 8. Kikai-Akahoya (Kikai); 9. Aira-Tn (Aira); 10. Aso-4 (Aso); 11. Toya; 12. Taupo; 13. Kawakawa (Taupo); 14. Rotoiti (Haroharo/Okataina); 15. Rangitawa (Wakamaru); 16. Potaka (?); 17. Katmai (Novarupta); 18. Old Crow (Emmons Lake?); 19. Mazama (Crater Lake); 20. Rockland (Brokeoff?); 21. Lava Creek (Yellowstone); 22. Bishop (Long Valley); 23. Mesa Falls (Yellowstone); 24. Huckleberry Ridge (Yellowstone); 25. Roseau; 26. Los Chocoyos (Atitlan)

other widespread tephra layers from many places of the world. Examples are the Youngest Toba tephra from Sumatra in the Indian Ocean, the largest known from the Quaternary (e.g., Ninkovitch *et al*., 1978a), the Campanian tephra from Italy in the East Mediterranean Sea (e.g., Thunell *et al*., 1978), the Los Chocoyos tephra from Guatemala in the three Seas around Central America (e.g., Rose *et al*., 1981) and the Old Crow tephra in Alaska and Canada (e.g., Westgate *et al*., 1985). All of them are products of large caldera volcanoes. Major approximate fallout areas of each are shown in Fig. 2. Solid lines are tentative outer limits of previously identified marker-tephras. Such occurrences should become larger in extent with the progress in field mapping and fingerprinting of fine-grained volcanic glass shards in marine and ice cores. In fact, the Mazama tephra has recently been identified from the GISP2 core, Greenland ~5,500 km from the source (Zdanowicz *et al*., 1999). Such identification is essential not only for determination of the magnitude of eruption but also high-resolution dating of the eruption.

Consequently we have to improve identification techniques for fine-grained volcanic glass shards from cores. In addition, we must have plenty of information about tephra deposits from all over the world. In fact, there remain many volcanic areas and deposits unknown in remote districts, marine and lacustrine sequences, and ice cores.

The Commission of Tephra Studies, one of the INQUA (International Quaternary Association) Commissions, is preparing to create a catalogue of large tephra deposits around the world for correlation and identification and for promoting research of widespread tephra.

A catalogue of the large volume tephras of the Quaternary around the world is tentatively listed in Table 1 (Machida and Arai, 1992; Machida and Okumura, 1996).

Such widespread tephra catalogue should play an important role in many aspects:

1) Standard characterization of individual marker-tephra layers will be essential for their long distance correlation and identification, resulting in the establishment of a chronostratigraphical network over extensive areas. It is clear that much progress on identification of tephra in abyssal sediment and ice cores will occur successfully.

2) A mapping of distribution of tephra provides fundamental information not only on physical volcanology but also on paleo-environmental studies.

3) Tephra database works will clearly indicate what is lacking now and what should be done further.

In principle, it will mainly consist of large explosive volcanism with VEI 7-8 class tephras as well as well-known tephras of VEI 6 and 5 classes. This does not mean the exclusion of smaller and older eruptions. It is clear that some more frequent and smaller Holocene and historic tephras and eruptions are important for discussion of environmental and climatic effects of explosive volcanism.

We must emphasize at first, however, that the database presented here is clearly incomplete because our data collection is still insufficient and also there are still many places in the world where many tephra layers are unrecorded. The style and media will be discussed and improved in the near future. This kind of database will keep growing as it obtains detailed information particularly on distal tephra layers. Continual revision and supplement action will be a task for future studies.

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Table 1 A list of representative widespread tephra layers of the Quaternary around the world. (Machida and Arai (1992); Machida and Okumura (1996), revised.)

Tephra name (symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurrence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
Iceland								
Oraefajokull AD1362	Oraefajokull	AD1362	pfa	SE Iceland, Greenland, British Isles [1000]	10	rhyolite		1-3)
Hekla 1 (H1)	Hekla	AD1104	afa, pfa	Iceland, N [>300]	2	dacite		4-6)
Hekla 3 (H3)	Hekla	2.8 or 1159BC (C, Ice)	pfa	NNE Iceland [>350]	12	rhyolite to basalt	useful for neoglaciation	4,6)
Hekla 4 (H4)	Hekla	3.8 (C)	pfa	C-N Iceland, British Isles [>350]	9	rhyolite to basalt		3,4,6,7)
Solheimar (Ash Zone 1(Z1), Skogar, Vedde)	Katla	11.0-11.1 (C)	pfa, afa	Iceland, N.Atlantic, Norway, North Sea [ice rafting, S1800]	VEI6?	rhyolite	useful for paleoceanography	8-10)
Thorsmork (THI) (Ash Zone 2(Z2), Dye3)	Tindfjallajokull	57.3-57.5 (^{18}O)	afa, pfl	S.Iceland, N.Atlantic, Greenland [ice rafting, S1800]		rhyolite (75%) to basalt	Fe-hedenbergite, fayalite, illmenite, cgt, bearing	9,12-17)
Ash Zone 3 (Z3)	Krafa or Hofsjokull	305 (^{18}O)	pfl, afa?	Iceland, N.Atlantic [ice rafting, S 1800]		rhyolite (low alkali)	useful for paleoceanography	9,14)

1) Thorarinsson (1958), 2) Thorarinsson *et al.*(1960), 3) Pilcher *et al.* (1996), 4) Larsen & Thorarinsson (1977), 5) Sigvaldason (1974), 6) Pilcher *et al.*(1995), 7) Thorarinsson (1976), 8) Lacasse *et al.*(1995), 9) Lacasse *et al.* (1996), 10) Bard *et al.* (1994), 11) Ruddiman & Glover (1975), 12) Jorgensen (1981), 13) Jorgensen (1987), 14) Ruddiman & Glover (1972), 15) Gronvold *et al.* (1995), 16) Ram *et al.* (1996), 17) Ruddiman & McIntyre (1984)

Europe								
Pompeian	Vesuvius (IT)	AD79	pfa, pfl	[SSE:>70]		phonolite-tephrite		8)
Avellino (Z-1)	Vesuvius (IT)	17th cent. BC (C)	pfa, afa	[SE:1200]	<40	leucite & melanite-tephrite		1,9,15)
Minoan (Z-2)	Santorini (GR)	16th-17th cent. BC (C,A)	pfa, afa, ps, pfl	[E:1300]	>40	rhyodacite, SiO$_2$ 71-72%	impact on Minoan civilization	2,3,16)
Laacher See	Laacher See (GM)	12.5 (V), 12.9 (AA)	pfa, ps	[NE:1100, S:600, SW:100]	16	phonolite, SiO$_2$ 56-58%	useful for west European archeology	4,10)
Neapolitan Yellow (C-2)	Campi Flegrei (IT)	12-14 (C) [MIS1-2]	pfa, pfl	[NE:300]		latite-alkali trachyte		11)
Biancavilla-Montalto (Y-1, Et-1)	Etna (IT)	14(C)	sfa, pfl	[N:600, SE:600]		Na-basalt		1,17)
Campanian (CI,Y-5)	Campi Flegrei	36-37 (AA) [MIS3]	pfl, afa	[E:>2000]	500	latite-alkali phononite	useful for paleoceanography and archeology in east Mediterranean	1,5,6,12,13,17)
C-13 (Citare)	Campi Flegrei	40 (C,KA) [MIS3]	pfl, afa	central Mediterranean		trachyte	a part of Citare tuff	7)
C-18 (Y-7)	Campi Flegrei? Mt.Epomeo?	60 (^{18}O) [MIS3-4]	pfl, afa	central Mediterranean, widespread		trachyte	a part of Green tuff	7)
Kos plateau (X-3)	Kos (GR)	145 (KA), 161 (AA) [MIS6]	afa, pfl	east Mediterranean		alkali rhyolite		14)

1) Keller *et al.* (1978), 2) Watkins *et al.* (1978), 3) Sparks *et al.* (1983), 4) Bogaard & Scmincke (1983), 5) Thunell *et al.* (1978), 6) Rosi *et al.* (1983), 7) Paterne *et al.* (1991), 8) Civetta *et al.* (1993), 9) Rolandi *et al.* (1993), 10) Baales *et al.* (2002) (1997), 11) Scarpati *et al.* (1993), 12) Fischer *et a*l. (1993), 13) Fedale (2002), 14) Smith *et al.* (1996), 15) Vogel *et al.* (1990), 16) Manning (1990), 17) Narcisi & Vezzoli (1999)

IT, Italy; GR, Greece; GM, Germany

Table 1 (*continued*)

Tephra name(symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
East Africa								
Kale	Main Etiopian Rift?	740 (KA)		NE & NW of Lake Turkana [E>1200]				1)
Silbo	Main Etiopian Rift?	740±10 (KA)		N & S of L. Turkana & Gulf of Aden & W. Indian Ocean [1500]				2,3)
Gale (ET-28)	Awasa-Corbetti?	1250±20; 960±100 (KA)						4-6)
Nariokotome (ET-29b)	Awasa-Corbetti?	1330±20; 1100±100 (KA)						1,5,7)
Chari		1390±20 (KA)						3,6)
Malbe (ET-29e)	Awasa-Corbetti?	1860±20; 1850±100 (KA)				trachyte		3,5,6)
KBS (ET-54, Wagebeta-Omo R. Canyon)		1880±20; 1900±90 (KA)						3,5,6)

1) Harris *et al*. (1988), 2) Brown *et al*. (1992), 3) Cerling & Brown (1982), 4) Feibel *et al*. (1989), 5) Wolde Gabriel *et al*. (1990), 6) McDougall (1985), 7) Brown *et al*. (1985)

Southeast Asia								
Krakatau	Krakatau (INDN)	AD1883.8.27			18-21	rhyodacite		15,16)
Tambora	Tambora (INDN)	AD1815.4.10	afa, pfa, pfl, afa	[WNW1000]	150, 50 (DRE)	trachyte		3,4)
Batur	Batur (INDN)	26 (C)	pfl		VEI 6-7	px-dacite SiO_2 62-66%		5)
Youngest Toba (YTT)	Toba (INDN)	70 (KA, AA, ^{18}O) [MIS5a-4]	pfl,afa	[WNW>3000], Bengal bay, Indian penisula, Indian Ocean, Sunda sea	2500-3000	rhyodacite; qt-latite rhyolite SiO_2 68-76%	very widespread; the largest Quaternary tephra in the world	9-12,17-19)
Manijau	Manijau (INDN)	280 (KA)	pfl		100-250	rhyolite, andesite		6-8)
Middle Toba (MTT)	Toba (INDN)	501 [N]	pfl		60 (DRE)	rhyolite SiO_2 72-76%		9,10)
Oldest Toba (OTT)	Toba (INDN)	840 [R]	pfl		500 (DRE)	rhyodacite, qt-latite SiO_2 61-74%		9,10)
Haramggoal (HDT)	Toba (INDN)	1200 (FT) [R]	pfl		35 (DRE)	dacite SiO_2 63-65%		9,10)
Bulsan	Bulsan (Irosin) [PHIL]	>36 (C)	pfl			rhyolite		13)
Dakatau	Dakatau (PNG)	1.1-1.2 (C)	afa, pfa, pfl	central-west New Britain	VEI 5-6	andesite		14)
Rabaul	Rabaul (PNG)	1.4 (C)	pfa, pfl	east New Britain	VEI 5-6	rhyodacite		1,2)
Witori-Kimbe2 (W-K2)	Witori (PNG)	3.3 (C)	afa, pfa, pfl	central-west New Britain	VEI 6	dacite		14)
Raluan	Rabaul (PNG)	3.5 (C)	sfa, pfl	east New Britain	VEI 6	rhyolite,(basalt)		1,2,14)
Malaguna	Rabaul (PNG)	1000 (AA)	pfa, pfl	east New Britain	VEI 6	dacite, andesite		1,14)

1) Nairn *et al*. (1989), 2) Walker *et al*. (1981a), 3) Sigurdsson & Carey (1989), 4) Self *et al*. (1984), 5) Wheller & Varne (1986), 6) Leo *et al*. (1980), 7) Nishimura (1980), 8) Purbo-Hadiwidjoyo *et al*. (1979), 9) Chesner & Rose (1991), 10) Chesner *et al*.(1991), 11) Ninkovich *et al*. (1978a), 12) Ninkovich *et al*. (1978b), 13) Philippine Inst. Volcanol. Seismol. (1984), 14) Machida *et al*. (1996), 15) Simkin & Fiske (1983), 16) Sigurdsson *et al*. (1991), 17) Rampino & Self (1992), 18) Acharyya & Basu (1993), 19) Schulz & Emeis (2002)

INDN, Indonesia; PHIL, Philippines; PNG, Papua New Guinea

Table 1 (*continued*)

Tephra name (symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurrence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
New Zealand								
Taupo (Tp)	Taupo	1.85 (C)	pfa, afa, pfa, pfl	[>660]	120 (pfa50+pfl70)	rhyolite		1-8)
Waimihia (Wm)	Taupo	3.28±0.02 (C)	pfa, pfl	[>560]	27 (pfa22+pfl5)	rhyolite		4,6,7,8,9,10)
Rerewhakaaitu (Rk)	Okataina	14.7 (C)		[>500]	14			4,8,10,11,26)
Kawakawa (Kk, Oruanui, Aokautere)	Taupo	26.5 (C)	pfa, afa, pfl	[>1370]	>750 (pfa430+pfl320)	rhyolite	very widespread around N.Z.	4,8,10,12-15, 30)
Rotoiti (Rotoehu, Matahi)	Haroharo, Okataina	64(KA)	pfa, pfl, afa		240 (pfa90+pfl150)	rhyolite		4,7,16-20)
Pre-Oruanui	Taupo	[N]			30-100			20)
Orakonui	Maroa	[N]			30-100			20)
Atiamuri	Maroa	[N]			30-100			20)
Korotai	Maroa	[N]			30-100			20)
Mamaku (Kutarere)	Rotorua	220,230 (ITFT) [MIS7.3, N]	pfa, pfl		>300	rhyolite		17,20,24)
Kaingaroa	Reporoa	230 [MIS8, N]			100-300			20)
Ohakuri	Kapenga	270 [N]			30-100			20)
Pokai	Reporoa	[N]			30-100			20)
Matahina	Okataina	280,340 [MIS9, N]	pfa, pfl		100-300			17,20,29)
Chimpanzee	Kapenga	[N]			30-100			20)
Rangitawa (Whakamaru, Mt.Curl, etc.)	Whakamaru	340-345 [MIS10, N]	pfl, afa	widespread [>3000]	300-1000	rhyolite	very widespread around N.Z.	21,22)
Waiotapu	Kapenga	710 [N]	pfl		100-300			20)
Tikorangi	Kapenga	890 (KA) [R]	pfl		30-100			20)
Kaukatea (upper Te Munga)		870±50 (ITFT) [R]						27,29)
Marshall	Mangakino	950 (AA) [R]	pfl		>50			20,23)
Potaka (lower Te Munga)	Mangakino	1000±30 (ITFT) [MIS28, N, top of Jaramillo]		[>2500]		rhyolite	very widespread around N.Z.	28,29)
Rocky Hill	Mangakino	1000 (AA)	pfl		>300?			20,23)
Unit E	Mangakino	970 (AA) [N]	afa,pfl		>300?			20,23)
Ahuroa	Mangakino	1180 (AA) [N-R]	pfl		100-300			20,23)
Unit D	Mangakino	1200 (AA)	afa,pfl		100-300			20,23)
Ongatiti	Mangakino	1210 (AA) [R]	pfl		>300	rhyolite		20,23)
Unit C	Mangakino	1680 (AA)	pfl		30-100			20,23)
Unit A	Mangakino	1550 (KA) [R]	pfl		100-300			20)

1) Baumgart (1954), 2) Healy (1964), 3) Froggatt (1981), 4) Pullar & Birrell (1973), 5) Pullar *et al.* (1977), 6) Wilson (1993), 7) Froggatt & Lowe (1990), 8) Carter *et al.* (1995), 9) Walker (1981), 10) Vucetich & Pullar (1964), 11) Lowe (1988a), 12) Vucetich & Howorth (1976), 13) Cambell (1986), 14) Wilson *et al.* (1988), 15) Pillans *et al.* (1993), 16) Vucetich & Pullar (1969), 17) Wilson *et al.* (1984), 18) Wilson *et al.* (1992), 19) Lowe & Hogg (1995), 20) Houghton *et al.* (1995), 21) Kohn *et al.* (1992), 22) Pillans *et al.* (1996), 23) Briggs *et al.* (1993), 24) Shane *et al.* (1994), 25) Froggatt (1983), 26) Stokes *et al.* (1992), 27) Seward (1976), 28) Shane (1994), 29) Shane *et al.* (1995), 30) Wilson (2001)

Table 1 (*continued*)

Tephra name (symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurrence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
Kurile ~ Kamchatka								
Opala	Opala (Baraniy Amfiteatr)	1.4-1.5 (C)	afa, pfl		10	rhyolite		1-3)
Ksudach1	Ksudach	1.7-1.8 (C)	pfa, pfl		18-19	rhyodacite		1,4)
Ksudach2	Ksudach	<6.0 (C)	pfa, pfl		9-11	andesite		1,4)
Khanger	Khanger	6.9-7.0 (C)	pfa, pfl		>10	dacite		1,5)
Kurile lake/Ilinsky	Kurile lake/Ilinsky	7.6-7.7 (C)	pfa, pfl		120-140	rhyolite		1,6)
Karymsky	Karymsky	7.7-7.8 (C)	pfa, pfl		13-16	rhyodacite		1,9)
Goreley Khrebet	Goreley Khrebet	33-34 (C)	pfl		>120	dacite		1,5,7)
Opala (old)	Opala	39-40 (C)	afa, pfl		30	silicic		1,8,9)
Uzon	Uzon	<39 (C)	pfl		VEI6?	dacite		1,5)
Golygin	Kurile Lake	41-42 (C)	pfl, afa?		VEI7?	silicic		1,7)

1) Braitseva *et al.* (1995), 2) Krayevaya (1967), 3) Melekestsev *et al.* (1992), 4) Braitseva *et al.* (1996), 5) Fedotov & Melekestsev (1991), 6) Braitseva *et al.* (1992), 7) Erlich (1986), 8) Ponopruzhenko (1988), 9) Braitseva & Melekestsev (1990)

Alaska								
Katmai	Novarupta (ALS)	AD1912	pfa, pfl	[E>1000]	pfa20, pfl11-15, 15 DRE)	dacite		1,2)
Okmok II	Okmok (ALT)	2.4 (C)	pfl		>50	andesite	useful for archeology	3)
Aniakchak II	Aniakchak (ALS)	3.4 (C)	pfa, pfl	[conc.80]	35 (DRE)	dacite		3,4)
Venimianof	Venimianof (ALS)	3.7 (C)	pfl, pfa	[50]	>50	dacite-andesite		3)
Okmok I	Okmok (ALT)	8.3 (C)	pfl, afa?	E	>50	andesite	useful for archeology	3,5)
Fisher	Fisher (ALS)	9.1 (C)	pfl, pfa	[E>120]	>50	dacite		3)
Old Crow	Emmons Lake? (ALS)	140 (ITPFT)	pfl, afa	[NE2000]	>300	px-rhyodacite	useful widespread marker in Alaska	3,6,7)

1) Hildreth (1983), 2) Hildreth (1987), 3) Miller & Smith (1987), 4) Hildreth (1981), 5) Black (1975), 6) Westgate *et al.* (1985), 7) Westgate & Stemper (1990)
ALS, Alaska; ALT, Alutian

North America								
Mazama	Crater Lake (OR)	7.63 (GISP2)	pfa, pfl, afa	[1700]	pfa38, pfl40	opx, ho dacite		1,2,15)
Rockland	Brokeoff? (CA)	614 (AA) [MIS15]	pfa, pfl, afa	[conc.>400]	>80	ho, opx rhyolite		3,13)
Lava Creek B	Yellowstone III (WY)	660 (AA) [MIS16]	pfl, afa	[ES>2000]	>=1000 (DRE)	rhyolite	very widespread	4,5,6,13,14)
Bishop	Long Valley (CA)	759 (AA) [N]	pfa, ps, pfl, afa	[E1800]	500 (DRE)	rhyolite	just above the B/M geomagnetic boundary	7,8,9,12)
Upper Bandelier	Valles (NM)	1150 (KA,FT)			300 (DRE)	rhyolite		10,11)
Mesa Falls	Yellowstone II (ID)	1270 (KA) [R]	pfa, pfl, afa	[ES1300]	>=280 (DRE)	rhyolite		4,5,6)
Lower Bandelier	Valles (NM)	1470 (KA,FT) [R]			300 (DRE)	rhyolite		10,11)
Older Valles	Valles (NM)	1780 (KA,FT)						10,11)
Huckleberry Ridge	Yellowstone I (WY)	2060 (AA) [N]	pfl, afa	[1800]	>=2500 (DRE)	rhyolite	one of the largest tephras	4,5,6,12)

1) Bacon (1983), 2) Sarna-Wojcicki *et al.* (1983), 3) Sarna-Wojcicki *et al.* (1985), 4) Izett & Wilcox (1982), 5) Christiansen (1984), 6) Christiansen & Blank (1979), 7) Bailey *et al.* (1976), 8) Izett *et al.* (1970), 9) Izett (1982), 10) Smith (1979), 11) Izett (1981), 12) Sarna-Wojcicki & Pringle (1992), 13) Lanphere *et al.* (1999), 14) Izett *et al.* (1992), 15) Zdanowicz *et al.* (1999)
OR, Oregon; CA, California; WY, Wyoming; NM, New Mexico; ID, Idaho

Table 1 (*continued*)

Tephra name (symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurrence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
Central & South America								
Tierra Blanka joven (tbj)	Ilopango (ESL)	AD300?	afa, pfl	Central America [>70]	>3.5	rhyodacite		11)
Roseau	Roseau (DMN)	30	pfa, pfl	[E:700,SSW:300]	>25	rhyodacite		1-3)
Los Chocoyos	Atitlan III (GTM)	84(U,^{18}O) [MIS5]	pfa, pfl, afa	conc. [1500]	270-280 [pfa120, pfl160] (DRE)	rhyolite	known as Y-8 ash in marine deposits,useful for paleoceanography	4-6)
La Primavera B	La Primavera (MXC)	95(KA) [MIS5]	pfa, pfl, pfa	NE	90 [pfa50; pfl40] (DRE)	peralkaline-metaluminous rhyolite		8,9)
Amatitlan T	Amatitlan (GUA)	240±170 (KA)	pfa, pfl	[NE: 500]	>16	ho, bi rhyodacite		7)
Diamantes	Diamantes (CHL)	450±60	pfl	15000 km^2	450 (DRE)	rhyolite		10)
Miravalles	Miravalles (CR)	500±150	pfl			rhyolite		9)
Lower Purico	Purico	1300	pfl	800000 km^2	VEI6-7?	bi, ho dacite		12)
Unnamed	Laguna Colorado	1700	pfl			bi, ho		13)

1) Sigurdsson (1972), 2) Sparks *et al*. (1980), 3) Carey & Sigurdsson (1980), 4) Rose *et al*. (1987), 5) Newhall *et al*. (1987), 6) Rose *et al*.(1981), 7) Wunderman & Rose (1984), 8) Mahood (1980), 9) Walker *et al*. (1981c), 10) Stern *et al*. (1984), 11) Harts & Steen-McIntyre (1980), 12) de Silva & Francis (1991), 13) Francis & Baker (1978)

ESL, El Sarvadol; DMN, Dominica; GTM, Guatemara; MXC, Mexico; CHL, Chile; CR, Costa Rica

Tephra name (symbol)	Source volcano	Reliable average age (ka) (method) [MIS, Geomagnetism]	Eruption sequence	Occurrence area [Max. distance, km or area, km^2]	Bulk volume {DRE}	Rock type	Remarks	Reference
Southern Pacific & Antarctica								
Southern Pacific Tephra Zones (Eltanin)	Marie Byrd Land	2430≥60(ST)		Ross Sea, off the west Antarctica		alkaline, felsic	widespread, multiple	1,2)

1) Huang *et al*. (1975), 2) Shane & Froggatt (1992)

Reliable average age and method: A, Archaeology; AA, ^{40}Ar-^{39}Ar; C, Radiocarbon; FT, Fission track; H, Historical document; ITPFT, Isothermal Plateau Fission Track; KA, K-Ar; ST, stratigraphy; ^{18}O, ^{18}O chronology.
MIS//Geomag: MIS, Marine isotope stage; Geomag: geomagnetism and/or chron, subchron.
Eruption sequence: p, plinian; ph, phreatomagmatic; i, ignimbrite-forming; c, co-ignimbrite fall; l, lava flow.
Mineral assemblage: af, alkali feldspar; am, amphibole; bt, biotite; cgt, cummingtonite; cpx, clinopyroxenes; ho, hornblende; ilm, ilmenite; lc, leucite; opx, orthopyroxens; pl, plagioclase; px, pyroxenes qt, quartz; sn, sanidine; sph, sphene.
Glass shard: bw, bubble walled; pm, pumiceous.

*A list of tephra layers in the Japan area is shown in Table 1 of the next chapter (p.23).

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