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Sun, C., Wang, L., Plunkett, G., Zhang, E., & Liu, J. (2021). An Integrated Late Pleistocene to Holocene Tephrostratigraphic Framework for South-East and East Asia. *Geophysical Research Letters*, 48(5), [e2020GL090582]. <https://doi.org/10.1029/2020GL090582>

Published in:
Geophysical Research Letters

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
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An integrated Late Pleistocene to Holocene tephrostratigraphic framework for South-east and East Asia

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Key Points:

- We present the first high-resolution late Pleistocene to Holocene cryptotephra sequence in mainland China
- A series of key widespread late Pleistocene to Holocene tephra isochrons around East Asia is established
- We refine the dating of late Pleistocene to Holocene eruptions from Pinatubo and a volcano from southwest Luzon

Abstract

Volcanic ash has been widely used as unique independent marker horizons for dating and synchronizing paleoenvironments and archeological records. Here, we report a series of key widespread late Pleistocene to Holocene tephra horizons from a lake sequence in southern China that have significant potential for dating and synchronizing paleoenvironmental records from East Asia. Translatitudinal paleoclimatological, paleoenvironmental and archeological correlations from the tropical Philippines, mainland China, and mid-latitude Japan are achievable through these extensively distributed tephra, including synthetic studies of the Younger Dryas and mid-Holocene climate events. Additionally, we establish refined ages for four pre-1991 Pinatubo eruptions and date three late Pleistocene Luzon eruptions based on the lake sequence age-model, which will facilitate future studies of tropical volcanic eruptions' forcing of climate change. Our results highlight the volcanic hazards around densely-populated East Asia, and bring solutions to resolving dating uncertainty in the synchronization of rapid climate events across the region.

1. Introduction

The Asian monsoon, comprised of East Asian and Indian subsystems, plays an important role in global hydrological and energy cycles, which affect the most densely populated regions on Earth (An et al., 2000; Wang et al., 2005). Synchronizing abrupt climate events across monsoon regions is fundamental to understanding the causal mechanisms and role of monsoon circulation in abrupt climate change. However, spatiotemporal syntheses of climate proxies are usually limited by inherent imprecision within the most common dating methods, such as ^{14}C . For example, there are ongoing debates regarding the synchronization of the Holocene Optimum in the East Asian monsoon region (An et al., 2000; Zhao et al., 2009), chiefly as a result of the chronological divergence between sedimentary archives. Moreover, it is difficult to define precisely spatiotemporal leads and lags in centennial to millennial scale rapid climate events with such dating imprecision. Ascertaining independently dated marker horizons in sedimentary records can help overcome such issues.

Volcanic ash ejected from explosive eruptions can be transported several thousand kilometers from the volcanic vent, thus forming excellent regional to global independent event horizons for precisely correlating and dating terrestrial, marine, and ice core records (Lane et al., 2013; Jensen et al., 2014; Sun et al., 2014). Explosive eruptions from the western Pacific "Ring of Fire" have been demonstrated to leave deposits across large regions, such as tephra from the 1991 Pinatubo eruption which has been found in Antarctica (Wiesner et al., 1995; Cole-Dai et al., 1997). Tephra from Japanese explosive eruptions have been extensively investigated for environmental, archeological and stratigraphic studies, some extending to the east of North America and Greenland (Moriwaki et al., 2011; Mackay et al., 2016; Bourne et al., 2016; McLean et al., 2018; Albert et al., 2019). Therefore, tephra from both the Philippines and Japan can form marker horizons across a large area. Widespread tephra layers around Japan have been well outlined in the last decades (Machida 1976; Machida 1999; Machida and Arai 2003), for example, the widespread ~7.3 ka K-Ah (Kikai-Akahoya, Volcanic Explosivity Index (VEI) 7) from Kikai volcano (Machida 1999; Smith et al., 2013). In addition, tephra layers from exterior eruptions

were also identified, including B-Tm (Baegdusan-Tomakomai) and QEA/B-Sg-08 (Qixiangzhan eruption ash/Baegdusan-Suigetsu-08) from Changbaishan volcano on the border between China and North Korea, and several from Ulleungdo including U-2, U-3, U-4, and perhaps U-1 (SG14-0433) (Sun et al., 2014; 2018; Chen et al., 2016; McLean et al., 2018; McLean et al., 2020). The ~12.8 ka Sz-S (Sakurajima-Satsuma, VEI 6) from Sakurajima volcano and ~14.9 ka N-Ym (Noike-Yumugi, VEI 6) from Kuchierabujima Island are the most voluminous late Pleistocene tephras erupted on Kyushu Island, southern Japan (Moriwaki 1992; Moriwaki et al., 2011, 2016). The tephrostratigraphic framework of Lake Suigetsu is the first comprehensive Holocene sequence in Japan, and several of the aforementioned tephra layers have been identified in it (McLean et al., 2018). High-resolution radiocarbon dates provide precise age constraints for tephra layers in the Suigetsu record (Staff et al., 2011; Mclean et al., 2018). However, whether these tephra layers can be found within the region mainly affected by the East Asian monsoon has not previously been investigated, despite the potential they offer in terms of directly correlating and dating climate proxies across the region.

Explosive eruptions not only produce extensively distributed tephras, but can also have significant sub-decadal regional to global climate impacts through the injection of large amounts of sulfates and volcanic ash into the atmosphere (McCormick et al., 1995; Robock, 2000). In particular, tropical eruptions have a greater likelihood of influencing global climate because their products can spread globally, as shown by the 1991 eruption of Pinatubo in the Philippines (McCormick et al., 1995; Self et al., 1996). However, eruptive histories around South-east Asia are not well known, impeding the understanding of past tropical volcanism and climate change. The poorly constrained eruptive history of volcanoes close to densely-populated regions (e.g., Manila city, with a population of 14 million people, is less than 100 km from Pinatubo) also hampers the understanding and evaluation of volcanic hazards. Volcanic ash provides direct evidence for past eruptions, and distal tephras can contribute to a more complete volcanic history.

In this study, we investigate a stratigraphic sequence from a lake in southern China to explore the potential for inter-regional tephrostratigraphic correlations in eastern Asia. We identify a series of key late Pleistocene to Holocene tephras from Japanese and Philippine volcanoes that offer excellent opportunities for precise stratigraphic correlations across the East Asian monsoon region whilst also allowing us to provide new insights into the eruptive histories of individual volcanoes.

2. Materials

The Huguangyan maar lake (HML, 21°9'N, 110°17'E) is located in the Leiqiong volcanic field, southern China (Fig. 1). The lake is ~ 1.7 km in diameter, 20 m in maximum deep, 2.25 km² in surface area, and surrounded by ~88 m tuff rings. There is no surface inflow or outflow around the lake, and the catchment area comprises only the inner slopes of the crater rim (Mingram et al., 2004). Two parallel sediment cores with a composite length of 13.28 m core were collected from the lake in 2010. A total of 33 samples were selected for AMS ¹⁴C dating, and a Bayesian age-depth model was constructed using the *P-Sequence* function in OxCal 4.4 (Bronk Ramsey 2008; 2009) with the INTCAL20 calibration dataset (Reimer et al., 2020; Fig. 2, Table S1).

Cryptotephra investigations were performed on the section 0–13 m using standard methods (methods descriptions can be found in SI).

3. Results

In total, we identified 14 tephra layers characterized by distinct peaks in glass shard concentrations (Fig. 2). Extended descriptions of results can be found in SI.

3.1 Correlations with Japan and surrounding region

Four tephra layers can be correlated with eruptions from Japan and surrounding volcanoes (Fig. 3a, b, Table 1, SI). Trachytic HGY368 (2965–2253 cal a BP) matches the major element geochemical composition of the SG14-0433 tephra (2737–2620 cal a BP) recorded in Lake Suigetsu (McLean et al., 2018). This tephra was tentatively correlated with the U-1 eruption of Ulleungdo (Sea of Japan) because of its age and evolved trachytic glass composition, but in the absence of proximal glass data for the U-1 tephra, the correlation cannot be confirmed (McLean et al., 2018, 2020). Rhyolitic HGY763 (7499–6485 cal a BP) correlates with the widespread K-Ah tephra from Kikai caldera south of Kyushu Island (Machida 1999). This tephra is identified in the Lake Suigetsu record (Smith et al., 2013; Albert et al., 2019) and has been most recently dated using the Suigetsu age model to 7307–7196 cal a BP (INTCAL13; McLean et al., 2018). The rhyolitic HGY1026 (13420–12657 cal a BP) corresponds to the ~12.8 ka Sz-S tephra from Sakurajima volcano situated within the Aira caldera, southern Kyushu Island, Japan. HGY995 (12738–12060 cal a BP) exhibits a very distinctive geochemical composition, and can be clearly separated from tephras from South-east Asia, central-south Japan, and Mariana-Izu-Bonin. It most closely resembles volcanic products from northern Japan (e.g., Kutcharo), although no confirmed eruptions with similar ages have been reported from this area (Fig. 3a, b; Albert et al., 2019). The origin of this tephra needs to be further investigated.

3.2 Correlations with the Philippines

A lack of glass geochemical datasets for Philippine eruptions hinders the firm attribution of distal tephras to volcanoes in this region. Nevertheless, four tephras with rhyolitic glass compositions can very likely be attributed to Pinatubo on the basis of their correlation with tephra from its 1991 eruption (Fig. 3c, d, Table 1, SI). The pre-1991 eruptives (i.e., the eruptions before the 1991 Pinatubo eruption; Table 1) share similar whole rock geochemical compositions with the 1991 ash, which means it is possible to compare tephras from different eruptions from this source (Luhr and Melson 1996; Newhall et al., 1996; Cole-Dai et al., 1997; Ku et al., 2008). HGY159 (927–729 cal a BP), HGY394 (3133–2719 cal a BP), and HGY702 (6166–5637 cal a BP) correspond with the Buag (800–476 cal a BP), Maraunot (3875–2342 cal a BP), and Crow Valley (6079–5004 cal a BP) eruptive epochs, respectively (Newhall et al., 1996). The glass composition of HGY1101 (14795–14080 cal a BP) also overlaps with the 1991 Pinatubo glass geochemical field, which suggests that it too derives from this source. The geochemistry of HGY1113, HGY1127 and HGY1136 (~15–14 ka) is not consistent with known tephras around East Asia, but closely matches the ~152 ka F1 tephra (~2 cm in thickness) recorded in marine core MD97-2142, which might suggest that it derives from the same source as the F1 tephra, likely originating in southwest Luzon (Ku et al., 2009; Fig. 3c, d; SI). Further work is needed to

establish the glass compositions of tephra around the Philippines (such as products from Taal and Mayon) to enable correlations between proximal and distal tephra layers in the wider region.

4. Discussion and conclusions

4.1 Extending and interlinking the tephrostratigraphic framework across South-east and East Asia

Cryptotephra of both tropical (Philippines) and mid-latitude (Japan and possibly South Korea) provenance identified in HML render it a key tephrostratigraphic type site of East Asia, providing the first integrated late Pleistocene to Holocene tephra framework for the region. The cryptotephra record of HML greatly extends the known distributions of several tephra layers in this region, including the Sz-S, K-Ah, SG14-0433 and the newly identified Pinatubo tephra. These widespread tephra layers can be traced from ~35°N Japan to ~20°N southern China, and to ~15°N Philippines (Fig. 1).

The Sz-S tephra has been widely used as an important marker bed for dating and synchronizing paleoenvironmental and archeological archives during last deglaciation in southern Japan (Moriwaki et al., 2011, 2016). Its distribution is towards the south of Sakurajima, and mainly constrained within ~200 km of the volcanic vent (Moriwaki 1992; Moriwaki et al., 2011; Albert et al., 2019). HML is ~2,350 km to the southwest of Sakurajima, and the presence of Sz-S tephra in HML indicates that its dispersal was significantly greater than previous studies have suggested, perhaps extending across a large part of East Asia (Fig. 1).

The ~7.3 ka K-Ah tephra has served as an important mid-Holocene visible isochron in Japanese terrestrial, volcanic and archeological sediments, and has been widely used to date marine sediments (e.g., East China Sea – Machida 1999; Machida and Arai 2003; Smith et al., 2013; Moriwaki et al., 2016; McLean et al., 2018). The known southwestern limit of this tephra extends to Okinawa Trough ~800 km away from Kikai (Li et al., 2019), but our recognition of this marker horizon in HML indicates that it can now be traced ~2,300 km from the volcanic vent. Although the source volcano of HGY368/SG14-0433 is not yet confirmed, the correlation of ~2.7 ka HGY368 and SG14-0433 implies that this tephra layer has been transported more than 2,900 km (from HML to Suigetsu).

Pioneering work has been carried out around Pinatubo, and various modern eruptions have been confirmed (Luhr et al., 1996; Newhall et al., 1996). The tephra from the 1991 eruption was mainly deposited in the South China Sea, and the southwestern limit of this tephra can be traced to Singapore (Wiesner et al., 1995; De Maisonnette and Bergal-Kuvikas 2020). However, there is no evidence with which to determine the extent of the tephra distributions from pre-1991 eruptions. The confirmation of Pinatubo tephra (HGY159, HGY394, HGY702 and HGY1101) in HML demonstrates for the first time that these tephra have been transported >1,000 km northwest of the volcanic vent.

These widespread tephra layers provide opportunities to interlink volcanic eruptive histories around South-east and East Asia. For example, we can now establish that the eruption that produced the HGY368/SG14-0433 tephra occurred ~300 years after the Pinatubo Maraunot period (equivalent to HGY394, section 3.2), the timing of the events not otherwise being separable on the basis of available dating evidence. The well characterized Sz-S tephra restrains the dating of the HGY995 tephra, robustly placing this event after ~12.8 ka.

4.2 Insights into Philippine volcanic eruptions

Refining volcanic histories is crucial for the assessment of volcanic hazards, and the tephrostratigraphic records of HML can help to establish a more complete eruptive history of less studied volcanoes around South-east and East Asia, and to reveal more comprehensive tephra dispersals. We present the first identifications of distal tephras from pre-1991 Pinatubo eruptions (HGY159: ~0.8 ka Buag; HGY394: ~2.9 ka Maraunot; HGY702: ~5.9 ka Crow Valley; Table 1) in southern China. In addition, we identify the ~14.4 ka HGY1101 tephra (14795–14080 cal a BP) that appears to be from an unknown Pinatubo eruption. In addition to these Pinatubo-derived tephras, three ~15–14 ka tephras (HGY1113, HGY1127 and HGY1136) possibly from southwest Luzon have also been identified, illustrating the frequency of large tropical eruptions from the Philippines.

Although we are unsure how many eruptive events occurred in each of pre-1991 Pinatubo eruptive epochs (Buag, Maraunot and Crow Valley), the HGY159, HGY394, and HGY702 tephras in HML likely represents large eruptions in each phase. The tephras are characterized by distinctive peaks, implying individual events of sufficient energy to disperse tephra widely. The Bayesian age-depth modeling of HML assigns relatively precise ages to these episodes. There is considerable debate about the timing of explosive activity in the Buag period (as early as 0.8 to 0.6 ka BP; Newhall et al., 1996; Gaillard et al., 2007; Rodolfo and Umbal 2008). The presence of HGY159 indicates at least one explosive eruption as early as ~0.8 ka, and the phase evidently endured for more than 300 years before a late dome-forming eruption at around 0.5 ka (Newhall et al., 1996; Gaillard et al., 2007). Notwithstanding two outlying dates of ~3.9 ka and ~2.3 ka, the Maraunot period is generally dated to ~3.6 to 2.7 ka (Newhall et al., 1996). The HGY394 tephra indicates one major event within the Maraunot period at ~2.9 ka. The ~5.9 ka HGY702 represents a major eruption during the Crow Valley period whose dates from proximal exposures cluster at ~6.0–5.5 cal ka BP (Newhall et al., 1996). HGY1101 similarly indicates an explosive eruption at ~14.4 ka BP. The absence of a proximal correlative of this age at Pinatubo may be due to poor tephra preservation. Overall, combining the dates of the distal tephras (~0.8 ka, ~2.9 ka, ~5.9 ka, and ~14.4 ka) with those of proximal eruptions at ~17 ka and ~9 ka, a repose interval ranging from ~3ka to ~0.8 ka with a decreasing trend in duration from late Pleistocene to late Holocene can be observed for the major Pinatubo eruptive episodes.

The improved dating of the Pinatubo eruptions identified in this study has implications for understanding volcanic impacts on global climate. The 1991 Pinatubo eruption had observable global climate impacts due to its large stratospheric loading of SO₂ which was mainly released during a major explosive phase on 15th June 1991 (McCormick et al., 1995; Newhall et al., 1996;

Self et al., 1996). The magnitudes of the pre-1991 Pinatubo eruptions that produced the tephras recorded in HML were unlikely smaller than the 1991 climactic eruption and it is highly possible that these major eruptions also released significant amounts of SO₂ into the atmosphere. It is reasonable, therefore, to expect that these earlier Pinatubo eruptions would have had climate impacts similar to or larger than the 1991 event.

4.3 Implications for tephra dispersals to southern China from South-east Asia and East Asia

Tephra dispersal can be controlled significantly by prevailing wind as well as eruption column height (Davies et al., 2010; Smith et al., 2016). The thermal contrast between sea and land leads to different prevailing wind directions during winter and summer around East Asia, which might control tephra distributions from this area (Lau and Yang 1997; Wang et al., 2005). Long distance dispersal of K-Ah, Sz-S and SG14-0433 tephras from Japan to southern China implies a northeasterly wind that today is typical of winter months. Our findings suggest potential to find tephra from older large Japanese eruptions in longer records from the region.

The same northeasterly winds do not favor the transport of Philippine tephras to southern China, suggesting that the Pinatubo and Luzon tephras were erupted during the summer months, assuming a similar climate regime since the late Pleistocene. However, we note the absence of the 1991 Pinatubo tephra in our study, that serves to highlight the complex confluence of westerlies and easterlies during onset of summer monsoon over this region or the impacts from typhoon Yunya which passed over the Philippines during the 1991 eruption (Lau and Yang 1997; Pinatubo Volcano Observatory Team 1991). The absence of tephra from the large magnitude ~9 ka Pinatubo eruption in HML may similarly be due to unfavorable meteorological conditions at the time of the event. Seasonality cannot therefore be reliably inferred from the presence or absence of cryptotephra deposits, but future tephrochronological research may help establish if ash dispersal was more prevalent in the past, that might imply shifts in atmospheric patterns.

4.4 Translatitudinal independent isochrons for linking rapid climate events

Dating uncertainties in sedimentary records frequently make it difficult to determine the synchronicity of paleoclimate events across large regions. Tephra layers identified in this study comprise an important series of time-equivalent event markers that can aid the synthesis of paleoclimate records around East Asia. For example, the Younger Dryas (YD) event has been detected in Lake Suigetsu where it is dated to 12.3–11.25 ka (Nakagawa et al., 2003) and in a previous study of HML where an age estimate of 12.8–11.6 ka was suggested (Yancheva et al., 2007). Although we cannot presently confirm that the ~12.4 ka HGY995 was from northern Japan or further along the Kurile arc, its geochemical composition indicates that it was from beyond southeast Asia and central-south Japan (Fig. 3a, b), implying that it too is likely a widely distributed tephra layer around East Asia erupted around the middle of the YD event. Like the translatitudinally distributed ~12.8 ka Sz-S tephra erupted at around the start of the YD event, it constitutes a critical independent isochron for integrating future paleoenvironmental studies

stretching from Japan to mainland China. Such linkages will facilitate a better understanding of the processes and mechanisms of the YD event across East Asia.

The co-occurrence of Japanese and Philippine derived tephras in southern China highlight the potential for future syntheses of paleoenvironmental archives from the tropical Philippines, to most parts of China, and to mid-latitude Japan. For example, the presence of the ~7.3 ka K-Ah and ~5.9 ka HGY702 tephras in southern China implies that they can be used as significant translatitudinal independent marker horizons for investigating contentious leads and lags relating to various mid-Holocene rapid events from South-east to East Asia (An et al., 2000; Zhao et al., 2009).

4.5 Implications for volcanic hazards

The discovery of widely distributed tephras in southern China (>2,000 km away from volcanic vents for Japanese tephras, and >1,000 km for Philippine tephras; Table 1) implies that these prehistoric eruptions may have frequently impacted on some of the most densely populated parts of East Asia. Tephra deposition can directly and indirectly impact on ecosystems in both positive (e.g., soil fertilization) and negative ways (e.g. physical damage to plants, chemical alteration of water bodies), the effects varying according to distance from source (e.g., Ayris and Delmelle 2012; Arnalds 2013). Very fine ash (< 10 µm) poses a threat to human health (Horwell and Baxter, 2006; Newnham et al., 2010), and can travel far from the vent. Although we did not examine the < 30 µm sediment fraction from HML, it is likely that some of tephras included a considerable amount of very fine ash, and the distal volcanic impacts should be considered in studies of past human cultures of the region. In the modern age, volcanic ash also poses a major risk to economies through its potential impact on transport infrastructure, as seen following the 2010 eruption of Eyjafjallajökull, Iceland (Budd et al., 2011). Compiling studies of these widespread tephras is a crucial step in understanding volcanic hazards, and our study provides the first recognition of the enormous area threatened by volcanic ash dispersal around East Asia.

Acknowledgments

This study was conducted as part of a Newton International Fellowship awarded to CS by the Royal Society and Newton Fund. Additional support was provided by the NSFC of China (grants 41772379, 41802253, 41561144010). Zhengtang Guo and Zhengfu Guo are thanked for their encouragement in this study, and Jinliang Gao for his help on sample preparations. We thank Paula Reimer and Takehiko Suzuki for their suggestions on age modelling and tephra correlations. We thank the anonymous reviewers for their constructive comments and suggestions, and the Editor Valerie Trouet for her handling of the manuscript. Data presented in this study are available on Figshare (<https://figshare.com/s/f0ad9ed556f1572f140c>, <https://figshare.com/s/9d96c44c82eae78d4963>).

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Figure 1. Location of Huguangyan maar lake (HML), related sites, confirmed tephra dispersals by this study, and active subaerial volcanoes (ladder shapes; GVP) around East Asia. Light blue shading represents the regional expression of the monsoon over East Asia and northern Australia (Wang et al., 2005). Luzon/Philippines represent those tephtras from the eruptions before the 1991 eruption of Pinatubo and southwest Luzon. SG represents Lake Suigetsu, Japan.

Figure 2. Tephrostratigraphy and chronology of Huguangyan maar lake (HML). Concentrations of glass shards against depth in the core of HML are shown: light gray shading refers to the number of glass shards per 0.5 gram of dried sediment in 5–10 cm increments; dark bands refer to glass shard concentrations in the 1 cm samples; and light grey dotted lines with sample codes indicate the peaks in glass shard concentration. The Bayesian age model is based upon ^{14}C dates, as well as the ages of SG14-0433 (2737–2620 cal a BP, equivalent to HGY368) and K-Ah (7307–7196 cal a BP, equivalent to HGY763) tephtras as derived from Lake Suigetsu (McLean et al., 2018).

Figure 3. Bi-plots of glass shard compositions of cryptotephtras from Huguangyan maar lake (HML), compared with published data from widely distributed tephtras in the western Pacific region. Data sources: AT (~30 ka): Smith et al., 2013; SG14-0433: McLean et al., 2018; K-Ah: Smith et al., 2013 and Albert et al., 2019; Aso-4 (~87 ka) and Kc-2/3 (Kutcharo volcano, ~85 ka): Albert et al., 2019; Sz-S: Albert et al., 2019 and Moriwaki et al., 2011; Izu-Bonin: Smith et al., 2013 and Schindlbeck et al., 2018; F1: Ku et al., 2009; 1991 PI (tephra from 1991 Pinatubo eruption): Luhr and Melson 1996, and Scaillet and Evans 1999; Toba including YTT (Younger Toba Tuff, ~74 ka) and MTT (Middle Toba Tuff, ~500 ka); Ranau (~33 ka): Natawidjaja et al., 2017; Samalas (AD 1257): Alloway et al., 2017; Krakatau (AD 1885): Mandeville et al., 1996; Mariana: Lee et al., 1995. Error bars (2SD) for the HML tephtras were calculated from secondary glass standards.

Table 1. Summary of the confirmed Late Pleistocene to Holocene tephtras within Huguangyan maar lake (HML).

Figure 1.

Figure 2.

Figure 3.

Table 1 Summary of the confirmed Late Pleistocene to Holocene tephras within Huguangyan maar lake (HML).

Tephra horizons	Depth (cm)	Modelled age (cal a BP)	Shard length (µm)	Tephra concentration (shards/0.5 g)	Glass compositions of main population (wt%)				Correlation	Eruption timings (cal a BP) ^b	Distance to source volcano (km)
					SiO ₂	FeO	K ₂ O	<i>n</i>			
HGY159 ^a	159	927–729	< 70	139	77.00–78.24	0.57–0.86	2.73–3.32	16	Pinatubo	800–476	1250 SE
HGY368	368	2965–2253	< 120	13	61.31–63.82	4.11–5.69	4.29–4.86	16	SG14-0433 (U-1?, Ulleungdo)	2737–2620	2650 NE
HGY394 ^a	394	3133–2719	< 70	58	78.25–78.77	0.51–0.75	2.62–3.05	12	Pinatubo	3875–2342	1250 SE
HGY702 ^a	702	6166–5637	< 90	44	77.73–79.47	0.82–1.15	2.76–3.96	20	Pinatubo	6079–5004	1250 SE
HGY763	763	7499–6485	< 90	36	73.94–75.76	2.33–2.75	2.58–2.70	5	K-Ah, Kikai	7307–7196	2300 NE
HGY995	995	12738–12060	< 120	105	73.74–76.28	2.30–2.82	1.69–1.88	8	Unknown	Unknown	-
HGY1026	1026	13420–12657	< 80	126	74.25–75.22	1.70–1.92	2.76–3.10	24	Sz-S, Sakurajima	~12.8 ka	2350 NE
HGY1101 ^a	1101	14795–14080	< 70	27	73.90–77.96	0.69–0.96	2.17–2.95	8	Pinatubo	Unknown	1250 SE
HGY1113	1113	15179–14346	< 80	229	69.08–70.26	4.08–4.48	3.12–3.35	12	Unknown	Unknown	-
HGY1127	1127	15493–14927	< 80	65	68.04–69.74	4.38–5.29	3.09–3.31	11	Unknown	Unknown	-
HGY1136	1136	15677–14959	< 80	14	68.89–71.08	4.01–4.70	3.33–3.61	9	Unknown	Unknown	-

^aSuggested names for the pre-1991 Pinatubo tephras: P-HGY159, P-HGY394, P-HGY702, and P-HGY1101.

^bThe known eruption timings are from McLean et al., 2018; Moriwaki et al., 2016; Newhall et al., 1996; Okuno 2002; Rodolfo and Umbal 2008.