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Short communication

Identification of the Changbaishan ‘Millennium’ (B-Tm) eruption deposit in the Lake Suigetsu (SG06) sedimentary archive, Japan: Synchronisation of hemispheric-wide palaeoclimate archives

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ABSTRACT

The B-Tm tephra, dispersed during the highly explosive Changbaishan ‘Millennium’ eruption (ca. 940–950 CE) and a key marker layer within the Greenland ice cores, has now been identified in the Lake Suigetsu (SG06) sedimentary sequence, central Japan. The major element geochemistry of the volcanic glasses within this tephra layer are compared to a new glass dataset from the distal type-locality (Tomakomai Port, Hokkaido) and other published ‘Millennium’ eruption/B-Tm deposits, to verify this correlation. The discovery of the B-Tm tephra in the Lake Suigetsu record provides, to date, the most southerly identification of this ash and, crucially, the first direct tie-point between this high-resolution, mid-latitude palaeoclimate archive and the Greenland ice cores. These findings present significant encouragement for on-going research into the tephrostratigraphy of East Asia, focusing on the identification of widely-dispersed tephra layers which can facilitate the synchronisation of disparate palaeoclimate archives and thus enable the assessment of spatio-temporal variations in past climatic change.

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1. Introduction

Our understanding of past climate systems and environmental change is formed through the comparison of numerous multi-proxy palaeoenvironmental archives. Volcanic ash (tephra) horizons have proved extremely valuable for such studies as they allow disparate sedimentary records to be precisely correlated and dated (e.g. Lane et al., 2014; Albert et al., 2015; Lowe et al., 2015; Abbott et al., 2016). Such isochronous tie-points are essential to assessing the spatio-temporal variability of major climatic events and to assess abrupt and short-lived fluctuations, controlled by driving systems such as the East Asian monsoon (EAM). The EAM is of major socioeconomic importance for the ~30% of the global population that reside in East Asia, yet its driving complexities are poorly understood and climatically modelled, partly due to limited

long-term observations (Liu and Ding, 1998; Cook et al., 2010; Ha et al., 2012). In addition, high-resolution palaeoenvironmental archives, such as the sediments of Lake Suigetsu in central Japan (Nakagawa et al., 2003, 2005), indicate that the magnitude and timing of major palaeoclimatic events do not necessarily occur synchronously with those reported in the polar and high-latitude regions. The identification of more widely-dispersed tephra layers, particularly connecting to key climate stratotypes including the Greenland ice cores, are fundamental to assessing the interplay between these regions and the forcing mechanisms of palaeomonsoon variability.

Here we outline the recent discovery of the Baegdusan-Tomakomai (B-Tm) tephra layer within the sediments of Lake Suigetsu, and thus the first direct tephra tie-point between this high-resolution, mid-latitude lacustrine palaeoclimate archive and the Greenland ice cores. This hemispheric-wide tephrostratigraphic marker is precisely dated using the Greenland (NS1-2011) chronology (Sigl et al., 2015) and therefore contributes a robust constraint to the Late Holocene sedimentation at Lake Suigetsu.

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2. Background

2.1. The B-Tm tephra

The B-Tm tephra was dispersed during the highly explosive 'Millennium' eruption of Changbaishan (also referred to as Tianchi or Baitoushan) volcano, situated on the border between China and North Korea ($128^{\circ}03'E$, $41^{\circ}00'N$) (Machida et al., 1990) (Fig. 1). This was one of the most violent eruptions of the past 2000 years, with a volcanic explosivity index (VEI) (Newhall and Self, 1982) of 7 (i.e. comparable to the 1815 CE eruption of Tambora, Indonesia).

The eruption had two explosive phases, with the initial main phase (ca. 95% by volume) associated with a ca. 25 km-high Plinian column, producing a widespread pumice fall unit (Machida et al., 1990; Horn and Schmincke, 2000). This fall unit is overlain by partially-welded pyroclastic density current (PDC) deposits attributed to the partial collapse of the Plinian column and are comenditic in composition. Trachytic magma was erupted in a late phase of the eruption, forming moderately welded PDC units, that post-date the comenditic fall and PDC deposits (Horn and Schmincke, 2000).

The B-Tm tephra was named and characterised (using glass

refractive indices and major element compositions) at a distal type-locality in Tomakomai Port, Hokkaido ($42^{\circ}39'18'N$, $141^{\circ}41'53'E$; 53 km SSE of Sapporo City), where it was identified above the Tarumai-c (ca. 50 BCE) and below the Tarumai-b (1667 CE) tephra layers (from the nearby Tarumae volcano) (Machida and Arai, 1983). The B-Tm tephra has since been identified in numerous marine, lacustrine and archaeological sequences across northern Japan, northeast China and coastal regions of Russia (Fig. 1). Moreover, a recent study found B-Tm glass shards in the Greenland ice cores, which provided a precise ice core-derived eruption age of $941 \text{ CE} \pm 1$ (Sun et al., 2014b). ^{10}Be and ^{14}C tree-ring markers have since shown that there is a seven-year offset in the Greenland ice core (GICC05) timescale, so this age for the B-Tm eruption has been corrected to 946–947 CE (NS1-2011; Sigl et al., 2015).

2.2. Lake Suigetsu (SG06) archive

The Lake Suigetsu (Fig. 1; $35^{\circ}35'0''N$; $135^{\circ}53'0''E$) SG06 sediment core provides a high-resolution palaeoenvironmental record from Honshu Island, central Japan (e.g. Tyler et al., 2010; Kossler et al., 2011; Saito-Kato et al., 2013; Schlolaut et al., 2014). The

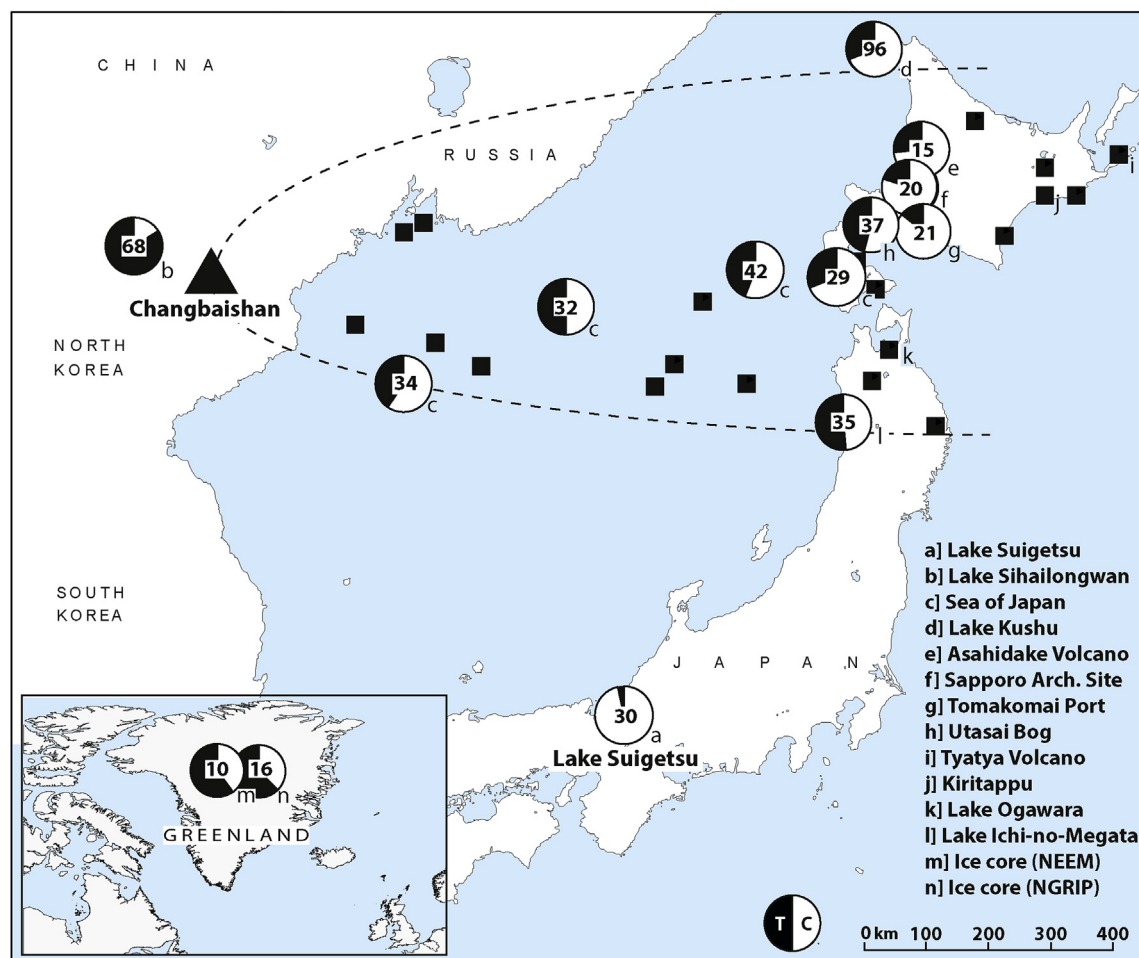


Fig. 1. Location of Changbaishan volcano (China/North Korea border), Lake Suigetsu (central Japan) and other sites that preserve the B-Tm tephra. Pie charts indicate the proportion of trachytic (black) and comenditic (white) glasses in sites where there is sufficient major element glass data published to form a meaningful assessment of correlation ($n > 10$; shown in the middle of each chart; n = number of shards). Squares represent sites that report the B-Tm tephra, based on physical characteristics of the unit, but with limited or no glass geochemical data. Dispersal boundaries (dashed line) for the B-Tm as previously mapped by Machida and Arai (1983). References: (a) this study; (b) Sun et al. (2015); (c) Furuta et al. (1986); Machida and Arai (1983); (d) Chen et al. (2016); (e) Wada et al. (2001); (f) Nakamura (2016); (g) this study; (h) Hughes et al. (2013); (i) Nakagawa et al. (2002); (j) Nanayama et al. (2003); (k) Fukusawa et al. (1998); (l) Okuno et al. (2011); (m) Sun et al. (2014b); (n) Coulter et al. (2012).

73.19 m-long composite core was extracted as part of the 'Suigetsu Varves 2006' project, and provides a continuous record of sedimentation spanning the last ca. 150 ka (Nakagawa et al., 2012). The sequence is annually laminated (varved) between ca.10 and 70 ka and has been extensively radiocarbon (^{14}C) dated and varve counted to generate a high-resolution chronology (Staff et al., 2011; Bronk Ramsey et al., 2012; Marshall et al., 2012; Scholaut et al., 2012) for this palaeoenvironmental record.

Hitherto, 31 visible tephra layers from SG06 have been identified and characterised (using major element geochemical analysis),

and provide a detailed record of Japanese and Korean eruption events (Smith et al., 2013). Due to the prevailing westerlies, tephra is largely dispersed northeast across this region. As Changbaishan is located northwest of Lake Suigetsu, coupled with the strong easterly dispersal of the eruptive plume implied from ash thicknesses (Fig. 1), the presence of a B-Tm ash layer in the sediments was previously considered unlikely. However, given its widespread distribution and recent ultra-distal identification in the Greenland ice cores (Fig. 1), the Lake Suigetsu sediments were carefully re-examined in order to attempt to identify this key tephra marker.

Table 1

Results of the WDS-EPMA normalised glass compositions of the SG06-0226 tephra layer and of the B-Tm distal type-site deposits at Tomakomai Port.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	CaO	Na ₂ O	K ₂ O	Cl	Analytical total
SG06-0226	74.96	0.18	10.23	3.99	0.22	5.34	4.46	0.51	97.99
	74.95	0.26	10.14	3.97	0.24	5.43	4.40	0.52	97.90
	74.83	0.26	10.30	4.20	0.23	5.29	4.41	0.48	98.03
	75.14	0.19	10.17	4.02	0.23	5.34	4.35	0.46	97.31
	75.06	0.18	10.18	4.02	0.22	5.45	4.33	0.50	97.38
	74.89	0.23	10.32	3.97	0.23	5.51	4.21	0.49	97.36
	75.17	0.24	10.18	3.95	0.23	5.19	4.43	0.48	96.97
	74.84	0.21	10.22	3.92	0.18	5.71	4.40	0.46	97.35
	74.57	0.19	10.28	4.27	0.18	5.51	4.44	0.50	97.59
	74.85	0.19	10.53	3.90	0.21	5.33	4.38	0.47	97.15
	74.84	0.19	10.22	4.05	0.21	5.53	4.31	0.50	96.91
	74.65	0.28	10.28	4.19	0.20	5.42	4.27	0.52	96.88
	75.20	0.23	10.19	4.19	0.24	5.12	4.22	0.49	96.17
	74.87	0.29	10.39	3.98	0.29	5.19	4.35	0.50	96.56
	74.67	0.23	10.31	4.10	0.24	5.49	4.43	0.48	96.72
	74.96	0.19	10.22	3.99	0.19	5.48	4.25	0.50	96.33
	74.89	0.23	10.28	4.06	0.22	5.42	4.30	0.48	96.39
	74.80	0.24	10.30	4.27	0.23	5.33	4.27	0.50	96.42
	75.04	0.17	10.19	4.20	0.21	5.20	4.41	0.46	95.89
	75.49	0.20	10.20	3.72	0.22	5.09	4.44	0.48	95.12
	74.80	0.23	10.39	3.91	0.24	5.46	4.27	0.52	95.83
	74.94	0.25	10.25	4.28	0.21	5.26	4.21	0.52	95.38
	75.08	0.20	10.24	4.05	0.19	5.27	4.45	0.44	94.53
	75.06	0.20	10.25	4.20	0.21	5.17	4.42	0.47	94.55
	74.61	0.27	10.43	3.73	0.23	5.62	4.44	0.56	94.93
	74.55	0.26	10.30	4.13	0.22	5.36	4.50	0.51	94.98
	74.61	0.23	10.49	4.06	0.23	5.16	4.55	0.54	94.05
	74.88	0.18	10.23	4.02	0.23	5.45	4.48	0.51	93.48
	74.73	0.20	10.16	4.17	0.23	5.34	4.48	0.52	93.22
	65.14	0.57	16.10	4.55	1.48	5.41	6.15	0.10	96.87
Average (n = 30)	74.57	0.23	10.47	4.07	0.26	5.36	4.43	0.48	
1σ	1.79	0.07	1.07	0.17	0.23	0.15	0.34	0.08	
SG06-0226 outliers	77.50	0.18	12.61	1.22	1.11	3.75	3.27	0.12	94.00
	73.86	0.48	12.97	2.45	1.95	3.08	4.35	0.14	98.28
Tomakomai Port	74.80	0.18	10.46	3.98	0.25	5.36	4.31	0.59	93.49
	75.27	0.22	10.65	3.92	0.25	4.80	4.31	0.52	96.91
	74.51	0.23	10.65	4.08	0.31	5.29	4.36	0.47	97.88
	75.13	0.18	10.51	4.08	0.27	4.98	4.26	0.47	99.41
	67.33	0.44	15.00	4.65	1.20	5.90	4.98	0.19	98.78
	74.88	0.21	10.51	3.87	0.25	5.28	4.37	0.50	97.90
	74.97	0.23	10.58	3.98	0.23	5.25	4.19	0.48	97.73
	74.41	0.25	10.86	3.85	0.30	5.07	4.62	0.52	97.82
	74.47	0.23	11.08	3.90	0.33	5.09	4.31	0.50	98.54
	75.08	0.20	10.59	3.97	0.23	5.10	4.21	0.55	96.35
	74.67	0.17	10.35	4.26	0.32	5.29	4.29	0.59	95.24
	74.10	0.28	10.90	4.14	0.28	5.34	4.44	0.47	98.96
	74.53	0.26	10.72	3.99	0.22	5.20	4.49	0.49	97.22
	74.46	0.25	10.54	4.11	0.30	5.31	4.41	0.56	93.69
	67.05	0.36	15.02	4.62	1.05	6.04	5.43	0.17	98.60
	69.91	0.30	13.66	4.26	0.59	5.81	5.12	0.31	94.54
	73.95	0.19	10.68	4.09	0.29	5.82	4.37	0.51	97.36
	75.01	0.18	10.40	4.05	0.26	5.08	4.41	0.48	96.71
	74.68	0.20	10.42	4.11	0.24	5.27	4.51	0.46	97.60
	74.62	0.20	10.35	3.96	0.24	5.51	4.50	0.51	96.90
	74.20	0.25	10.71	4.12	0.29	5.44	4.49	0.47	97.79
Average (n = 21)	73.72	0.24	11.17	4.09	0.37	5.34	4.49	0.47	
1σ	2.43	0.07	1.45	0.21	0.26	0.32	0.31	0.11	

The data have been filtered to remove analyses of a <93% analytical total; MgO, MnO and P₂O₃ values are below the statistical detection threshold and have been removed (see supplementary material).

3. Materials and methods

3.1. Sampling and laboratory procedures

A new, thin ash layer (<1 mm) was observed within overlapping core sections of the SG06 sequence at a composite depth (CD) of 225.5 cm (the CD was determined using the 20 April 2015 version of the correlation model; see Nakagawa et al., 2012 for more details). Herein, this tephra is labelled as SG06-0226. A subsample was extracted from core section D-01 at 104.7cm depth and wet sieved using distilled water through a 25 μm mesh. Microscopic examination identified an abundant concentration of colourless glass shards with a distinct, highly vesicular morphology. These were handpicked using a micromanipulator (Lane et al., 2014) and mounted in epoxy resin for geochemical analysis. To confirm the stratigraphic positioning of the peak, cryptotephra analysis was performed in sediments above and below the layer. A sample of the B-Tm tephra from its type-locality at Tomakomai Port was also prepared for geochemical analysis to verify the correlation.

3.2. Compositional analysis

Major and minor element glass compositions were measured using a JEOL-8600 wavelength-dispersive electron microprobe (WDS-EPMA) at the Research Laboratory for Archaeology and History of Art, University of Oxford. All analyses were performed

using an accelerating voltage of 15 kV, beam current of 6 nA and 10 μm -diameter beam. The electron microprobe was calibrated using a suite of mineral standards, and the PAP absorption correction method was used for quantification. The precision and accuracy of these analyses were assessed using the MPI-DING reference glasses (Jochum et al., 2006), which were run with our samples. All data comparisons are based on normalised glass compositions.

4. Results and discussion

4.1. Geochemical results

The geochemical analyses of glass shards from the SG06-0226 layer and from the B-Tm type-locality (Tomakomai Port) are shown in Table 1 and selected bi-plots in Fig. 2. Volcanic glasses erupted from the Changbaishan volcano can be easily discriminated from those originating from volcanic centres in Russia (Kamchatka), South Korea and along the Japanese arc (Fig. 2a). The eruption that produced the B-Tm tephra tapped both comenditic and trachytic magma batches, with particularly alkali-enriched compositions. The SG06-0226 dataset includes two outliers, which have the same composition as other shards present in low concentrations throughout some other sections of the core and are considered to be background material. These outlier glass compositions are chemically distinct from the B-Tm tephra and clearly erupted from a Japanese volcano (Fig. 2a), so are therefore not discussed further.

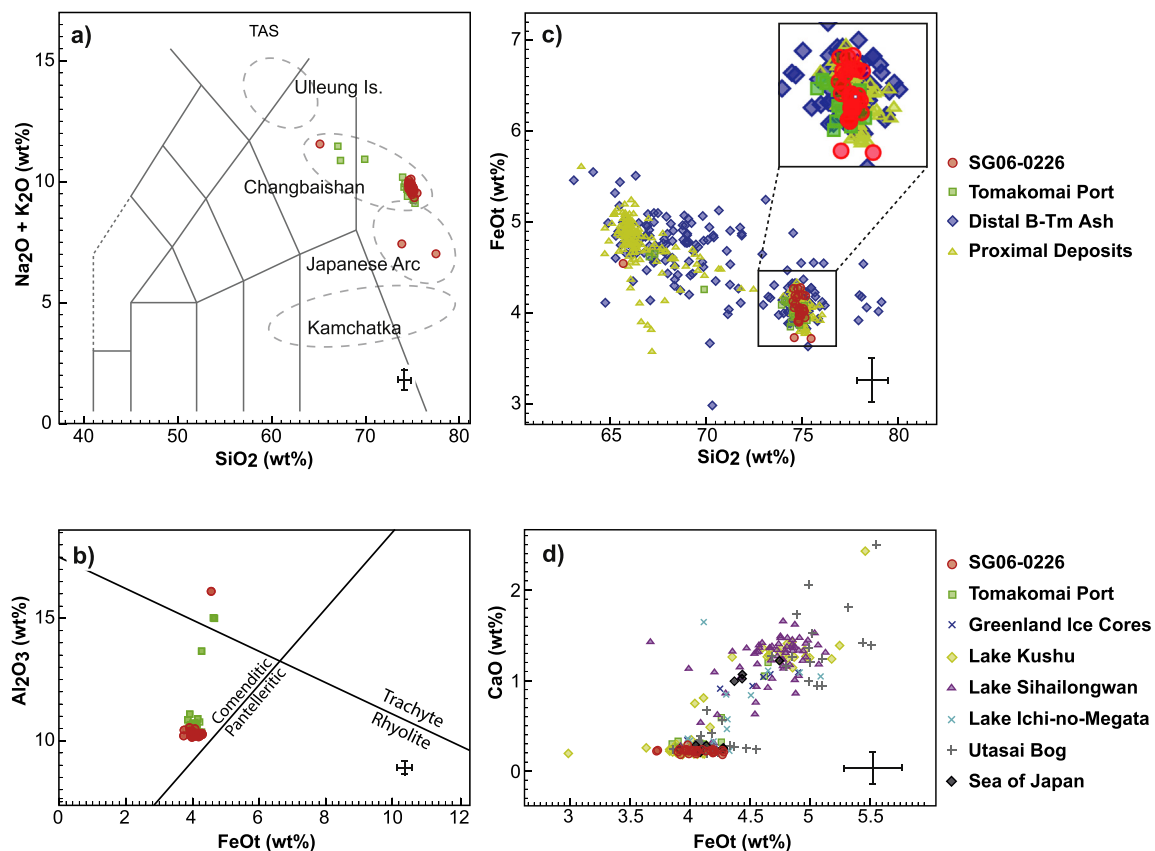


Fig. 2. Major element glass compositions of the SG06-0226 tephra (red circles) and the B-Tm type-locality from Tomakomai Port (green squares) (a) Total alkalis versus silica plot (TAS; Le Bas et al., 1986) showing the glass composition of Changbaishan tephra relative to those from Ulleung Island (Smith et al., 2013), volcanoes in the Japanese arc (Smith et al., 2013), and Kamchatka (Kyle et al., 2011); (b) peralkaline classification diagram (McDonald, 1974); (c) the composition of glass shards from proximal Changbaishan 'Millennium' eruption deposits (Guo et al., 2002; Zou et al., 2010; Sun et al., 2014b, 2015; Chen et al., 2016) and composite published distal B-Tm data (Furuta et al., 1986; Okuno et al., 2011; Coulter et al., 2012; Hughes et al., 2013; Sun et al., 2014b, 2015; Chen et al., 2016); (d) the glass composition of distal B-Tm units compared to that of the SG06-0226 glasses. Error bars represent 2 x standard deviation of repeat analyses of the SThs6/80-G MPI-DING standard glass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The SG06-0226 glasses are compositionally heterogeneous, with SiO₂ ranging from 65.14 to 75.49 wt%, CaO from 0.18 to 1.48 wt%, FeOt (all Fe as FeO) from 3.72 to 4.55 wt% and K₂O from 4.21 to 6.15 wt% (n = 30). The deposit is dominated by a comenditic glass component (Fig. 2), with a single glass shard showing a trachytic composition. The comenditic glasses contain a lower Al₂O₃ (ca. 10 wt%) and FeOt (ca. 4.0 wt%) content compared to the single trachytic glass shard (Fig. 2b). The glass compositions of SG06-0226 are consistent with the new glass data from the B-Tm type-locality at Tomakomai Port, confirming they are the same tephra. The new Tomakomai Port dataset also contains compositions that lie on a mixing line between the comenditic and trachytic end members of the SG06-0226 tephra, which suggests that the two distinct magma batches were in contact before the eruption.

The geochemistry of the SG06-0226 and Tomakomai Port glasses are also consistent with published data for proximal Changbaishan 'Millennium' eruption deposits (Fig. 2c) and other distal/ultra-distal B-Tm glass compositions, including those preserved in the Greenland ice cores (Fig. 2d). The glass compositions of the tephra at these distal sites provide information on the spatial distribution of the different phases of the Changbaishan 'Millennium' eruption (Fig. 1). Given that the trachytic compositions were erupted in the late PDC phase of the eruption, the dispersal of glass with such compositions to the distal sites must have been via the plume that lofted off the top of the PDCs, i.e., a co-PDC plume. The compositions from the sites directly to the east of Changbaishan are predominately comenditic (ca. 50–80%), and therefore mostly associated with the Plinian column or the co-PDC plume associated with the PDC generated during the collapse of the Plinian column, or both. These sites also have a trachytic component (ca. 15–50%) implying that the dispersal axis for the late co-PDC plume was also to the east. The compositions of glass shards from sites northwest of the vent are mostly trachytic, implying that these glasses were deposited from the co-PDC plume. Glass shards in SG06-0226 are almost entirely comenditic in composition and associated with the Plinian column and the co-PDC associated with its collapse, and indicate that the late phase trachytic co-PDC plume did not disperse tephra towards the south. The trachytic compositions are more dominant in the Greenland ice cores implying that the tephra was mostly transported ultra-distally (~7000 km from vent) via the co-PDC plume. This inference is consistent with some studies of other large explosive eruptions that show that the ultra-distal transport of tephra is largely associated with co-PDC plumes (e.g., Campanian Ignimbrite eruption, Smith et al., 2016; Younger Toba Tuff, Costa et al., 2014).

4.2. Age-depth modelling

The age model for the SG06 sedimentary sequence (Staff et al., 2011) was constructed using a Bayesian Poisson-process 'P_Sequence' depositional model in OxCal (ver. 4.2; Bronk Ramsey, 2008, 2016), and the IntCal13 calibration curve (Reimer et al., 2013) (Fig. 3). This model includes 124 AMS ¹⁴C dates obtained from terrestrial plant macrofossils from the non-varved Holocene part of the core (Staff et al., 2011). An age of 880–956 cal. CE (95.4% confidence) was obtained for the SG06-0226 tephra, consistent with other published dates for the 'Millennium' eruption (see Sun et al., 2014a). The lack of varved sedimentation throughout the late Holocene means that this SG06-derived age is not as precise as those reported elsewhere. We are, however, able to import the NS1-2011 age of 947 CE ± 1 (Sigl et al., 2015) into the Lake Suigetsu age model, thus further constraining the chronology of the upper part of SG06. This imported ice-core-based age will significantly improve the chronological analysis of proxy palaeoenvironmental data and any subsequent cryptotephra layers identified in the Suigetsu sediments within this timeframe.

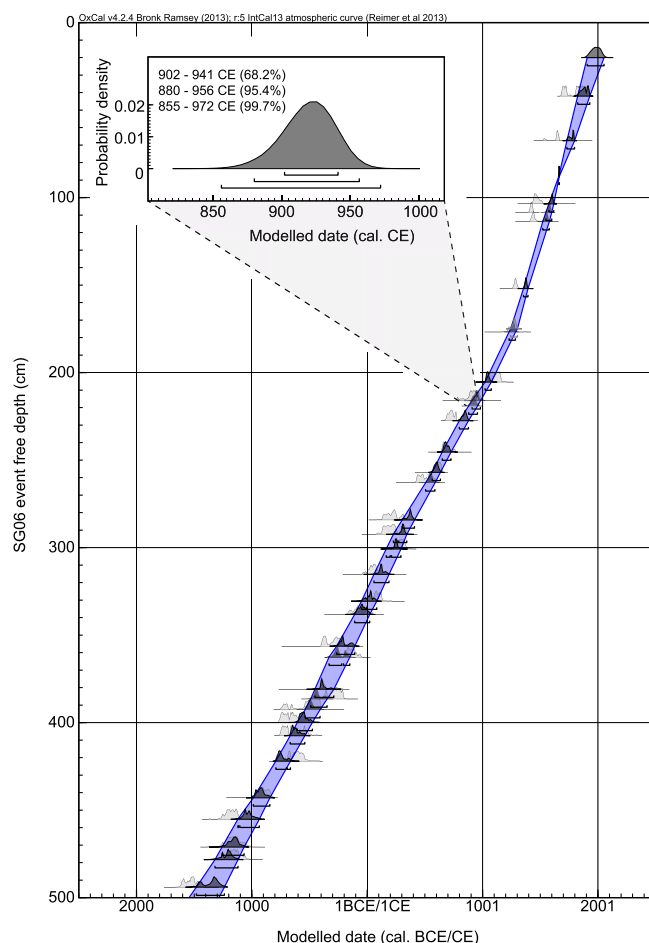


Fig. 3. The age-depth model for the upper 5 m of the SG06 core (after Staff et al., 2011). The blue envelope represents the 95.4% probability range. Inset: posterior probability density function (PDF) generated for the deposition of the SG06-0226 tephra, located at 219.1 cm event-free CD (determined using 29 Jan. 2011 version of the event-free depth model). The bars underlying the PDF represent the 68.2%, 95.4% and 99.7% probability ranges, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Implications

5.1. Palaeoenvironmental potential for the B-Tm tephra

The stratigraphic positioning of the B-Tm tephra holds significant potential to help constrain late Holocene climatic variations, such as the onset of the Medieval Warm Period (ca. 900–1300 CE). Although this warming episode has been identified in numerous global paleoclimate proxy records, its spatio-temporal variability and regional magnitude is intensely debated (Broecker, 2001; Hunt, 2006). Once high-resolution palaeoenvironmental proxy data from Lake Suigetsu are obtained from this interval, the dynamics of such rapid and short-lived climatic episodes can be evaluated. Our discovery may also encourage others to look for the B-Tm tephra in other key palaeoenvironmental records, including sites further south.

5.2. Future potential

This study provides the first direct tephra tie-point between a high-resolution, mid-latitude palaeoclimate archive (Lake Suigetsu sediments) and the Greenland ice cores, a major goal of research communities examining palaeoenvironmental change (e.g.

INTIMATE; Lowe et al., 2015; Blockley et al., 2014). This discovery therefore provides significant encouragement for the on-going research into refining the tephrostratigraphy of East Asia, research which aims to establish more hemispheric-wide tephra tie-points suitable for the synchronisation of key palaeoclimate archives.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2016.08.022>.

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