~5.9 cal ka BP Towada-Chuseri tephra from Towada volcano: A mid-Holocene marker layer from Japan to northeast China

~5.9 cal ka BP Towada-Chuseri tephra from Towada volcano: A mid-Holocene marker layer from Japan to northeast China

Journal:	*Journal of Quaternary Science*
Manuscript ID	JQS-21-0076.R1
Wiley - Manuscript type:	Rapid Communication
Date Submitted by the Author:	21-Jul-2021

Complete List of Authors:	Sun, Chunqing; Institute of Geology and Geophysics Chinese Academy of Sciences Plunkett, Gill; Queen's University Belfast, Geography, Archaeology and Palaeoecology Zhu, Zeyang; Institute of Geology and Geophysics Chinese Academy of Sciences Zhang, Lei Zhang, Bin; Institute of Geology and Geophysics Chinese Academy of Sciences Zhang, Di; Institute of Geology and Geophysics Chinese Academy of Sciences Mao, Qian; Institute of Geology and Geophysics Chinese Academy of Sciences You, Haitao Wang, Lou; Institute of Geology and Geophysics, Chinese Academy of Sciences, Chu, Guoqiang; Chinese Academy of Sciences, Liu, Jiaqi; Institute of Geology and Geophysics Chinese Academy of Sciences

Keywords:	Towada, Tephra, Cryptotephra, To-Cu, Gushantun

~5.9 cal ka BP Towada-Chuseri tephra from Towada volcano: A mid-Holocene marker layer from Japan to northeast China

Chunqing Sun[a,b,c*], Gill Plunkett[b], Zeyang Zhu[a,c], Lei Zhang[d], Bin Zhang[a,c], Di Zhang[e], Qian Mao[e], Haitao You[f], Luo Wang[a,c], Guoqiang Chu[a,c], Jiaqi Liu[a,c]

[a]Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

[b]Archaeology and Palaeoecology, School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK

[c]Innovation Academy for Earth Science, Chinese Academy of Sciences, Beijing 100029, China

[d]Key Laboratory of Active Tectonics and Crustal Stability Assessment, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China

[e]State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

[f]Key Laboratory of Computational Geodynamics of Chinese Academy of Sciences, College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China

[*]Corresponding author: C. Sun (suncq@mail.iggcas.ac.cn)

Abstract

Far-travelled ash layers from explosive volcanic eruptions can provide invaluable marker horizons for dating and correlating regional to global sedimentary archives. Here, we present a new cryptotephra associated with the ~5.9 cal ka BP Towada Chuseri eruption (To-Cu) in a peat sediment record from northeast China. This tephra exhibits a rhyolitic glass composition that can be distinguished from other widespread tephra layers around the region of Japan and northeast China. Our findings extend the known range of this ash significantly, making it now traceable about 1,200 km from its source, Towada volcano, Japan. Notably, this tephra provides an important isochron for synchronizing palaeoenvironmental studies during the mid-Holocene period from the western Pacific, central Japan, Japan Sea, and northeast China.

1. Introduction

Volcanic ash can form regional to global time-equivalent marker horizons, and thus provide a unique dating method for synchronizing studies of regional palaeoclimatic and palaeoenvironmental archives (Lowe 2011). The development of cryptotephra (invisible volcanic ash) analysis has extended the applications of tephrochronology to ultra-distal regions several thousand kilometers away from the volcanic vent, yielding trans-continental marker horizons (Bourne et al., 2016; Cook et al., 2018; Jensen et al., 2014; Lane et al., 2013; Mackay et al., 2016; Pyne-O'Donnell et al., 2016; Sun et al., 2014, 2021; van der Bilt et al., 2017). Japan has one of the largest number of subaerial volcanoes of the Earth, and explosive volcanic eruptions are very frequent here (Machida 2002). Tephras of Japanese origin have been identified in ultra-distal regions; for example, Hokkaido and Tohoku tephras have been reported from eastern North America and Greenland ice cores (Bourne et al., 2016; Mackay et al., 2016). Sun et al. (2021) found tephras from the ~7.3 cal ka BP Kikai and ~12.8 cal ka BP Sakurajima eruptions in Huguangyan Maar Lake in southern China. However, whether Japanese tephras can be traced across northeast China is still unknown, and due to limited applications of tephrochronology in this region.

In this study, we demonstrate the potential for long-distance sedimentary linkages through the identification of a Japanese tephra in Gushantun peat sediment from northeast China. Its glass shard composition indicates that corresponds to the ~5.9 cal ka BP Towada-Chuseri (To-Cu) eruption. The occurrence of distal To-Cu tephra in continental northeast China, >1,200 km away from the volcanic vent, implies that this tephra can be used to link palaeoclimatic records from central Japan's Lake Suigetsu to northeast China, and it can potentially be used as a mid-Holocene dating horizon within marine sediments from the Japan Sea.

2. Material and methods

2.1 Study site

Our study site, Gushantun bog (42°18′ N, 126°17′ E; Fig.1), is located in the Huinan Country of Jilin Province, western flank of the Changbai Mountains. The bog is about 1 km in diameter, and is surrounded by a basaltic platform. Peat sediments were collected from near the center of the bog using a Russian peat corer to a depth of 6.45 m. The section of sediment used in this study (2.70– 4.20 m) consists of fibrous peat with some plant remains.

2.2 Tephra separation

The cryptotephra separation method developed by Turney (1998) and Blockley et al. (2005) was used in this study. First, contiguous 10 cm intervals were burned at 550 ℃ for 4 hours, and then sieved through 80 and 30 μm meshes, retaining the fraction 30–80 μm. Secondly, 2.15 g/cm^3 and 2.5 g/cm^3 sodium polytungstate (SPT) was used to float glass shards from the sediments. A polarizing microscope was used to check for the presence of glass shards. Where shards were located, further samples were prepared at 1 cm sampling resolution; these samples were treated using the same approach to determine the peak concentration of glass shards. Further samples from levels corresponding to shard concentration peaks were treated using acid digestion (Dugmore et al., 1992) to remove organic materials in preparation for major element geochemical analysis. Samples were mounted on glass slides and covered in Buehler EpoxyCure2 resin, which were then ground and polished to expose fresh glass surfaces for electron microprobe analysis (EPMA).

2.3 Geochronology

Plant remains were hand-picked and submitted for accelerator mass spectrometry (AMS) ^{14}C dating to the Beta Analytic Radiocarbon Laboratory, Florida, USA (Table 1; Fig. 2A, 2B). A Bayesian age-depth model was established using the P-sequence depositional model in OxCal 4.4 (Bronk Ramsey 2008; 2009) with the IntCal20 calibration dataset (Reimer et al., 2020).

2.4 Geochemical analysis

We measured major and minor element oxide concentrations using wavelength dispersive spectrometer electron microprobe analysis (WDS-EPMA) on a JEOL JXA 8100 at the State Key Laboratory of Lithospheric Evolution of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing. Ten elements (Na, Mg, Al, Si, K, Ca, Fe, Ti, Mn, and P) were analyzed with an accelerating voltage of 15 kV, a beam current of 6 nA, and a beam diameter of 5 μm. The Na content was determined at the start of the analysis, and peak counting times used were 20 s for all elements except for Na (10 s). Secondary standard glass of MPI-DING including ATHO-G and StHs6/80-G were used to check the precision and accuracy of the data (Jochum et al., 2006). Data presented in figures have been normalized to an anhydrous basis.

3. Results and discussion

A cryptotephra layer with 160 shards/0.5g dry sediments was identified at a depth of 314 cm in the Gushantun core, and thus the tephra layer was labelled GST-314. This tephra layer is composed of colourless and vesicular glass shards (Fig. 2C), of which seven were analyzed. All glass shards exhibit a consistent rhyolitic composition, with SiO_2 concentrations ranging from 73.59 to 75.48 wt%, and low

K_2O concentration (1.11 to 1.26 wt%) (Table 2, Fig. 3, Fig. 4). The age of GST-314 is constrained by the age model to between 6030 and 5676 cal a BP (95% probability).

To identify the source of GST-314, we considered the geochemical compositions of tephra from the surrounding volcanic region. Gushantun bog is located in the Longgang volcanic field (LVF), and the composition of the volcanic products from this region is basaltic with no known silicic products (e.g., Fan et al., 2000; Liu et al., 2009; Sun et al., 2016). Therefore, the rhyolitic GST-314 tephra was not from a local eruption of the LVF. Changbaishan volcano on the border between China and North Korea, ~120 km to the west, experienced frequently felsic volcanic eruptions during the Quaternary period (Chen et al., 2016; Liu et al., 2015; Sun et al., 2014, 2017, 2018; Yi et al., 2021; Zhang et al., 2018). However, Changbaishan tephras predominantly with trachytic and rhyolitic glass compositions exhibit higher potassium content than GST-314, which excludes it as the source (Fig. 3). Ulleungdo is a Quaternary volcanic island in the Japan Sea that is known to have produced many explosive eruptions (Kim et al., 2014; McLean et al., 2018, 2020), including the U2 tephra (5681–5619 cal a BP) which has a similar age to GST-314. With an even higher potassium content than the Changbaishan tephras, Ulleungdo can also be ruled out as the source for the GST-314 tephra (Fig. 3).

Considering other coincident large explosive (volcanic explosivity index: VEI >5) eruptions from southeast to east Asia that have widespread tephra dispersals, there are also some potential source candidates for GST-314: the 7307–7196 cal a BP Kikai-Akahoya eruption (K-Ah, Kikai volcano, Japan), the 6079–5004 cal a BP Pinatubo (Philippines) eruption, the 4894–4827 cal a BP SG14-0704 tephra recorded in Lake Suigetsu (unknown eruption), the 7340–7180 cal a BP KS_2 tephra from Ksudach caldera (Russia), the 6375–6220 cal a BP IAv12 (AV_4) tephra from Avachinsky volcano (Russia), the 7920–7620 cal a BP KHG tephra from Khangar volcano (Russia), and the 5986–5899 cal a BP Towada-Chuseri eruption (To-Cu, Towada volcano, Japan) (Ishimura and Hiramine 2020; McLean et al., 2018; Plunkett et al., 2015; Ponomareva et al., 2017; Portnyagin et al., 2020; Smith et al., 2013; Sun et al., 2021). Geochemically, the GST-314 tephra has a diagnostic glass composition with low potassium content and high silicon content which is consistent only with the To-Cu tephra and clearly separable from other broadly contemporary tephras (Fig. 3 and Fig. 4). Consequently, on the basis of comparable glass composition and eruptive age, we attribute GST-314 in Gushantun bog to the To-Cu eruption.

Towada is an active volcano located in northern Tohoku, Honshu Island, northeast Japan (Fig. 1). The Towada-Chuseri (To-Cu, ~5.9 cal ka BP) and Towada-a (To-a, AD 915) tephras were produced by the largest volcanic events of Towada during the Holocene. The To-Cu eruption has been attributed a VEI of 5 based on a total estimated tephra volume of 9.18 km^3 (Hayakawa, 1985; Newhall and Self 1982). To-Cu can be divided into three units: Chuseri pumice (Cu), Kanegasawa pumice (Kn), and Utarube ash (Ut), of which the Cu pumice is the lowermost bed and most widely distributed (Hayakawa, 1985; Ishimura and Hiramine 2020). While there is some overlap in their glass composition, Ishimura and Hiramine (2020) have shown that the units are separable on the basis of shard morphology and major element geochemistry, especially Ut, the youngest unit which is the product of phreatic eruptions. On the basis of previous investigations, To-Cu dispersal was mainly towards the south of Towada, and tephra has been identified in various sedimentary archives, the most distal occurrence being in Lake Suigetsu ~700 km southwest of the vent (Hirose et al., 2014; Ishimura et al., 2017; Kariya et al., 2016; McLean et al., 2018). The GST-314 tephra exhibits a homogeneous glass composition which cannot be separated from the Cu and Kn pumices and which is also similar to the records in Lake Suigetsu (Fig. 4), but it does not show the heterogeneous geochemistry of the Ut ash. Therefore, the GST-314 tephra is likely related to the pyroclastic fall deposits (Cu or Kn) of the To-Cu eruption rather than its late stage phreatic eruption (Ut).

^{14}C dating has been widely used to constrain the eruptive timing of To-Cu: for example, charcoal within the tephra deposit yielded an age of 5390 ± 140 BP (GaK-9761, 6487–5898 cal a BP, 95% probability, calibrated using IntCal20) (Hayakawa 1983). Recently, the identification of the tephra in Lake Suigetsu has enabled a precise age of 5986–5899 cal a BP (95% probability) to be attributed to this eruption based on varve chronology combined with ^{14}C dating (Bronk Ramsey et al., 2012; McLean et al., 2018; Staff et al., 2011). The precisely constrained Lake Suigetsu age makes this tephra a valuable age marker in sedimentary sequences. When we apply the Suigetsu age of To-Cu to the Gushantun age-model, age uncertainty is reduced considerably during this period (Fig 2B).

During the Holocene, major tephras reported from Japan Sea marine sediments are mainly visible beds (e.g., Furuta et al., 1986; Machida 2002), amongst which ash from ~7.3 cal ka BP K-Ah and AD 946 Changbaishan Millennium Eruption (B-Tm) are the most commonly reported layers (Furuta et al., 1986; Machida 2002). The presence of To-Cu in northeast China increases the known dispersal of this tephra to more than 1,200 km from the vent, and suggests that it too may have been deposited in the Japan Sea, but perhaps only as cryptotephra. The To-Cu tephra also was found in marine sediments from the Pacific coast of the Tohoku region (Ikehara et al., 2017). Thus, it can provide a high-precision mid-Holocene age marker linking the western Pacific Ocean, central and north Japan, very likely the Japan Sea, and northeast China (Fig. 1).

The isopachs of proximal To-Cu deposits show a mainly eastern distribution (Hayakawa 1985). However, identification of this tephra in distal sedimentary archives from central Honshu confirms a southwestern dispersal (Ikehara et al., 2017; Ishimura et al., 2017; Ishimura and Hiramine 2020; Kariya et al., 2016; McLean et al., 2018). The finding of To-Cu in northeast China now also shows that tephra was transported to the west during this eruption. Most tephras around northeast Asia have eastern dispersals, reflecting the prevailing westerly winds in the region (Lane et al., 2017; Machida 2002). During the summer season, however, the Asian Summer Monsoon brings wind from the Pacific Ocean towards the Asian continent. This weather pattern is consistent the south-westerly dispersal of To-Cu tephra. Consequently, the eruptive season of To-Cu is unlikely to be winter, assuming a similar weather pattern as today.

4. Conclusions

Our discovery of the ~5.9 cal ka BP To-Cu tephra in Gushantun bog, northeast

China, extends the known dispersal of this tephra to ~1,200 km west of Towada. Its presence in China suggests that it can be used as a mid-Holocene age marker horizon for various sedimentary archives in the wider region that will facilitate the dating and synchronization of mid-Holocene palaeoenvironmental records around northeast Asia. The tephra also raises the possibility that other tephra layers of Japanese origin may be detected here, emphasizing the potential for cryptotephrochronological applications across northeast Asia.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (grants 42072329, 41802253). Part of the work was undertaken while CS held a Newton International Fellowship at Queen's University Belfast. Prof. Karoly Nemeth and an anonymous reviewer are thanked for their constructive reviews.

References

Abbott, P. M., B. J. L. Jensen, et al. (2020). "Crossing new frontiers: extending tephrochronology as a global geoscientific research tool." Journal of Quaternary Science 35: 1-8.

Blockley, S. P. E., S. D. F. Pyne-O'Donnell, et al. (2005). "A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments." Quaternary Science Reviews 24: 1952-1960.

Bourne, A. J., P. M. Abbott, et al. (2016). "Underestimated risks of recurrent long-range ash dispersal from northern Pacific Arc volcanoes." Scientific Reports 6: 29837.

Bronk Ramsey, C., R. A. Staff, et al. (2012). "A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr B.P." Science 338: 370-374.

Bronk Ramsey, C. (2008). "Deposition models for chronological records." Quaternary Science Reviews 27: 42-60.

Bronk Ramsey, C. (2009). "Bayesian analysis of radiocarbon dates." Radiocarbon 51: 337-360.

Chen, X.-Y., S. P. E. Blockley, et al. (2016). "Clarifying the distal to proximal tephrochronology of the Millennium (B-Tm) eruption, Changbaishan Volcano, northeast China." Quaternary Geochronology 33: 61-75.

Cook, E., M. Portnyagin, et al. (2018). "First identification of cryptotephra from the Kamchatka Peninsula in a Greenland ice core: Implications of a widespread marker deposit that links Greenland to the Pacific northwest." Quaternary Science Reviews 181: 200-206.

Dugmore, A. J., A. J. Newton, et al. (1992). "Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland." Journal of Quaternary Science 7: 173-183.

Fan, Q., J. Sui, et al. (2000). "Petrology and Ggeochemistry of Jinlongdingzi Aactive volcano—the most Rrecent basaltic explosive volcano at Longgang." Chinese Journal of Geochemistry 19: 312-317.

Furuta, T., K. Fujioka, et al. (1986). "Widespread submarine tephras around Japan — Petrographic and chemical properties." Marine Geology 72: 125-142.

Hayakawa, Y. (1983). "Chuseri tephra formation from Towada volcano, Japan." Bulletin of the Volcanological Society of Japan 28: 263-273.

Hayakawa, Y. (1985). "Pyroclastic geology of Towada volcano." Bulletin of the Earthquake Research Institute, University of Tokyo 60: 507-592.

Hirose, K., Y. Nagahashi, et al. (2014). "Lithostratigraphy and dating of lacustrine sediment core (INW2012) from Lake Inawashiro-ko, Fukushima Prefecture, Japan." The Quaternary Research (Daiyonki-Kenkyu) 53: 157-173.

Ikehara, K., K. Usami, et al. (2017). "Three important Holocene tephras off the Pacific coast of the Tohoku region, Northeast Japan: Implications for correlating onshore and offshore event deposits." Quaternary International 456: 138-153.

Ishimura, D., Y. Yoshinaga, et al. (2017). "Newly identified Towada-Chuseri tephra from lacustrine deposits in Lake Aoki, Nagano Prefecture, central Japan." The Quaternary Research (Daiyonki-Kenkyu) 56: 265-270.

Ishimura, D. and R. Hiramine (2020). "Proximal–distal fall deposit correlation of VEI-5 tephra (Towada-Chuseri) from Towada volcano, northeast Japan." Journal of Quaternary Science 35: 334-348.

Jensen, B. J. L., S. Pyne-O'Donnell, et al. (2014). "Transatlantic distribution of the Alaskan White River Ash." Geology 42: 875-878.

Jochum, K. P., B. Stoll, et al. (2006). "MPI-DING reference glasses for in situ microanalysis: New reference values for element concentrations and isotope ratios." Geochemistry, Geophysics, Geosystems 7: Q02008.

Kariya, Y., K. Aoki, et al. (2016). "A middle Holocene wide-spread tephra, Towada-Chuseri, discovered from a subalpine soil on Mount Aizu-komagatake and the Gassan volcano, northern Japan." The Quaternary Research (Daiyonki-Kenkyu) 55: 237-246.

Kim, G. B., S. J. Cronin, et al. (2014). "Post 19 ka B.P. eruptive history of Ulleung Island, Korea, inferred from an intra-caldera pyroclastic sequence." Bulletin of Volcanology 76: 1-26.

Lane, C. S., B. T. Chorn, et al. (2013). "Ash from the Toba supereruption in Lake Malawi shows no volcanic winter in East Africa at 75 ka." Proceedings of the National Academy of Sciences 110: 8025-8029.

Lane, C. S., D. J. Lowe, et al. (2017). "Advancing tephrochronology as a global dating tool: Applications in volcanology, archaeology, and palaeoclimatic research." Quaternary Geochronology 40: 1-7.

Liu, J., G. Chu, et al. (2009). "Volcanic eruptions in the Longgang volcanic field, northeastern China, during the past 15,000 years." Journal of Asian Earth Sciences 34: 645-654.

Liu, J.-q., S.-s. Chen, et al. (2015). "Geological background and geodynamic mechanism of Mt. Changbai volcanoes on the China–Korea border." Lithos 236–237: 46-73.

Lowe, D. J. (2011). "Tephrochronology and its application: A review." Quaternary Geochronology 6: 107-153.

Machida, H. (2002). "Volcanoes and Tephras in the Japan Area." Global Environmental Research 6: 19-28.

Mackay, H., P. D. M. Hughes, et al. (2016). "A mid to late Holocene cryptotephra framework from eastern North America." Quaternary Science Reviews 132: 101-113.

McLean, D., P. G. Albert, et al. (2018). "Integrating the Holocene tephrostratigraphy for East Asia using a high-resolution cryptotephra study from Lake Suigetsu (SG14 core), central Japan." Quaternary Science Reviews 183: 36-58.

McLean, D., P. G. Albert, et al. (2020). "Refining the eruptive history of Ulleungdo and Changbaishan volcanoes (East Asia) over the last 86 kyrs using distal sedimentary records." Journal of Volcanology and Geothermal Research 389: 106669.

Newhall, C. G. and S. Self (1982). "The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism." Journal of Geophysical Research: Oceans 87: 1231-1238.

Pyne-O'Donnell, S. D. F., L. C. Cwynar, et al. (2016). "West Coast volcanic ashes provide a new continental-scale Lateglacial isochron." Quaternary Science Reviews 142: 16-25.

Plunkett, G., S. E. Coulter, et al. (2015). "Distal tephrochronology in volcanic regions: Challenges and insights from Kamchatkan lake sediments." Global and Planetary Change 134: 26-40.

Ponomareva, V., M. Portnyagin, et al. (2017). "A full Holocene tephrochronology for the Kamchatsky Peninsula region: Applications from Kamchatka to North America." Quaternary Science Reviews 168: 101-122.

Portnyagin, M. V., V. V. Ponomareva, et al. (2020). "TephraKam: geochemical database of glass compositions in tephra and welded tuffs from the Kamchatka volcanic arc (northwestern Pacific)." Earth System Science Data 12: 469-486.

Reimer, P. J., W. E. N. Austin, et al. (2020). "The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP)." Radiocarbon 62: 1-33.

Smith, V. C., R. A. Staff, et al. (2013). "Identification and correlation of visible tephras in the Lake Suigetsu SG06 sedimentary archive, Japan: chronostratigraphic markers for synchronising of east Asian/west Pacific palaeoclimatic records across the last 150 ka." Quaternary Science Reviews 67:

121-137.

Staff, R. A., C. Bronk Ramsey, et al. (2011). "New ^{14}C determinations from Lake Suigetsu, Japan: 12,000 to 0 cal BP." Radiocarbon 53: 511-528.

Sun, C., G. Plunkett, et al. (2014). "Ash from Changbaishan Millennium eruption recorded in Greenland ice: Implications for determining the eruption's timing and impact." Geophysical Research Letters 41: 694-701.

Sun, C., H. You, et al. (2016). "Difference between whole rock and in situ analysis on tephra: Evidence from the 1600 a cal. BP eruption of Jinlongdingzi volcano." Earth Science 41: 97-104.

Sun, C., J. Liu, et al. (2017). "Tephrostratigraphy of Changbaishan volcano, northeast China, since the mid-Holocene." Quaternary Science Reviews 177: 104-119.

Sun, C., L. Wang, et al. (2018). "Ash from the Changbaishan Qixiangzhan eruption: A new early Holocene marker horizon across East Asia." Journal of Geophysical Research: Solid Earth 123: 6442-6450.

Sun, C., L. Wang, et al. (2021). "An integrated Late Pleistocene to Holocene tephrostratigraphic framework for South-east and East Asia." Geophysical Research Letters 48: e2020GL090582.

Turney, C. S. M. (1998). "Extraction of rhyolitic component of Vedde microtephra from minerogenic lake sediments." Journal of Paleolimnology 19: 199-206.

van der Bilt, W. G. M., C. S. Lane, et al. (2017). "Ultra-distal Kamchatkan ash on Arctic Svalbard: Towards hemispheric cryptotephra correlation." Quaternary Science Reviews 164: 230-235.

Yi, J., P. Wang, et al. (2021). "Modeling the multi-level plumbing system of the Changbaishan caldera from geochemical, mineralogical, Sr-Nd isotopic and integrated geophysical data." Geoscience Frontiers 12: 101171.

Zhang, M., Z. Guo, et al. (2018). "The intraplate Changbaishan volcanic field (China/North Korea) and its active Tianchi (Paektu, Baekdu) caldera: a review on eruptive history, magma origin and evolution, geodynamic significance, recent dynamics and potential hazards." Earth-Science Reviews 187: 19-52.

Figure 1. Locations of the study site (Gushantun bog), Towada volcano, and major active volcanoes around northeast Asia. The black solid line represents the confirmed dispersal of Towada-Chuseri (To-Cu) tephra. The known distribution of other major Holocene tephras around this area are highlighted by dashed lines (data source: U-Oki and K-Ah is from McLean et al., 2018; QEA/B-Sg-08 is from Sun et al., 2018; B-Tm is generated from Chen et al., 2016, McLean et al., 2016, and Sun et al., 2015). The locations of other key sites mentioned in the text are also shown (SHL: Sihailongwan; YC: Yuanchi, SG: Suigetsu; CBS: Changbaishan).

Figure 2. Tephrostratigraphy and age-depth model for the section of Gushantun peat discussed in this paper (A). Light grey shading is the number of glass shards per 0.5 g of dried sediment in 10 cm increments, and black bands refer to glass shard concentrations in the 1 cm samples. When the initial age for the GST-314 was found to be consistent with To-Cu, the age-depth model was re-run with the precisely constrained age for the To-Cu from Lake Suigetsu as determined by McLean et al. (2018) (B). Photos of the colourless glass shards from the GST-314 tephra (C).

Figure 3. Bivariable plots that compares the glass shard compositions of GST-314 with the discussed known eruptions. Data sources: K-Ah, SG14-0704, Ulleungdo: McLean et al., 2018; Pinatubo: Sun et al., 2021; KHG: Cook et al., 2017; IAv12: Ponomareva et al., 2017; KS_2: Plunkett et al., 2015 and Ponomareva et al., 2017; Changbaishan: Sun et al., 2017, 2018.

Figure 4. Biplots comparing glass shard composition of GST-314 recorded in Gushantun peat, with To-Cu recorded in Lake Suigetsu (SG14-0840; McLean et al., 2018), and three proximal units of To-Cu tephra from Japan (Ishiruma and Hiramine, 2020).

Table 1. Radiocarbon dates from plant remains from Gushantun peat. Radiocarbon ages were calibrated using the IntCal20 curve in OxCal 4.4 (Bronk Ramsey 2008, 2009; Reimer et al., 2020).

Depth (cm)	Lab code Beta-	$\delta^{13}C$ (‰)	^{14}C Age (yr BP)	Calibrated Age (cal a BP, 95% probability)
282	448787	-29.6	4490 ± 30	5297–5040, 5001–4986
311	448788	-27.7	5010 ± 30	5895–5805, 5794–5783, 5769–5653, 5623–5607
408	448789	-27.3	7580 ± 40	8450–8327, 8234–8225

388 **Table 2**. WDS-EPMA analyzed glass shards for the tephra from Gushantun peat (GST-314). All the
389 data have been normalized to an anhydrous basis (original analytical totals shown). Comparative
390 glass data of the To-Cu tephra in Lake Suigetsu is from McLean et al. (2018).

391

392

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Analytical total
GST-314											
	74.67	0.43	13.34	2.47	0.09	0.61	2.68	4.44	1.18	0.08	99.94
	74.20	0.45	13.48	2.51	0.17	0.59	2.78	4.63	1.15	0.03	97.86
	74.73	0.40	13.33	2.46	0.20	0.59	2.80	4.18	1.24	0.08	98.34
	74.63	0.42	13.32	2.46	0.11	0.62	2.65	4.50	1.21	0.09	96.95
	74.18	0.48	13.45	2.42	0.10	0.65	2.73	4.57	1.26	0.17	100.63
	73.59	0.49	13.64	2.79	0.09	0.64	2.87	4.72	1.11	0.06	99.63
	75.48	0.44	13.21	1.88	0.07	0.50	2.54	4.59	1.23	0.05	98.72
ATHO-G											
Average (n=3)	75.39	0.24	12.29	3.33	0.10	0.09	1.68	4.23	2.64	0.01	
2σ	0.57	0.04	0.56	0.34	0.19	0.05	0.01	0.17	0.07	0.05	
Preferred value	75.60	0.26	12.20	3.27	0.11	0.10	1.70	3.75	2.64	0.03	
Uncertainty (95%)	0.70	0.02	0.20	0.10	0.01	0.01	0.03	0.31	0.09	0.00	
StHS6/80-G											
Average (n=3)	63.22	0.71	17.92	4.51	0.11	1.94	5.21	4.95	1.28	0.15	
2σ	0.28	0.06	0.40	0.14	0.04	0.05	0.08	0.51	0.04	0.10	
Preferred value	63.70	0.70	17.80	4.37	0.08	1.97	5.28	4.44	1.29	0.16	
Uncertainty (95%)	0.50	0.02	0.20	0.07	0.00	0.04	0.09	0.14	0.02	0.02	
Suigetsu Lake SG14-0840											
Average (n=25)	74.15	0.47	13.54	2.33	0.11	0.61	2.81	4.57	1.22	0.08	
2σ	0.45	0.06	0.36	0.23	0.11	0.12	0.21	0.30	0.10	0.05	

393

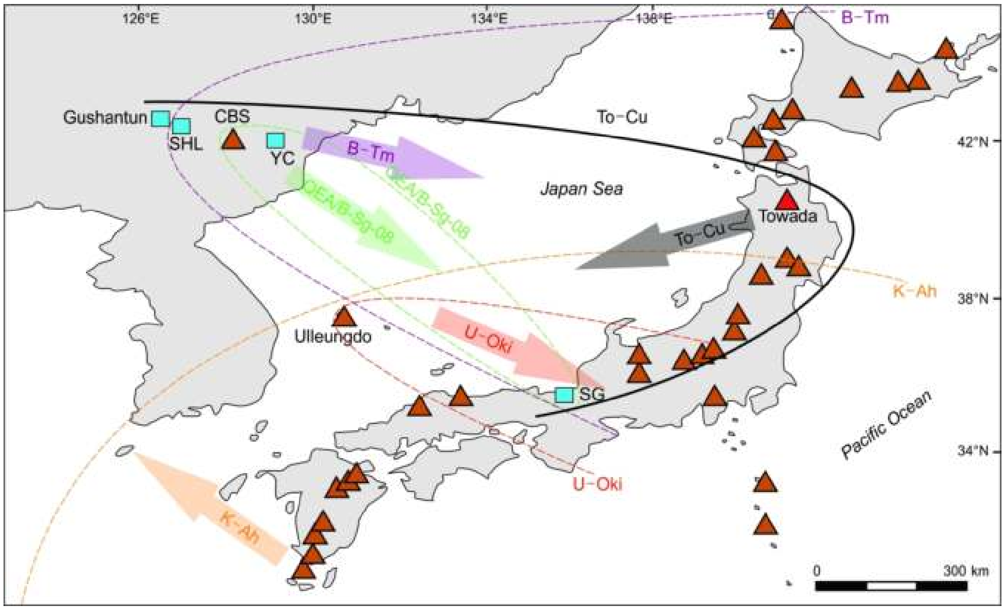

Figure 1

203x122mm (300 x 300 DPI)

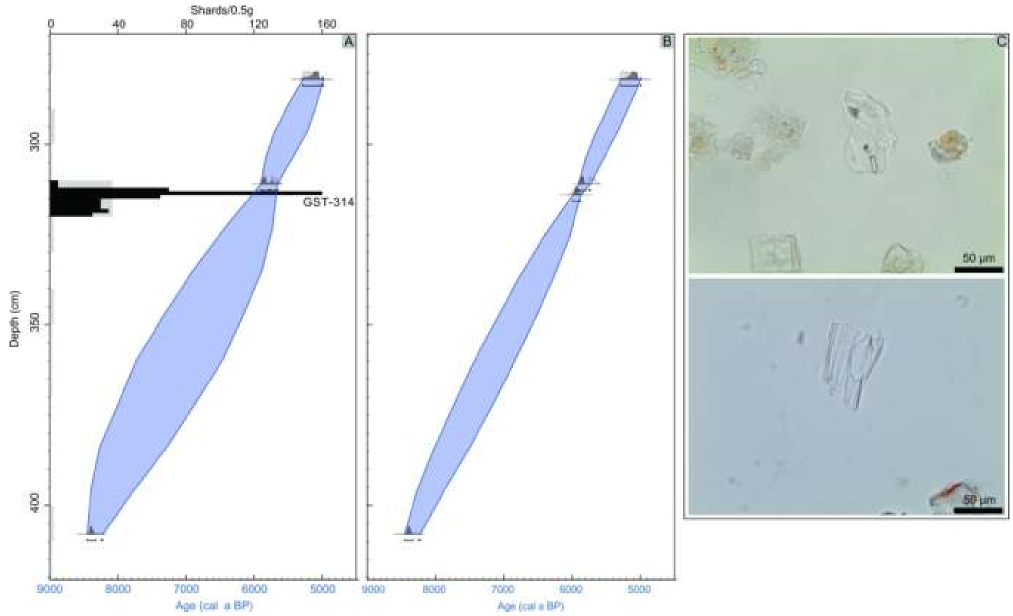

Figure 2

305x185mm (300 x 300 DPI)

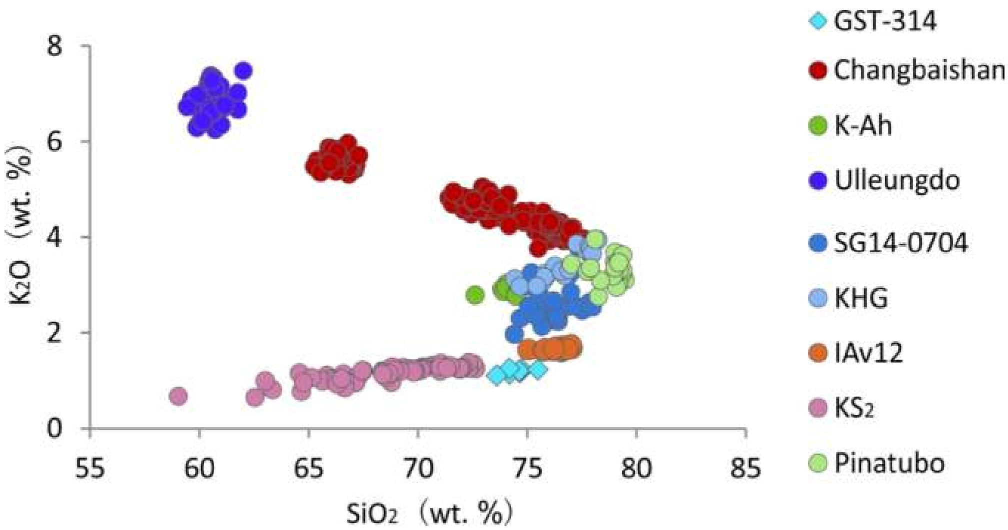

Figure 3

115x59mm (300 x 300 DPI)

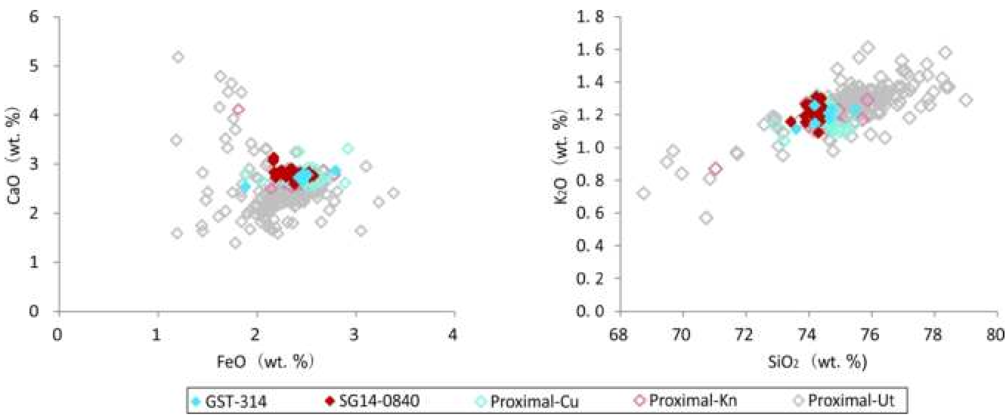

Figure 4

194x78mm (300 x 300 DPI)