Gondwana Research 28 (2015) 52–60

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

GR letter

New evidence for the presence of Changbaishan Millennium eruption ash in the Longgang volcanic field, Northeast China

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ARTICLE INFO

Article history:
Received 27 June 2014
Received in revised form 5 January 2015
Accepted 8 January 2015
Available online 17 February 2015

Handling Editor: W.J. Xiao

Keywords:
Cryptotephra
Lake Sihailongwan
Changbaishan volcano
Millennium eruption
Tephrochronology
Varve chronology

ABSTRACT

The Changbaishan Millennium eruption (~AD 940s) produced a widely distributed tephra layer around northeast Asia. This tephra layer serves as a marker bed in Greenland ice cores and in marine, lake, archeological and tsunami sediments in Japan and the surrounding region. However, little attention has been paid to the widespread sediments west of Changbaishan volcano. Here we present new stratigraphic, geochemical, varve chronology, and ^{14}C geochronological data from the varved sediments in Lake Sihailongwan, Longgang volcanic field, Northeast China, extending the westerly margin of this eruption. The distinctive geochemical characteristic of volcanic glass (ranging from trachyte to rhyolite), similar to those of proximal and distal tephra, confirmed the occurrence of Changbaishan Millennium eruption ash in the lake, illustrating the westward dispersal fan of the ash deposits. The position of the peak concentration of glass shards of this tephra was dated to 953 ± 37 AD by varve chronology, and the radiocarbon samples immediately above this tephra gave a date of 940–1020 AD, overlapping the most recent ages for this eruption. The occurrence of Changbaishan Millennium eruption ash in this lake enables a direct and precise synchronization with other high-resolution archives in Northeast Asia, such as maar lakes and peat and marine sediments, thus providing an isochronous marker for a range of sedimentary contexts.

1. Introduction

Volcanic ash (tephra), produced by explosive eruptions, is deposited rapidly; hence, it can serve as a distinctive and widespread synchronous marker horizon, correlating terrestrial, marine and ice core records (Haflidason et al., 2000; Davies et al., 2005; Lowe, 2011; Alloway et al., 2013). In regions distal to volcanic sources, cryptotephra layers or glass shards can be used as an important constraint in the chronology of sedimentary sequences; however, such layers are often overlooked, especially in lake sediments where a high proportion of inorganic components have considerably diluted the concentration of glass shards. Only through careful detection and with a targeted technique can some of the cryptotephra layers be detected (Turney, 1998; Blockley et al., 2005; Ranner et al., 2005). Though the most explosive eruptions can disperse ash over thousands of kilometers (e.g. Lane et al., 2013a; Sun et al., 2014a), the distribution of tephra within sediments is frequently discontinuous due to atmospheric dynamics and catchment processes (Lane et al., 2012; Lawson et al., 2012). Additionally, tephra distribution and glass compositions may be heterogeneous as a result of multiple magmas, magma-mingling, or syn-eruptive changes in dispersal patterns (spatial differentiation) (e.g. Lowe et al., 2008; Shane et al., 2008; Lane et al., 2012).

The Changbaishan volcano, an intraplate stratovolcano located on the border between China and North Korea, is known for its Millennium eruption about 1000 years ago. This eruption is considered to be one of the most violent eruptions over the past 2000 years because of its vast volume (a total volume of ~100 km^3 loose tephra, and magma volume (DRE ~25 km^3)) and widely distributed volcanic products (Horn and Schmincke, 2000; Sun et al., 2014a). The fall-out pumice was predominantly deposited on the volcano's eastern slope and a tephra layer up to ~16 cm was identified in the Sea of Japan (Machida and Arai, 1983; Horn and Schmincke, 2000).

Distal tephra from the Changbaishan Millennium eruption was first identified and described in Japan, where it is found as a visible tephra layer, and named B–Tm tephra after the source volcano (Baitoushan or Changbaishan) and the finding site (Tomakomai, Hokkaido) (Machida and Arai, 1983). Since than, tephra layers correlating with

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http://dx.doi.org/10.1016/j.gr.2015.01.013
1342-937X/

B–Tm tephra have been identified and serve as an important marker horizon across the Sea of Japan to Japan. The marker layer is applied in studies such as vegetation evolution, volcanic activities, archeology, and event stratigraphy (Fig. 1) (e.g. Furuta et al., 1986; Nakagawa et al., 2002; Ikehara, 2003; Nanayama et al., 2003, 2007; Okuno et al., 2011; Hughes et al., 2013; Tanigawa et al., 2014). In the Sihailongwan sediments (Fig. 1), Guo et al. (2005) reported a tephra layer with a rhyolitic glass composition, which they traced to the Changbaishan Millennium eruption. However, its major element composition is distinctly different from the proximal, distal and ultra-distal B–Tm tephra, which all display bimodal glass compositions sourced from the same eruption (Sun et al., 2014a,b). Meanwhile, other studies claimed that ash from the Changbaishan eruptions could not have been transported to the Longgang volcanic field (e.g. Cheng et al., 2008;

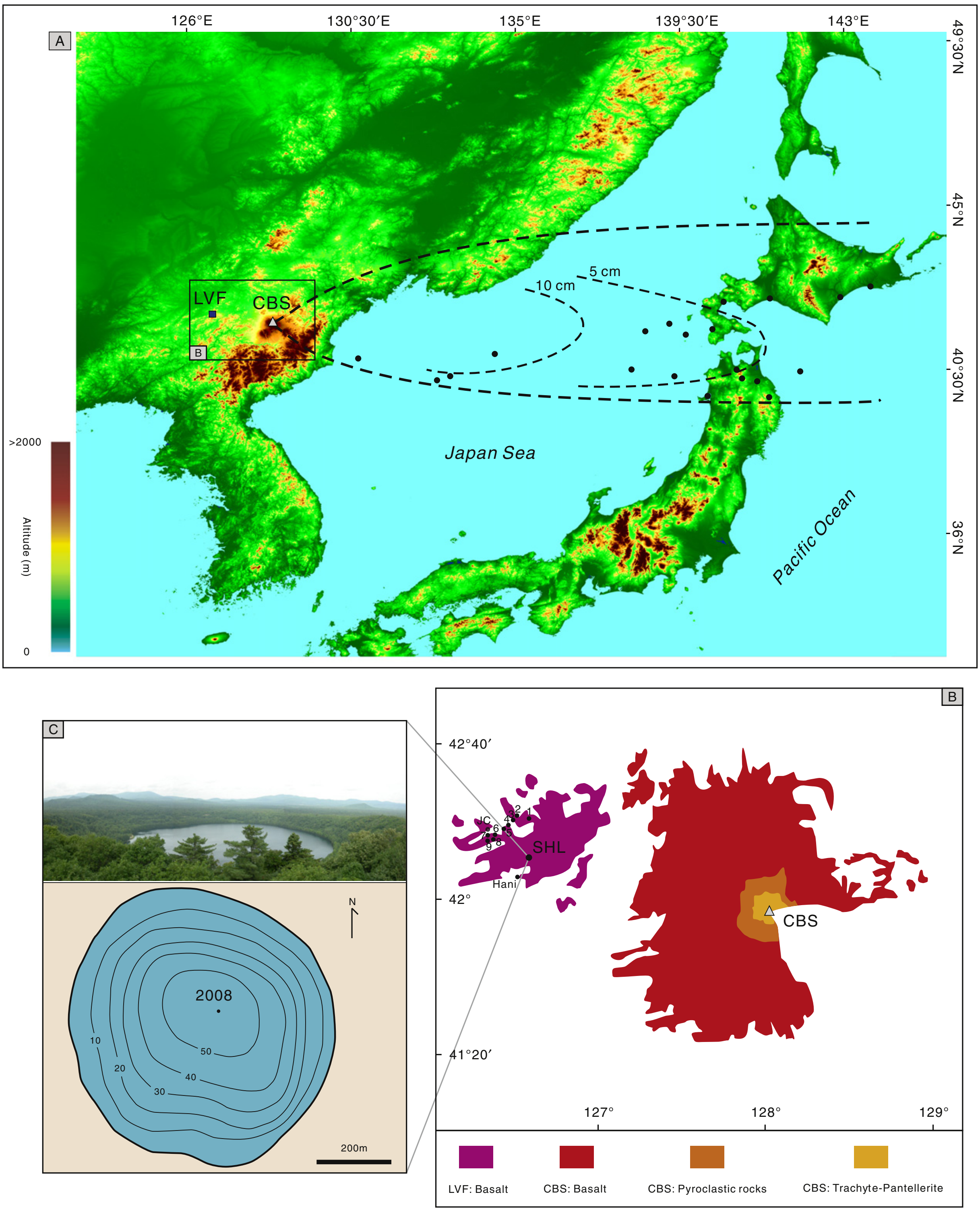

Fig. 1. A: Locations of the Changbaishan volcano (CBS) and the Longgang volcanic filed (LVF), dispersal fan of the Changbaishan Millennium eruption, and the representative sites where the B–Tm tephra were found. B: Locations of maar lakes and peat bogs around the LVF. Modified from Fan et al. (2006) and Zhao and Liu (2012). C: A photo and a bathymetric curve sketch map of Lake Sihailongwan. Solid black circle is the coring site. Abbreviation: JC is Jinchuan and Hani is Hani mire. Number 1 is Lake Longquanlongwan, 2 is Lake Donglongwan, 3 is Lake Nanlongwan, 4 is Lake Sanjiaolongwan, 5 is Lake Hanlongwan, 6 is Lake Dalongwan, 7 is Gushantun peat, 8 is Lake Erlongwan and 9 is Lake Xiaolongwan.

Mao et al., 2009). Thus there have been no validated findings that confirm the existence of a macro-tephra or micro-tephra (cryptotephra) layer in Northeast China (west of Changbaishan volcano), a region that includes a number of sedimentary contexts such as maar lakes and peat bogs (Fig. 1).

In this paper we report on the discovery of a discrete cryptotephra layer sourced from the Changbaishan Millennium eruption in a sediment sequence cored from Lake Sihailongwan, Longgang volcanic field (LVF), Northeast China. We thus extend the known western footprint of the Changbaishan Millennium eruption ash (CMA). Chemical characterization of the glass shows a distinctive composition extending from trachyte to rhyolite that can be reliably compared with proximal and eastern distal tephra from this eruption. We present a full chemical characterization the CMA from proximal tephra and distal tephra and test its chemical correlation to CMA found around northeastern Asia. Based on the stratigraphic and geochemical records of glass shards, varve chronology and ^{14}C geochronology, we conclude that it is highly likely that the tephra/cryptotephra horizon from the Changbaishan Millennium eruption can be traced in a range of sedimentary contexts throughout Northeast China; identifying this marker will significantly improve the potential for robust correlation of palaeoenvironmental records between the regions of Northeast China and Japan.

2. Study site

Lake Sihailongwan (42°17′N, 126°36′), ~125 km away from Changbaishan volcano, is a maar lake located in the LVF, Northeast China. A 10–119 m tuff ring around the lake makes it an ideal candidate for paleoclimatic and tephrostratigraphic studies (Chu et al., 2012). This lake is fed primarily by groundwater inflow and rainfall during summer, with no outlets for stream transportation (Liu et al., 2005). Sediments comprising of annual laminated layers are well developed in this area mainly owing to the distinct biannual depositions and very minor impact of human activity. The varved sediments provide a reliable timescale for dust flux rates, vegetation evolution, paleoclimatic, and paleohydrological studies over the last decade (e.g. Mingram et al., 2004; Chu et al., 2005; Schettler et al., 2006a,b; Chu et al., 2009, 2012, 2013; Li et al., 2013; Zhu et al., 2013).

3. Methods and materials

3.1. Cryptotephra investigation

Drill core for cryptotephra investigation was taken from Lake Sihailongwan at 2008. Contiguous 2 cm samples were taken from the core and then freeze-dried and weighed so as to give an estimation of the number of glass shards per 0.5 g of dry weight sediment (gdw). A 10% HCl solution was added to all the samples overnight to dissolve carbonates and other inorganic materials. After acidizing, the treatment of H_2O_2 was performed to disaggregate the sediments and remove organic material (e.g. Brauer et al., 2007; Koren et al., 2008). All the samples were sieved through 30–100 μm sieves and material of diameter <30 μm was discarded. For each 2-cm segment where glass shards were detected, further contiguous 1-cm samples were taken at depths corresponding to the greatest glass shard concentration to determine more precisely the position of the peak concentration of shards and perform EPMA analysis on glass shards. The treatment of 1-cm samples followed the procedures performed on the 2-cm segments above. The shard concentrations were counted under a high-power optical microscope.

3.2. Geochemical analysis

After the depths of peak cryptotephra concentration were determined, samples treated with H_2O_2 were taken from these depths for geochemical analysis. Glass shards were mounted, ground and polished to expose the internal sections for electron microprobe analysis (EMPA), and to diminish the effect of the peroxide treatment. A major element analysis was carried out using a JEOL JXA 8100 electron microprobe at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Ten major elements (Na, Mg, Al, Si, K, Ca, Fe, Ti, Mn, Cl) were analyzed with an accelerating voltage of 15 kV, a beam current of 6 nA, and a beam diameter of 5–10 μm according to the size of the glass shards. Peak counting times used were 20 s for all elements except for the Na (10 s). In addition, determination of Na content was made at the start of analysis to reduce the impact of its mobilization. Two secondary standard glasses from the MPI-DING fused glass, ATHO-G (rhyolite) and StHs6/80-G (andesite) (Jochum et al., 2006), were used to monitor the precision and accuracy of the data.

3.3. Chronology

Varve chronology was carried out on this core. Sediment slabs were cut off from the core, and then shock-frozen with nitrogen, vacuum-dried, impregnated with epoxy resin and cut into thin sections. Varves were identified and counted from thin sections under a Leitz polarizing microscope. In this lake, varves appear as rhythmic units of a diatom-rich layer (autumn), followed by a light-colored siliciclastic layer (spring), and a subsequent mixed layer (summer) (Chu et al., 2005). The error of the varve chronology is less than 4%. Additionally, ^{14}C dating was also performed on terrestrial plant leaves extracted at 51 cm overlapping the depth of the peak concentration of glass (Fig. 2). The leaves were washed with dilute HCl, NaOH, and distilled water and then dated by the accelerator mass spectrometry method of ^{14}C radiocarbon measurement at the Beta Analytic Radiocarbon Laboratory, Florida, USA.

4. Results

4.1. Position and morphology of the cryptotephra layer

A visible black scoria layer (T1 tephra horizon; Fig. 2) was found at 78–79 cm in this core, corresponding to an extensive time-parallel marker horizon across the LVF such as Lake Xiaolongwan (e.g. Mingram et al., 2004; Liu et al., 2009). This basaltic tephra layer came from the local volcanic eruption of LVF and its composition is distinct from recent eruptions of the Changbaishan volcano (Guo et al., 2005; Liu et al., 2009). An age of AD 367–191 was assigned to this tephra layer by varve-chronology (Chu et al., 2009), which servers as a time point around LVF.

The initial 2-cm segment scans showed that the CMA presented at 51–52 cm in the Lake Sihailongwan core. Further 1-cm slides and scans demonstrated that the cryptotephra layers were located at 52 and 53 cm where peak concentrations of light brown and colorless glass shards were found, respectively (Fig. 2). A peak in the shard concentrations of 2657 shards/0.5 gdw for colorless glass was detected at 53 cm and 669 shards/0.5 gdw for light brown glass were found at 52 cm. Colorless glass shards take up the major component in this tephra horizon and have vesicular morphology, while most of the light brown glass are platy shards. No signs of corrosion or mechanical wear due to secondary processes were observed in this horizon (Fig. 3). In addition, there are no obvious microphenocryst/microlite inclusions within the glass, which confirms the reliability of the geochemical analysis (Hunt and Hill, 2001).

4.2. Geochemical characteristics

The major element compositions of the glass shards from this horizon are shown in Table 1 and presented in Fig. 4. Only analyses with acceptable analytical totals (>93%) and no distinct migration of sodium (>3%) are presented here. All the data were normalized to an

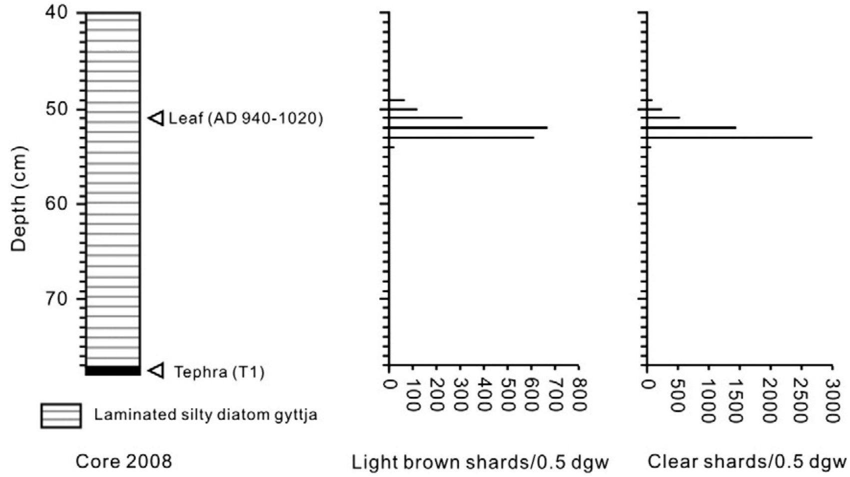

Fig. 2. Simplified tephrostratigraphy and lithology of Lake Sihailongwan along with the numbers of glass shards. Glass shards are plotted as the number of shards per 0.5 g of dry sediment. The age of terrestrial plant leaves at 51 cm is 930–1010 cal a BP.

anhydrous basis to facilitate a reliable correlation of tephra layers between various settings, especially those in lacustrine and marine sediments where water might be absorbed into glass shards (Pearce et al., 2014). According to the total alkali silica (TAS) (Le Maitre et al., 1989) and harker diagrams of the major elements, the geochemical composition of the volcanic glass in this tephra is heterogeneous, ranging from trachytic to rhyolitic (based on anhydrous normalized data) with a few analysis results plotting in-between. The SiO_2 values range between 66 and 77 wt.%, CaO values between 0.2 and 1.6 wt.%, FeO_t values between 3.6 and 5.0 wt.%, K_2O values between 4.2 and 6.0 wt.% and TiO_2 between 0.2 and 0.6 wt.% (Table 1).

Data from Lake Sihailongwan were compared with previous analyses of distal and ultra-distal CMA glass shards and to a set of new analyses of proximal CMA (gray pumice) from Changbaishan volcano (sampling site: Wuhaojie on its western caldera rim) under the same analytical protocol (Table S1). These new data show a geochemical characteristic similar to that of the proximal and distal tephra (Fig. 4, Tables 1 and S1). The major-element geochemistry results for the glass shards separated from Lake Sihailongwan tend to fall within the compositional range exhibited by the proximal tephra from Changbaishan, the distal tephra from the Japan areas and ultra-distal tephra from the Greenland ice cores (Fig. 4).

4.3. Chronology

The peak concentration of glass shards of this tephra layer was dated to 953 ± 37 AD, in agreement with the reported ages for the Millennium eruption (Table 2); the stated uncertainty is the maximum counting error estimated by re-counting the varves three times. The AMS ^{14}C age of the leaves at 51 cm was calibrated based on the Intcal 2013

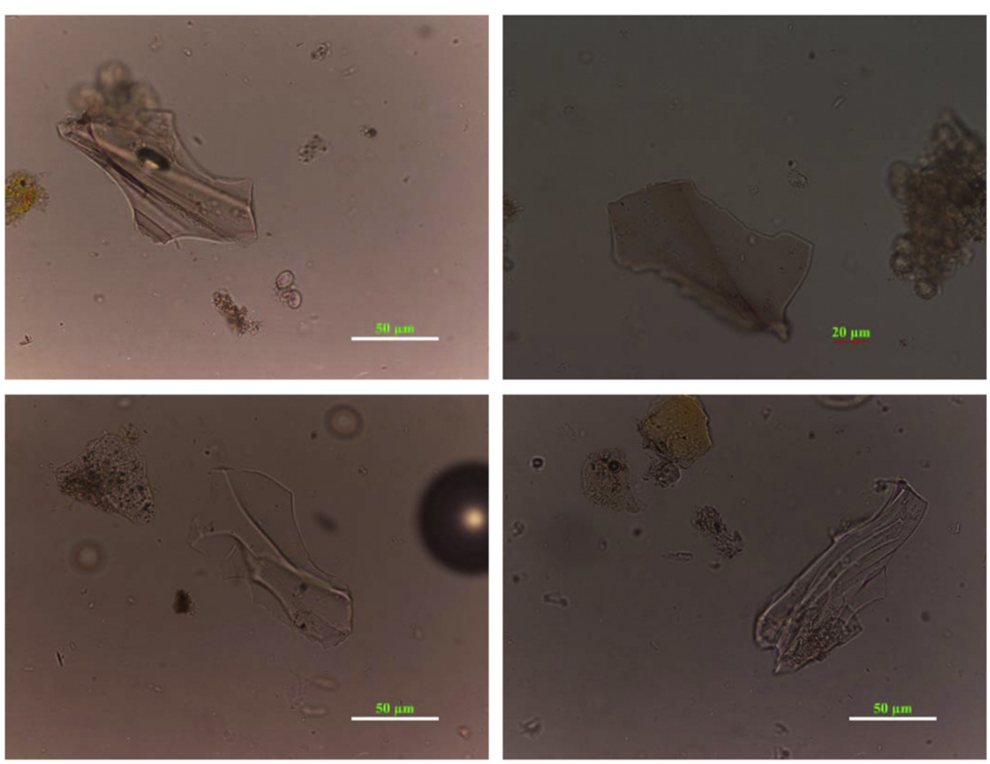

Fig. 3. Light microscope photographs of shards extracted from Lake Sihailongwan at 52–53 cm. All glass show a primary morphology with angular edges.

Table 1
WDS–EPMA results of glass shards for SHL 52 and SHL 53 from Lake Sihailongwan. Proximal data from Wuhaojiebei are available online. All data have been normalized to anhydrous basis with original analytical totals. MPI-DING fused volcanic glass standards ATHO-G and StHs6/80-G was used as secondary standards.

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	Analytical total
Tephra analysis											
53 cm	76.42	0.22	10.20	3.96	0.15	0.00	0.20	3.79	4.76	0.39	97.49
	75.78	0.24	10.18	3.81	0.09	0.00	0.27	4.31	5.00	0.41	97.20
	76.09	0.26	10.29	3.87	0.09	0.02	0.24	3.90	4.93	0.42	96.31
	75.87	0.24	10.62	3.95	0.11	0.04	0.25	4.40	4.21	0.41	95.84
	75.14	0.18	10.72	4.02	0.07	0.01	0.30	4.79	4.50	0.35	96.18
	72.92	0.29	12.10	3.96	0.07	0.03	0.52	4.76	5.13	0.29	96.88
	72.86	0.27	12.30	4.07	0.09	0.00	0.60	4.50	5.11	0.27	96.28
	71.96	0.25	11.86	4.71	0.14	0.08	0.83	4.59	5.37	0.25	96.52
	73.21	0.25	12.22	4.25	0.12	0.05	0.59	4.30	4.79	0.27	93.60
	72.17	0.26	12.53	4.31	0.11	0.08	0.72	4.33	5.34	0.21	94.78
	70.31	0.32	13.63	4.48	0.02	0.04	0.89	4.77	5.39	0.19	96.39
	70.93	0.27	13.48	4.09	0.10	0.05	0.82	4.69	5.44	0.19	95.20
	68.46	0.35	14.88	4.65	0.11	0.08	1.25	4.68	5.43	0.14	98.36
	71.25	0.40	14.13	4.29	0.11	0.05	0.88	3.54	5.18	0.24	94.22
	68.43	0.32	15.20	4.47	0.09	0.13	1.16	4.70	5.42	0.10	98.02
	69.04	0.33	15.13	3.87	0.07	0.09	1.10	4.89	5.40	0.11	97.04
	69.32	0.28	15.19	4.68	0.15	0.07	1.40	3.23	5.59	0.12	96.45
	68.76	0.54	15.37	4.53	0.16	0.21	0.99	3.66	5.64	0.17	96.72
	67.56	0.36	15.19	4.67	0.13	0.16	1.11	5.29	5.44	0.12	97.73
	68.20	0.41	14.93	4.21	0.12	0.10	1.28	5.32	5.39	0.06	96.72
	67.34	0.44	15.16	4.85	0.19	0.14	1.23	5.03	5.52	0.12	97.69
	65.98	0.50	15.89	4.82	0.15	0.23	1.39	5.15	5.81	0.09	99.31
	68.29	0.41	14.86	4.70	0.13	0.13	1.01	4.91	5.43	0.17	95.82
	66.47	0.52	16.00	4.65	0.15	0.29	1.32	4.68	5.85	0.10	98.44
	67.07	0.34	15.35	4.94	0.16	0.11	1.15	5.29	5.49	0.12	97.38
	66.29	0.49	16.02	4.50	0.12	0.22	1.37	5.19	5.72	0.09	98.38
	66.57	0.47	15.86	4.77	0.12	0.24	1.35	4.84	5.72	0.09	97.91
	68.44	0.32	14.90	4.64	0.11	0.11	0.96	4.69	5.75	0.09	95.22
	67.03	0.49	15.41	4.43	0.12	0.20	1.28	5.46	5.49	0.13	96.98
	68.03	0.37	14.87	4.33	0.13	0.08	1.24	5.17	5.71	0.11	95.45
	66.94	0.43	15.27	4.71	0.10	0.20	1.32	5.47	5.49	0.10	96.98
	66.55	0.45	15.73	4.78	0.15	0.22	1.30	5.08	5.64	0.13	97.44
	66.29	0.59	16.09	4.58	0.13	0.25	1.35	5.04	5.60	0.07	97.81
	66.57	0.50	15.75	4.65	0.07	0.19	1.33	5.33	5.55	0.08	96.73
	67.15	0.52	15.31	4.73	0.11	0.12	1.27	5.34	5.37	0.08	95.68
	66.53	0.45	15.79	4.61	0.15	0.20	1.60	5.02	5.61	0.03	96.54
	66.43	0.56	15.34	4.69	0.09	0.17	1.56	5.64	5.46	0.10	96.24
	65.84	0.47	15.84	4.67	0.10	0.29	1.43	5.45	5.83	0.10	97.07
	66.24	0.48	15.89	4.73	0.12	0.17	1.42	5.27	5.61	0.09	96.30
52 cm	75.28	0.25	10.74	4.05	0.10	0.02	0.30	4.53	4.43	0.39	96.50
	66.06	0.58	16.07	4.52	0.10	0.28	1.40	4.96	5.95	0.10	95.08
	65.81	0.56	15.76	4.75	0.15	0.24	1.35	5.48	5.81	0.12	95.67
	66.84	0.38	15.35	4.85	0.13	0.34	1.24	5.30	5.50	0.10	94.57
	65.55	0.59	15.99	4.79	0.14	0.27	1.39	5.27	5.97	0.05	96.15
	66.09	0.46	15.89	4.82	0.13	0.24	1.46	5.41	5.42	0.09	95.67
	66.71	0.40	15.35	4.84	0.09	0.17	1.33	5.54	5.48	0.11	95.52
	67.58	0.40	15.14	4.65	0.09	0.14	1.15	5.26	5.49	0.15	94.14
	66.02	0.58	15.99	4.62	0.09	0.28	1.45	5.19	5.73	0.07	97.20
	66.15	0.48	16.27	4.46	0.11	0.29	1.33	5.17	5.71	0.05	97.44
	65.59	0.53	16.18	4.58	0.12	0.27	1.34	5.30	6.02	0.08	98.22
	65.81	0.52	16.01	4.65	0.12	0.33	1.38	5.24	5.86	0.12	98.14
	66.05	0.54	15.95	4.47	0.14	0.27	1.29	5.40	5.83	0.07	98.16
	67.32	0.40	15.02	4.62	0.13	0.16	1.26	5.40	5.55	0.18	96.33
	66.31	0.45	15.88	4.60	0.13	0.27	1.34	5.26	5.69	0.11	98.49
	66.29	0.49	16.13	4.54	0.16	0.23	1.40	4.88	5.79	0.09	98.69
	66.93	0.45	15.54	4.70	0.14	0.14	1.31	5.10	5.60	0.11	98.06
	67.85	0.42	14.76	4.65	0.14	0.11	1.12	5.54	5.29	0.15	96.79
	67.76	0.32	14.88	4.65	0.17	0.12	1.13	5.36	5.52	0.12	96.23
	67.71	0.40	14.97	4.67	0.14	0.12	1.28	5.29	5.36	0.10	96.20
	67.10	0.28	15.31	4.64	0.14	0.10	1.20	5.13	5.99	0.15	97.19
	66.45	0.47	16.25	4.44	0.15	0.33	1.35	4.93	5.56	0.10	99.31
	66.96	0.42	15.43	4.71	0.13	0.19	1.22	5.44	5.45	0.06	98.80
	67.60	0.25	15.83	4.11	0.09	0.13	1.07	5.20	5.65	0.10	97.79
	68.32	0.26	15.34	3.57	0.10	0.11	1.39	4.92	5.86	0.17	97.31
	67.61	0.36	15.28	4.36	0.10	0.05	1.02	5.67	5.45	0.13	98.65
	68.03	0.30	15.04	4.34	0.13	0.16	1.13	5.12	5.65	0.12	98.32
	67.65	0.39	15.06	4.68	0.16	0.12	1.14	5.28	5.43	0.11	98.05
	67.95	0.42	14.87	4.58	0.18	0.13	1.20	5.23	5.35	0.11	97.97
ATHO-G ($n = 10$)											
Average	74.84	0.24	12.07	3.28	0.10	0.10	1.65	3.64	2.62	0.04	
2σ	1.60	0.06	0.20	0.25	0.05	0.03	0.11	0.17	0.16	0.04	

Table 1 (*continued*)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	Analytical total
Preferred value	75.60	0.26	12.20	3.27	0.11	0.10	1.70	3.75	2.64	0.04	
Uncertainty (95%)	0.70	0.02	0.20	0.10	0.01	0.01	0.03	0.31	0.09	–	
StHS6/80-G ($n = 10$)											
Average	63.87	0.70	17.78	4.25	0.08	1.89	5.15	4.53	1.27	0.03	
2σ	1.01	0.07	0.31	0.15	0.05	0.08	0.12	0.17	0.10	0.02	
Preferred value	63.70	0.70	17.80	4.37	0.08	1.97	5.28	4.44	1.29	0.02	
Uncertainty (95%)	0.50	0.02	0.20	0.07	0.00	0.04	0.09	0.14	0.02	0.01	

program (Reimer et al., 2013), and then a date range of 1010–930 cal BP (95% confidence) years was given for constraining the age of this tephra layer in Lake Sihailongwan. This age also overlaps precisely the ice core and proximal wiggle-matching ^{14}C ages for the CMA (e.g. Xu et al., 2013; Sun et al., 2014a).

5. Discussion

5.1. Evidence for the CMA in the LVF

The existence of a cryptotephra layer from the sedimentary contexts to the west of Changbaishan volcano is very significant to the understanding of the correlations of tephra layers. Moreover, it provides a direct and precise correlation and synchronization between Northeast China, the Japan areas and Greenland ice cores.

Previous studies suggested that products from the Changbaishan eruptions could not have been transported to the LVF, Northeast China (e.g. Cheng et al., 2008; Mao et al., 2009), while others found some layers with composition similar to that of certain phases of the Changbaishan eruptions, but found no compelling evidence to confirm this (e.g. Guo et al., 2005; Zhao and Liu, 2012). For example, the tephra layer detected by Guo et al. (2005) from Lake Sihailongwan was located at 69–70 cm of the core and has a unique rhyolitic glass composition, which is distinctly different from our finding (Fig. 4). The age of this tephra layer was restricted to 1630–1038 AD, younger than our new results (Table 2) and the most recent dating results (e.g. Xu et al., 2013; Sun et al., 2014a). The stratigraphy, morphology, geochemistry and chronology should be considered as fully as possible when correlating tephra layers among sedimentary settings (Blockley et al., 2007; Lowe, 2011). Therefore, it is insufficient to state that the CMA was deposited at the LVF based on the evidence provided by Guo et al., 2005 or to correlate the cryptotephra layer recorded in Jinchuan peat with the 1702 AD eruption of Changbaishan volcano (Zhao and Liu, 2012) without a reference from proximal tephra.

The age of this tephra constrained by varve chronology and AMS^{14}C age on the plant leaves at 51 cm in our core (Table 2) overlaps the recent

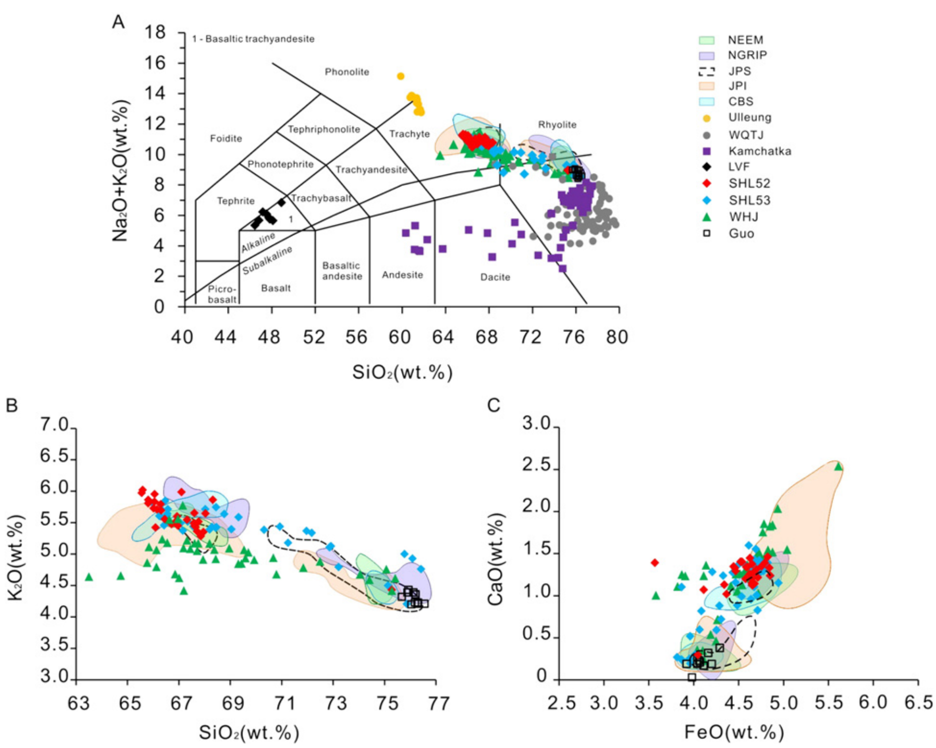

Fig. 4. TAS (A) and harker diagrams (B and C) for glass shards extracted from Lake Sihailongwan (52–53 cm). Glass data from proximal and distal tephra were also presented here for comparison. All data have been normalized to anhydrous basis. Abbreviation: WHJ is Wuhaojie; CBS is Changbaishan volcano; SHL is Lake Sihailongwan; JPI is Japan; JPS is the Sea of Japan; NEEM is The North Greenland Eemian Ice Drilling; NGRIP is North Greenland Ice Core Project; WQTJ is the widespread Quaternary tephra around Japan; Kamchatka is the marker tephra layers from major Holocene eruptions, Kamchatka Peniunsula, Russia; and Ulleung is the major tephra layers from Ulleung Island, South Korea. TAS diagram was based on Le Maitre et al. (1989). The boundary line dividing alkaline and subalkaline series is from Irvine and Baragar (1971).
CBS and NEEM (Sun et al., 2014a); Guo (Guo et al., 2005); JPI (Hughes et al., 2013); JPS (Machida et al., 1990); NGRIP (Coulter et al., 2012); WQTJ (Aoki and Machida, 2006); Kamchatka (Philip et al., 2011); Ulleung (Machida et al., 1984); and LVF (Fan et al., 1999; Liu et al., 2009).

Table 2
Summary of varve chronology and ^{14}C dating results from the Lake Sihailongwan and the various published dating results from proximal and other distal environments on the Changbaishan Millennium eruption.

Sites	Methods	Results	Reference
Lake Sihailongwan	Varve chronology	953 ± 37 AD	This study
	Conventional ^{14}C age	940–1020 AD (2σ)	This study
Changbaishan	^{14}C wiggle matching	921–941 AD (2σ)	Yin et al. (2012)
	^{14}C wiggle matching	940–952 AD (2σ)	Xu et al. (2013)
	^{14}C wiggle matching	930–943 AD (2σ)	Nakamura et al. (2007)
	^{14}C wiggle matching	945–960 AD (2σ)	Yatsuzuka et al. (2010)
	^{14}C wiggle matching	945–984 AD (2σ)	Horn and Schmincke (2000)
	Ar–Ar	1.75–0.73 ka (2σ)	Yang et al. (2014)
	U-TIMS	1.65–0.35 ka (1σ)	Wang et al. (1999)
Japan	Varve chronology	937–938 AD	Fukusawa et al. (1998)
	Varve chronology	929 AD	Kamite et al. (2010)
Greenland ice core	GICC05 chronology	940–941 AD	Sun et al. (2014a)

dating results from Changbaishan proximal ^{14}C wiggle-matching and ice core ages, AD 940s (Xu et al., 2013; Sun et al., 2014a). The vesicular nature of the glass is similar to that of the proximal tephra and distal tephra from the Japan areas (e.g. Machida and Arai, 1983; Horn and Schmincke, 2000). In addition, the irregular morphology of the glass shards, the prominent peak of glass concentration, and a consistent glass composition indicate that there are no clear secondary processes working on this layer (Haflidason et al., 2000). More importantly, the glass composition in this layer (ranging from trachyte to rhyolite) is consistent with that of the proximal tephra, distal tephra from the Japan areas, and ultra-distal tephra from the Greenland ice cores (Fig. 4).

Thus, this is the first time that reliable evidence of the deposition of CMA in the LVF is presented and we can confidently extend the western limit of CMA deposition to the LVF. Our results also show that:

- This eruption was more violent than previously thought.
- CMA dispersal may have blanketed the entire region of the LVF.
- We predict that further cryptotephra investigations in other sedimentary contexts will find this time-parallel marker.

5.2. Chemical characterization of the CMA

Many eruptions from different volcanoes and some tephra from the same volcano may share identical major and minor element glass compositions (e.g. Allan et al., 2008), which can lead to incorrect correlations of tephra horizons. For example, during the late Pleistocene and Holocene, there was extensive explosive volcanism in the LVF, Japan areas, the east of Russia (Kuril–Kamchatka areas and Udokan volcanic field) and the Ulleung Island, and their ejected tephra may be transported and deposited all around the northeast Asia. Therefore, careful inspections of published geochemical data from the contemporary explosive volcanoes around this region should be carried out before anchoring the source volcano of tephra layer in this lake.

There are no felsic volcanic eruptions in the LVF during the Quaternary period (Fan et al., 1999; Guo et al., 2005; Liu et al., 2009) and thus this tephra layer could not be from LVF (Fig. 4 A). Ulleung Island is a Quaternary volcanic island and many of its tephra layers have been serving as excellent marker layers around the Sea of Japan and Japan (Machida et al., 1984; Furuta et al., 1986). But, its distinctive trachytic/phonolitic chemical composition of glass shards is very differrent from CMA (Fig. 4 A) and the predominant dispersal of tephra to the east (Machida et al., 1984) make it impossible to be a source for this tephra. There are also numerous explosive volcanic fields in Japan and Kamchatka peninsula during this period, however, these calcalkaline volcanoes affected mainly by subduction related processes (e.g. Aoki and Machida, 2006; Ponomareva et al., 2007; Philip et al., 2011) can be excluded as a possible source for this tephra because of distinct different glass geochemistry (Fig. 4 A). The intracontinental characterized tephra from Udokan volcanic field also can be ruled out as relative small eruptions, different eruption timings and long distance to LVF (Ivanov et al., 2011). Though certain of the widespread Quaternary tephra around Japan falling in the field of CMA (Fig. 4 A), they can be separated easily using the ratios of FeO_t to CaO (Sun et al., 2014a).

CMA has a unique geochemical feature among these surrounding and contemporary eruptions; the composition of glass ranges from trachytic to rhyolitic member and only limited analysis results plotting in between (Fig. 4 A). The major-element plots show that the CMA is characterized by an alkaline composition (Fig. 4 A), and suggest that it did not originate from a subduction related tectonic environment, but rather from intra-continental vents characterized by high alkalis. A broad spectrum and a linear change between pairs of oxides of glass compositions (not shown here) indicate a complex magma mixing or mingling system before this eruption.

Geochemically, the composition of this tephra in the Lake Sihailongwan similar to CMA and typical plots (SiO_2 vs. K_2O and FeO vs. CaO) (Fig. 4 B and C) implies that the CMA is the source of this tephra. However, there are some differences between this tephra and the published tephra from the east of Changbaishan volcano. Our results show a contiguous composition ranging from trachyte to rhyolite and concentrated mainly in the trachytic member, while others have a bi-modal glass composition with only limited points in between (Fig. 4 B and C). Furthermore, the dispersal of tephra is different between the finding environments from the east and west of Changbaishan volcano, that is the visible and invisible tephra found east (e.g. Machida and Arai, 1983; Hughes et al., 2013) and west of this volcano (this study), respectively. Both compositional variations and differentiated tephra dispersal are probably the results of a syn-eruptive dispersal change or the effect of western low-level wind during this eruption (e.g. Lowe et al., 2008; Shane et al., 2008; Sun et al., 2014b).

5.3. Chronological implications and linkage between Northeast China and Japan areas

A precise timescale and geochemical characterization of glass are useful for the construction of a chronological sequence pivotal to the applications of tephrochronology in paleoclimatic research (Hall and Pilcher, 2002). In the varved lake sediments, radiocarbon dating or varve-chronological results from the host can assign ages for unknown layers (e.g. Zillén et al., 2002; Liu et al., 2009; Wulf et al., 2012). Moreover, characterized tephra layers dated by historical records or very high-resolution dating methods can be used to estimate the chronology and verify the precision of ages dated by other techniques (e.g. Bramham-Law et al., 2013). There is a very abrupt lower limit of glass shard concentration at Lake Sihailongwan (Fig. 2), which implies that the impact of downward mobilization is negligible. Therefore, the lower boundary of the peak may signify the onset of glass deposition at this lake (e.g. Lowe and Turney, 1997). This tephra layer has been accurately dated (Table 2) by ice core chronology, ^{14}C wiggle matching and varve chronology (Xu et al., 2013; Sun et al., 2014a); therefore, it can serve as a credible absolute time scale to refine other dating results in this region.

There are about eight maar lakes, a dry maar, and peat bogs such as Hani, Jinchuan and Gushantun peats (Fig. 1) (e.g. Hong et al., 2001; Cheng et al., 2008; Jiang et al., 2008; Mao et al., 2009; Zhou et al., 2010; Zhao and Liu, 2012), in the LVF, Northeast China. Our finding is significant in developing and extending the tephrochronology framework of this area and opens up a new perspective into studies of the late Holocene chronology for such widely distributed sedimentary contexts. B–Tm, used as an isochronous marker, has been detected in tsunami, marine, and lake sediments in Japan and surrounding region (e.g. Furuta et al., 1986; Nakagawa et al., 2002; Ikehara, 2003; Nanayama et al., 2003, 2007; Okuno et al., 2011; Hughes et al., 2013; Tanigawa et al., 2014). Consequently, the CMA offers a unique chance to link these sediment sequences across Northeast China to the Japan areas. Furthermore, the occurrence of this tephra in Greenland ice cores (Sun et al., 2014a) makes it possible to synchronize and precisely compare terrestrial, marine, and ice core archives.

The Medieval period of climate anomaly AD 950 to 1250 has been recorded at Northeast China (e.g. Chu et al., 2012; Wang et al., 2012; Chu et al., 2013), Japan (e.g. Goto et al., 2005), and other sites (e.g. Laird et al., 1996; Chu et al., 2002; Mann et al., 2009); however, their timing and intensity appear to vary regionally. High-precision chronology constrained by tephra layers can be used to reveal abrupt climatic transition and its geographic leads and lags effectively (e.g. Lane et al., 2013b), providing an insight into the mechanism of regional climatic change. The CMA, occurred at the onset of the Medieval climate anomaly (MCA) and can be used as a robust synchronization event, providing a valuable and unique opportunity to delineate time-transgressive processes in climatic studies around Northeast Asia during the MCA.

6. Conclusions

We present, for the first time, evidence that supports the extension of the western limit of the Changbaishan Millennium eruption to the LVF, ~120 km west of Changbaishan volcano, Northeast China. This stratigraphic, geochemical and ^{14}C geochronological data from Lake Sihailongwan sediments show a direct and precise correlation with continental records in Northeast China, marine records in the Sea of Japan, terrestrial records in Japan and Greenland ice cores. It also suggests that a great potential exists to detect distal cryptotephra layers in the sediments from Northeast China, facilitating a dated framework for archives of the Medieval period of climate anomaly.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2015.01.013.

Acknowledgments

We are grateful to G. Plunkett for her valuable suggestions during cryptotephra separation and comments on glass results. We acknowledge Y. G. Ma, J. Wu, L. C. Guo, Y. Z. Gong, Q. Gao and Y. Y. Li for their assistance in the lab. This work was supported by the National Natural Science Foundation of China (Grant Nos. 41272369, 41320104006, 41472320 and 41302102). The authors would like to thank to Dr Christine Lane, an anonymous reviewer and the editor for detailed and constructive reviews.

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