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Ash from the Changbaishan Qixiangzhan eruption: A new early Holocene marker horizon across East Asia

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Key Points:
- A tephra layer from Qixiangzhan eruption (QE) was identified in Yuanchi Lake ~30 km east of the Changbaishan volcano.
- Qixiangzhan explosive eruption was dated to ~8100 cal yr BP.
- Ash from Qixiangzhan eruption (QEA) can serve as a marker layer around East Asia.
Abstract

Prehistoric Holocene eruptions of Changbaishan volcano in Northeast China are poorly dated, with the exception of the AD 946 Millennium eruption (ME). Poorly refined age estimates for the earlier eruptions present problems for the reconstruction of the eruptive history of the volcano. The Qixiangzhan eruption (QE) is a major controversial event in terms of its eruptive timing (ranging from ~88 kyr to ~4 kyr) and style (effusive or explosive). As a result of the imprecise age estimates for the eruption, a geomagnetic field excursion recorded within the QE comendite has been variably correlated with a number of different excursion events observed elsewhere. In this study, a visible early Holocene tephra was identified in Yuanchi Lake, ~30 km east of the Changbaishan volcanic vent, and was dated to 8831-8100 cal yr BP using Bayesian age modelling. Glass shard compositions enable the correlation of this tephra with the poorly dated QE, as well as with a tephra (SG14-1058) recorded in Lake Suigetsu, in central Japan. These correlations confirm that the QE was explosive, and that the ash from Qixiangzhan eruption (QEA) can serve as an important early Holocene marker bed across East Asia. In addition, we propose an age of ~8100 cal yr BP for the QE based on the precise date of the Suigetsu SG14-1058 tephra. Our results also confirm that the geomagnetic field excursion recorded in the Qixiangzhan comendite dates to ~8100 cal yr BP.

1. Introduction

Changbaishan volcano (also known as Paektu, or Baitoushan; 128°03'E, 42°00'N), an intraplate stratovolcano on the border between China and North Korea (Fig. 1), is known for its Millennium eruption (ME) at AD 946 which erupted ~100 km³ of tephra into the atmosphere (Horn and Schmincke, 2000; Oppenheimer et al., 2017; Xu et al., 2013; Wei et al., 2003). Tephra from this eruption is an important marker bed from northeast China to Japan, and in the Greenland ice sheet (e.g. Chen et al., 2016; Hughes et al., 2013; Machida and Arai 1983; McLean et al., 2016; Sun et al., 2014a, 2015). Changbaishan volcano experienced several explosive eruptions during the Holocene, in addition to the ME (Sun et al., 2017; Wei et al., 2013; Zou et al., 2010).
However, the other explosive eruptions of Changbaishan, such as the controversial Qixiangzhan eruption (QE), are less well-studied. The latter eruption produced the Qixiangzhan comendite and derives its name from the weather station (qixiangzhan in Chinese) on the northern summit of Changbaishan volcano (Fig. S1).

Characterizing geomagnetic field excursions is crucial for understanding the operation of the geodynamo (Singer et al., 2014). The QE is of substantial interest because it recorded a geomagnetic field excursion within its welded pyroclastic deposits (e.g. Singer et al., 2014; Zhu et al., 2000). Previous age estimates for the QE ranged from ~88 kyr to ~4 kyr (Table 1; Li et al., 1999; Liu and Wang 1984; Pan 2016; Singer et al., 2014; Wei et al., 2013; Yang et al., 2014; Yin et al., 1999). However, the precise timing of QE is still unresolved which has resulted in miscorrelations of this geomagnetic field excursion with excursions recorded elsewhere. For example, Zhu et al. (2000) tried to correlate this excursion to the ~120 kyr Blake event using relatively imprecise K-Ar and $^{40}$Ar/$^{39}$Ar dating results. Most recently, Singer et al. (2014) correlated it with the Hilina Pali excursion at around 17 kyr using new $^{40}$Ar/$^{39}$Ar dating results directly obtained from the Qixiangzhan comendite, and thus reported a new excursion event which they named “Hilina Pali/Tianchi”.

There is a ~30 m pyroclastic fall deposit (corresponding to the sub-units of lower grey fall NS-1 and upper yellow fall NS-2 described by Sun et al. (2017), hereafter referred to as the pre-ME event) on the northern summit of Changbaishan volcano, and $^{40}$Ar/$^{39}$Ar dating of the fall deposits assigned an age of ~4 kyr to this eruption (Yang et al., 2014). However, there is still uncertainty regarding the relationship between the timing of QE and that of the explosive pre-ME eruption due to the unresolved dating of the QE (Table 1). Consequently, precise dating of the QE is crucial, not only for paleomagnetic studies but also for correlations of the Changbaishan proximal field exposures.

Tephra from explosive eruptions can be deposited over a large area, forming widely distributed marker beds which are important chronological tools for palaeoenvironmental, geological, and archaeological studies (e.g. Cook et al., 2018; Lane et al., 2013, 2017; Lowe 2011; van der Bilt et al., 2017). Whether the QE
produced extensive pyroclastic deposits or merely effusive lava flows has been debated for several decades (Fan et al., 1999; Li et al., 1999; Liu et al., 1998, 2007; Pan et al., 2013). Tephra from the Holocene explosive eruptions of Changbaishan may have been transported and deposited several kilometers away from the volcanic vent (Sun et al., 2017). Therefore, characterizing the eruptive style of the QE is also important for tephrochronological research during the early Holocene.

A Changbaishan sourced tephra layer (SG14-1058) dated to around 8166-8099 cal yr BP (95% confidence) has been detected in Lake Suigetsu, central Japan (McLean et al., 2018). However, it is still not clear which eruption of Changbaishan volcano can be correlated with this tephra layer. The age of this tephra layer is near the abrupt cooling transition that occurred at around 8.2 kyr BP (i.e. the north hemispheric ‘8.2 event’, the duration of which is about 300 yr; Alley et al., 1997). Regional and global correlations of this event in palaeoenvironmental records is useful for understanding its causes, timing and mechanisms. Therefore, characterizing this Changbaishan-sourced tephra layer is important not only for its chronological marker significance for synchronizing the ‘8.2 event’ across regions, but also for better understanding the eruptive sequence of the less-studied Changbaishan volcano.

In this study, we use the tephrochronological method (from proximal Changbaishan exposures to distal lacustrine tephra records) to constrain the eruptive timing and style of the QE. We find that Changbaishan volcano experienced an explosive eruption at ~8100 cal yr BP, i.e. the QE. In addition, the ash from Qixiangzhan eruption (QEA) is confirmed as forming another important time-equivalent marker bed across East Asia through its correlation with the tephra record in central Japan. Our results also confirm that tephrochronology is important for dating the explosive eruptions of this less well-studied volcano.

2. Material and methods

2.1 Proximal Qixiangzhan comendite

At the Tianwenfeng Peak on the northern summit of Changbaishan volcano, there
is a conspicuous ‘lava flow’-like landform: the Qixiangzhan comendite (Fig. S1). The feature extends to about 5 km in length, about 400-800 m in width and about 50-150 m in thickness (Pan et al., 2013; Yang et al., 2014). It consists of welded grey pyroclastic deposits, which were sampled in this study to characterize the major element geochemistry of its glass component (Fig. S1; Pan et al., 2013).

2.2 Yuanchi Lake

Yuanchi Lake (YC: 42°01′55″N, 128°26′07″E 1270 m a.s.l; Fig. 1), ~30 km east of the Changbaishan volcanic vent, is a shallow lake, ~200 m in diameter with a maximum water depth of ~1 m (Fig. 2). The lake is mainly supplied by rainwater and groundwater, and there are no inflowing or outflowing streams. Previous studies ascribed the formation of Yuanchi Lake to a phreatomagmatic eruption given its circular-shape, and thus it is designated a maar lake (Jin and Zhang 1994). However, there are no phreatomagmatism-related tuff rings around the lake and its origin needs to be studied in more detail in the future.

In March 2017, three parallel sediment cores with a composite length of 4.45 m were obtained from the center of Yuanchi Lake. The cores were transported to the laboratory in Beijing, split, described and sampled. The core can be divided into five lithological units: Unit 1 (4.45-4.15 m) consists of yellow coarse sand; Unit 2 (4.15-2.01 m) consists of silty mud containing occasional volcanic breccias; Unit 3 (2.01-0.91 m) consists of dark organic mud with a visible patchy tephra layer at around 162 cm; Unit 4 (0.91-0.41 m) is the Millennium light grey pyroclastic fall deposit consisting of well-sorted pumice lapilli; and Unit 5 (0.41-0 m) consists of silty clay interbedded with pyroclastic deposits.

2.3 Tephra separation

A visible patchy grey tephra layer was identified at 1.62 m depth (YC162) in Yuanchi Lake sediment. It consisted of a discontinuous tephra layer, with tephra patches extending up to 1.58 m. Usually, such an irregular distribution of a tephra bed in sedimentary sequences signifies post-depositional processes, e.g., the fallout of
tephra on snow cover (Housley and Gamble, 2015). Tephra samples were picked from the core, and then were treated with 10% HCl to remove carbonates and with 30% H$_2$O$_2$ to remove organic material. Chemically-treated samples were sieved, and particles between 30 μm and 80 μm were retained and then mounted and polished for electron microprobe analysis (EPMA).

2.4 Chronology

For the uppermost 221 cm of Yuanchi sediment, a total of seven plant macrofossil samples were selected and dated by accelerator mass spectrometry (AMS) at the Beta Analytic Radiocarbon Laboratory, Florida, USA (Table S1; Fig. 2). Radiocarbon ages were calibrated using the IntCal13 curve, and the calibrated ranges are reported as two standard deviations (Reimer et al., 2013).

2.5 Geochemical analysis

The major element composition of glass shards of proximal Qixiangzhan comendite and tephra recorded in YC was measured using a JEOL JXA 8100 electron probe microanalyzer (EPMA, with a wavelength-dispersive spectrometer (WDS)) at the State Key Laboratory of Lithospheric Evolution of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing. Ten major and minor 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 10 μm. Peak counting times used were 20 s for all elements except for Na (10 s), and the Na content was determined at the start of the analysis. Secondary standard glass from the MPI-DING fused glass, ATHO-G rhyolitic in composition, was used to check the precision and accuracy of the data (Jochum et al., 2006).

3. Results

Proximal Qixiangzhan comendite from Changbaishan volcano contains colorless glass (Fig. 3A, B). The tephra layer (YC162) consists predominantly of colorless cuspate and pumiceous glass shards with a maximum length of 300 μm (Fig. 3C, D).
For the YC162 tephra, SiO$_2$ varies from 73.60-77.73 wt %, CaO from 0.16-0.32 wt %, and FeO from 4.02-4.50 wt % (Fig. 4; Table S2). Volcanic glass compositions from the Qixiangzhan comendite range from 75.49-76.16 wt % SiO$_2$, 0.12-0.23 wt % CaO, and 3.65-4.26 wt % FeO (Fig. 4; Table S2).

When considering the evidently patchy distribution of the YC162 tephra, the first appearance of the tephra should represent the timing of volcanic eruption. In this study, we established a Bayesian-based chronology using the age-depth modelling software Bacon v2.2 (Blaauw and Christen, 2011), and an age of 8831-8100 cal yr BP (95% confidence; Fig. 2) was assigned to the YC162 tephra.

4. Discussion

4.1 Source of the YC162 tephra and eruption timing of the QE

The ratio of FeO to CaO of the glass component of tephras from Changbaishan enables tephra from this source to be easily separated from those from the neighboring volcanic regions of Japan, Kamchatka, and Ulleungdo (Fig. 5; Sun et al., 2014b). YC162 tephra falls in the field of Changbaishan volcano, illustrating that this tephra most likely derives from Changbaishan.

During the Holocene, Changbaishan volcano experienced historical eruptions at around AD 1403, AD 1668, AD 1702 and AD 1903, the Millennium eruption (ME) at AD 946, and the pre-ME event at ~4 kyr (Oppenheimer et al., 2017; Sun et al., 2017; Wei et al., 2003; Yang et al., 2014). When considering the previous dating results for the Qixiangzhan comendite (Table 1), the controversial QE also might be considered as a Holocene eruption.

The stratigraphic relationships between the Qixiangzhan comendite and the pre-ME fall deposits on the northern summit are unclear because of the incomplete preservation of the proximal eruptive sequences caused by subsequent eruptions. Unfortunately, the previously poorly resolved dating (Table 1) of the Qixiangzhan comendite has resulted in the ages of these eruptives becoming increasingly unclear. However, the glass geochemical composition of the Qixiangzhan comendite and
YC162 tephra are evidently distinct from the pre-ME fall deposits, which have a substantially higher FeO content (Fig. 4). Consequently, regardless of the ages of these two events, it is clear that the YC162 tephra in Yuanchi Lake is not from the eruption corresponding to the ~ 4 kyr pre-ME.

Ash geochemistry from the Changbaishan ME has been relatively well-characterized over the past few decades based on extensive proximal sampling and distal tephra records (Chen et al., 2016; Hughes et al., 2013; McLean et al., 2016; Sun et al., 2014a, b, 2015, 2017). The Qixiangzhan comendite has a glass composition which cannot be separated from the rhyolitic member of the ME (Fig. 4). However, ash from the ME usually has light brown shards (Sun et al., 2015), which are absent in the QEA (Fig. 3), and typically the Changbaishan ME has glass compositions ranging from rhyolite to trachyte. In addition, the field exposures near Yuanchi Lake show that the ME ash also contains glass shards ranging in composition from trachytic to rhyolitic (Sun et al., 2017). Therefore, the YC162 tephra cannot be from the rhyolitic member of the ME.

The field-observed vesicular Qixiangzhan comendite, and the vesicular structure of the glass shards (Fig. 3), demonstrate that the QE was an explosive eruption (e.g. Pan et al., 2013). The YC162 tephra has a glass composition consistent with that of the Qixiangzhan comendite (Fig. 4) implying that this tephra is from the QE. The Bayesian-modelled age for the YC162 (8831-8100 cal yr BP, 95% confidence) falls in the age range of the QE (Table 1), which also supports our contention that the YC162 tephra is from QE. The QEA detected in the Yuanchi Lake ~30 km away from the Changbaishan volcanic vent strongly supports that the QE being an explosive eruption.

The most recent tephrochronological studies from Lake Suigetsu revealed a tephra layer (SG14-1058) dated to around 8166-8099 cal yr BP (95% confidence) (McLean et al., 2018). The authors correlated it with Changbaishan given that the same volcano usually produced similar products; however, it is difficult to constrain the tephra to a specific eruption because of the lack of proximal sequences with which to compare it. The modelled age-range of YC162 tephra from Yuanchi Lake also
overlaps with that of the Suigetsu SG14-1058 tephra (8166-8099 cal BP) at the 95% confidence interval, and we propose that the two tephras were erupted by the same event.

The SG14-1058 tephra exhibits similar glass major element compositions to those from YC162 tephra and Qixiangzhan comendite within the range of uncertainty (Fig.4 and Fig. 5). Minor alkaline (i.e. Na$_2$O and K$_2$O) and SiO$_2$ offsets between YC162, Qixiangzhan and the published SG14-1058 tephra may be explained by slight differences in instrumental precision, as revealed by the secondary glass (ATHO-G) standard data reported here and by McLean et al. (2018) and with respect to accepted values for this standard (Jochum et al., 2006). Therefore, we propose that both the SG14-1058 tephra recorded in Lake Suigetsu and the YC 162 tephra can be correlated with the Qixiangzhan comendite, and thus we assign an age of ~8100 cal yr BP to the eruption timing of QE using the more refined date of the SG14-1058 tephra from Lake Suigetsu.

4.2 Geochronological implications

Previous age estimates of the QE are typically older than 10 kyr (Table 1). Tephrochronological constraints by Bayesian age modelling from Yuanchi and Suigetsu Lakes assign an age of ~8100 cal yr BP to the QE, which is younger than most $^{40}$Ar/$^{39}$Ar-derived age estimates. Only Heizler et al. (2015)'s $^{40}$Ar/$^{39}$Ar age estimate is similar to our modelled age for QE. Older age estimates obtained by $^{40}$Ar/$^{39}$Ar dating may have resulted from excess argon in melt inclusions, and xenocrysts or phenocrysts (Heizler et al., 2015; Ramos et al., 2016). Tephra layers recorded in the lake and peat sediments around the volcano therefore offer an important means to resolve problems relating to the eruption timing and to reconstruct the eruptive sequence of an active volcano, such as the less studied Changbaishan volcano. In addition, our modelled age for the QE also implies that a geomagnetic field excursion younger than the 17 kyr Hilina Pali excursion was recorded in the Changbaishan Qixiangzhan comendite (e.g., Singer et al., 2014; Zhu et al., 2000). $^{238}$U-$^{230}$Th dating yielded an age of about 12 kyr for the QE (Wang et al., 2001;
Zou et al., 2014), and this zircon age is also older than the tephrochronological age estimate obtained in the Yuanchi and Lake Suigetsu records. Combining the zircon ages with tephrochronologically-constrained eruption timing implies that the magma residence time for the QE was about 4 kyr. Zircon age and Ra/Th isotopes suggest that the ME magma residence time is about 6-10 kyr (Ramos et al., 2016; Zou et al., 2010, 2014). Such a residence time of ME magma is similar to the age of QE assigned by this study (i.e. ~8100 cal yr BP). In addition, temperature estimated from alkali feldspar-glass geothermometry assigned a temperature of ~740 °C to the Millennium comenditic magma, and ~710 °C to the Qixiangzhan comenditic magma (Zou et al., 2010, 2014). Therefore, it is highly plausible that the comenditic magma existed beneath the Changbaishan volcano for a long time, and the QE was a precursor for the ME.

4.3 A new marker horizon across East Asia

Correlations of the YC162 tephra and SG14-1058 tephra recorded in Lake Suigetsu firmly establishes the QEA as another important Changbaishan-sourced marker horizon from central Japan to northeast China (Fig. 1). The timing of the QE eruption is near the ‘8.2 event’ which is an important rapid cooling event which occurred at around 8.2 kyr BP (Alley et al., 1997), and this event also can be detected in the Hani peat bog from Longgang volcanic field, ~120 km west of Changbaishan (Hong et al., 2009a, b). When considering the occurrence of the QEA in central Japan, and the relative short distance from Changbaishan to Hani peat, the widespread QEA has the potential to serve as an important marker bed for synchronizing palaeoenvironmental records around the time of the ‘8.2 event’ from Japan to northeast China.

Ash clouds from Changbaishan eruptions were predominantly transported to the east of this volcano, such as the eastern tephra dispersal of the ME and several visible tephra layers recorded in the Japan Sea while only the cryptotephra from ME was identified in Lake Sihailongwan to the west of Changbaishan (Fig. 1) (Ikehara 2015; Sun et al., 2015). Ash from the Changbaishan ME has been identified in sediments
from northeast China to the Japan Sea, Japan Island, and even Greenland ice cores, and thus forms an important north-hemispheric marker horizon (Chen et al., 2016; Hughes et al., 2013; Machida and Arai 1983; McLean et al., 2016; Sun et al., 2014a, 2015). The correlations of the Qixiangzhan comendite, YC162 tephra and SG14-1058 in Lake Suigetsu at least implies that the QEA was mainly transported to the southeast of Changbaishan volcano (Fig. 1). The similarity in the distribution of the ME and QE tephas may indicate that the QEA was also predominantly transported to the east of Changbaishan volcano, and the eruption season of QE may be in line with that of ME (autumn to winter) assuming a similar early Holocene weather pattern (i.e., wind direction) with that today (Oppenheimer et al., 2017). The high concentration of QEA glass recorded in Lake Suigetsu (> 5,000 shards per gram of sediment; McLean et al., 2018) strongly suggests that the QEA may be dispersed in a wider area than the present modest estimated distribution of this study (Fig. 1). Thus this tephra layer potentially offers an important early Holocene marker horizon around East Asia that has not before been recorded because of the limited application of cryptotephra studies in this region. This study implies that searching for cryptotephra in the sedimentary archives beyond the volcanic regions of East Asia would be of immense value to palaeoclimate and volcanological studies.

5. Conclusions

The ash from Qixiangzhan eruption (QEA) was identified in Yuanchi Lake ~30 km east of Changbaishan volcano. The visible YC162 tephra and distal tephra (SG14-1058) layers recorded in Lake Suigetsu, Japan (Maclean et al., 2018), demonstrate that the Qixiangzhan eruption (QE) was explosive and that the resulting QEA can serve as a marker bed from central Japan to northeast China. This study assigned a date of ~8100 cal yr BP to the QE. This age estimate for QE confirms that a geomagnetic field excursion younger than the 17 kyr Hilina Pali excursion was recorded in the Changbaishan Qixiangzhan comendite (Singer et al., 2014).

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Figure 1. Location and regional topography of Changbaishan volcano (CBS) and Yuanchi Lake shown by a digital elevation model (spatial resolution is ~30 m; data are from www.gscloud.cn). The inset map (base map from NaturalEarthData.com) shows the known tephra dispersal from the Changbaishan ME (dashed line) and QE (yellow shading), as well as the position of Lake Suigetsu and Sihailongwan maar lake (SHL). Black dots represent the locations of major sites from which the B-Tm tephra has been reported (Sun et al., 2017).

Figure 2. Bayesian age-depth model for the sediment core from Yuanchi Lake. Dashed line represents the position of the YC162 tephra attributed to the QE of Changbaishan volcano. Inset images show Yuanchi Lake, and the position of the coring site (upper), and the YC162 tephra in the lake sediment (lower).

Figure 3. Photos of the comendite from Qixiangzhan, north summit of Changbaishan volcano (A and B) and the tephra recorded in Yuanchi Lake (C and D).

Figure 4. Biplots of glass shards showing comparisons of the Qixiangzhan comendite from proximal Changbaishan volcano, Yuanchi Lake, and Lake Suigetsu from Japan. Envelopes represent the geochemical range of glass shards from the Changbaishan Millennium eruption (ME), and the pre-Millennium eruption (pre-ME, that is the fall deposit of subunits NS-1 and NS-2) is included. Glass data sources: ME is from Chen et al., (2016), Hughes et al., (2013), Sun et al., (2015, 2017); pre-ME is from Sun et al., (2017); Suigetsu is from McLean et al., (2018). Representative error bars for the Yuanchi and Qixiangzhan tephras (2 SD) were calculated from secondary glass standard analyses.

Figure 5. FeO-CaO biplot differentiating tephra from Changbaishan from other adjacent volcanic regions. Glass data sources: Kamchatka is from Hesegawa et al., (2011), Kyle et al., (2011), Ponomareva et al., (2015, 2017); Japan is from Aoki and Machida, (2006); Ulleungdo is from Machida et al., (1984), Smith et al., (2011);...
Figure 1.
Figure 2.
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Table 1. Published dating results of the Qixiangzhan eruption (QE).

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<td>This study</td>
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