Terminal middle Pleistocene eruptions of Changbaishan-Tianchi volcano in northeast China: Triggered by the glacial/interglacial climatic transition?

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Key Points

- Bingchang eruptions took place around 137.7-124.2 ka
- Bingchang eruptions were likely triggered by the Penultimate Deglaciation
- The peak timing of the Penultimate Glacial Maximum dated to 142.7-137.7 ka

Abstract

High-resolution $^{40}Ar/^{39}Ar$ dating of Bingchang (BC) eruptions of Changbaishan-Tianchi volcano in NE China yields an oldest plateau age of 137.7 ka, well coinciding with the onset of the Penultimate Deglaciation (PDG). Subsequent eruptions occurred at 132.5-131.7 and 124.2 ka during the PDG and the early phase of the Last Interglacial. The BC tephra in marine sediments from the Japan Sea was deposited during the glacial/interglacial climatic transition. These findings suggest that the BC eruptions were likely triggered by depressurization of the volcano's magma chamber through mountain glacial melting/retreat during the early phase of the PDG. The peak timing of the Penultimate Glacial Maximum thus derived falls between 142.7-137.7 ka, closely tied to the time of maximum global ice volume/sea level drop at ~140 ka. Since the BC tephra is widely dispersed in marine sediments in the Japan Sea, it will serve as a new well-dated stratigraphic marker for the region.

Plain Language Summary

Changbaishan-Tianchi volcano is a major active stratovolcano in northeast China. It had an episode of explosive Bingchang (BC) eruptions that might have been triggered by major climate changes during the terminal middle Pleistocene. High-resolution radiometric dating of the volcanics indicates that the BC eruptions took place around 137.7-124.2 ka. The distal tephra deposits of these eruptions are linked to the previously-identified B-KY1 tephra in marine sediment cores from the Japan Sea, which was deposited during the penultimate glacial/interglacial transition. Our findings suggest that the BC eruptions were likely triggered by depressurization of the magma reservoirs of the volcano due to glacial melting and retreat during the early phase of the Penultimate Deglaciation (~138-128 ka). This study also yields new well-dated age constraints of 142.7-137.7 ka for the peak timing and duration of the Penultimate Glaciation.

Keywords: Bingchang eruption; B-KY1 tephra; magma chamber depressurization; glacial/interglacial climatic transition; Penultimate Glacial Maximum.

1. Introduction

The Changbaishan-Tianchi volcano (CBS-TC; 42°01`N/128°03`E) is a major active stratovolcano located at the border region between China and Democratic People's Republic of Korea (DPRK) (Figure 1). It is well known for its 946-947 CE Millennium Eruption (ME) and has been of intensive research focus following its 2002-2005 unrest episode (Pan et al., 2017; Xu et al., 2012). Volcanic activities at CBS-TC began around ~22 Ma with widespread basaltic shield-building basaltic magmas. Cone-formation started at ~1 Ma with magmatic compositions ranging from trachytic to peralkaline rhyolitic. Multiple Plinian eruptions during the late Pleistocene are considered to be responsible for the formation of the summit caldera (Wei et al., 2013). The ME was the last major eruption of this volcano (VEI 6.2-7.0) (Oppenheimer, 2017; Yang et al., 2021), with distal tephra deposits (B-Tm) identified in marine sediment cores from the Japan Sea and Hokkaido, Japan (Chen et al., 2016) (Figure 1). Various Cenozoic explosive eruptions prior to the ME have been identified but still remain poorly studied (Jin & Zhang, 1994; Liu et al., 2008).

Here we report a proximal suite of grey tephra and black tuff along Heishi Valley (HSV) and Erdaobai Valley (EBV) in the CBS-TC volcanic field (Figure 1). High-resolution $^{40}Ar/^{39}Ar$ dating of the volcanics indicates that they were produced during the Bingchang (BC) eruptions around 137-124 ka. Electron microprobe analyses of the BC eruptives reveal that their chemical compositions closely match that of the B-KY1 tephra in marine sediment cores from the Japan Sea, which was deposited at the boundary of Marine Isotope Stage (MIS) 6/5 during the glacial/interglacial climatic transition (Chun et al., 2006; Chun & Cheong, 2020). These findings suggest that the BC eruptions were likely triggered by depressurization of the volcano's magma chamber through mountain glacier melting and retreat during the early phase of the Penultimate Deglaciation (PDG, ~138-128 ka) (Menviel et al., 2019). Furthermore, the $^{40}Ar/^{39}Ar$-dated BC/B-KY1 tephra yields new age constraints of 142.7-137.7 ka on the peak timing and duration of the Penultimate Glacial Maximum (PGM) recorded in the marine sediment cores, which substantiate the LR04-based chronology of the PGM (Lisiecki & Raymo, 2005; Menviel et al., 2019).

2. The BC eruptions and the B-KY1 tephra layer

The proximal products of the BC eruptions were first described by Jin and Zhang (1994). These eruptives outcrop mainly as tephra fall (BC-T) in HSV and as pyroclastic deposit (BC-P) in EBV

(Figure 1). BC-T is ~2 m thick and composed of white to grey pumice at the bottom and pale-yellow pumice at the top (Figure S1) with abundant lithic and crystal fragments. Discrete, juvenile pumice comprises ~80% of the deposit, with a maximum clast size of ~5 cm and modal size of 2-3 cm. Lithic fragments are primarily of trachyte and basalt with a maximum size of ~1 cm. Crystal fragments are primarily of ~1 mm-sized feldspar with minor quartz, pyroxene, and olivine. BC-P is exposed along EBV, with a total thickness of ~200 m (Figure S1). Owing to its proximity to the edifice of the volcano, BC-P is moderately to intensely welded, composed of volcanic ash and deformed clasts (fiamme) with abundant feldspar crystal fragments (~30%). Large lithic fragments up to 10s of cm are observed in BC-P. The eruptive products from the trachytic phase of the ME (ME-Tr, 20-30 m thick) are superficially similar to the BC eruptives here, but they can be distinguished via welding extent and/or $^{40}Ar/^{39}Ar$ dating (Pan et al., 2017).

The B-KY1 tephra layer was first reported in the 20EEZ-1 core (611.5-615.6 cmbsf) and later fully described in the ODP 794A core (585.6-587.2 cmbsf) from the Janpa Sea (Chun et al., 2006; Chun & Cheong, 2020) (Figure 1). It is about 1.6 to 4.1 cm thick in the marine sediment cores and consists of pumice shards, bubble-wall shards, and minor phenocrysts. The compositions of B-KY1 tephra range from alkaline trachyte to sub-alkaline rhyolite, similar to that of B-Tm tephra (Figure 2; Table S1). Moreover, B-KY1 tephra was noted as a sharp boundary layer between the underlying dark laminated mud (DLM) and the overlying light bioturbated mud (LBM) in the marine sediments (Chun & Cheong, 2020; Tamaki et al., 1990). The deposition of both DLM and LBM layers reflects dramatic changes in the regional dynamics of oceanic current systems and bottom water conditions (anoxia vs. oxygenation) associated with the glacial/interglacial climatic transition (Chun & Cheong, 2020; Khim et al., 2007; Saavedra-Pellitero et al., 2019; Tada et al., 2018).

3. Sample collection and age determination

One sample of BC-T was collected from HSV (Figure S1). Loose tephra of size 2-4 cm was manually picked, then rinsed with deionized water in an ultrasonic bath for 30 minutes to remove surface impurities. Four samples of BC-P were collected from the east wall of EBV (i.e., BC-P3 at top and BC-P2 at bottom) and along the river channel (BC-P1L and BC-P1R) (Figure S1). They were cut to remove all surface material. Petrographic thin sections of the samples were prepared by Wagner Petrographic Inc., USA and then studied for textural and mineralogical characteristics.

Major elemental compositions of glass in BC-T (matrix) and BC-P (fiamme) were analyzed using a Cameca SX-100 electron microprobe (EPMA) at Oregon State University (OSU), USA. Sanidine phenocrysts were separated and prepared for $^{40}Ar/^{39}Ar$ dating. The phenocryst grains were irradiated for 1 hour at the OSU TRIGA reactor and then extracted and analyzed using a 25 W Synrad CO_2 laser and an ARGUS VI multi-collector mass spectrometer at the OSU Argon Geochronology Lab. The detailed processes of sample preparation and $^{40}Ar/^{39}Ar$ dating are given in the supporting material.

4. Results

4.1. Petrology and geochemical characteristics of the BC eruptions

BC-T is typically white or light yellow, vesicular (30-40%) with thin vesicle walls, and phenocryst-poor with 5-8 volume% crystals, composed of anorthoclase/Na-sanidine (~80%), Hedenbergite (~10%), fayalitic olivine (~5%), and quartz (~5%). BC-P is black welded tuff with abundant fiamme, and phenocryst-rich with 30-60 volume%, consisting of Na-sanidine (~90%), Hedenbergite (~5%), fayalitic olivine (~3%), and quartz (~2%). The compositions of BC eruptives broadly parallel that of the ME deposits, with BC-T similar to the ME comendite (ME-Com), and BC-P similar to the ME trachyte (ME-Tr) (Pan et al., 2017, 2020). Major element compositions of the BC glass display coherent trends between trachytic and comenditic (Figure 2).

4.2. $^{40}Ar/^{39}Ar$ geochronology of the BC eruptions

One BC-T and four BC-P samples were selected for $^{40}Ar/^{39}Ar$ dating via single-crystal incremental heating (SCIH) (Andersen et al., 2017; Ramos et al., 2016). Four to eight sanidine grains from each sample were measured with 15-17 steps of incremental heating. All analyses yielded uniform plateau ages with increasing laser power, although some show abnormal ages at lower and higher laser power due likely to excess argon (Andersen et al., 2017) (Table S2). For each sample, we report $^{40}Ar/^{39}Ar$ dating results that show a relatively younger weighted plateau age with more released ^{39}Ar gas (>90%) and a smaller MSWD value (Table 1; Figure S2). BC-T tephra sampled from HSV yields the oldest plateau age of 137.7 ± 0.9 ka, and it is therefore interpreted as a marker for the initial phase of the BC eruptions (Table 1). BC-P1L and BC-P1R, sampled from the lower parts of BC-P tuff along EDV, yield intermediate plateau ages of 131.7 ± 1.1 ka and 132.5 ± 0.4 ka, respectively. BC-P2 sampled from the bottom of the east cliff of EDV yields a plateau age of

132.2 ± 1.8 ka. This date overlaps with that of BC-P1L and BC-P1R within the 2σ age range, suggesting that these deposits were mostly likely originated from the same eruption around 131.7-132.5 ka. BC-P3 was collected at top of the east cliff above BC-P2, with a plateau age of 124.2 ± 0.8 ka, making it the youngest known eruption from the BC episode. Figure S3 depicts a cross-sectional distribution of volcanic deposits at EBV, showing BC pyroclastic flow sequences and relevant $^{40}Ar/^{39}Ar$ ages, along with ME-Tr deposits produced in 946-947 CE. These $^{40}Ar/^{39}Ar$ ages gradually decrease from BC-T to BC-P3, systematically corresponding to their positions in the stratigraphic sequence.

5. Discussion

5.1. BC eruptions as the source of the B-KY1 tephra

The relatively low FeO-CaO ratio of glass composition of BC-T tephra enables it to be easily identified among other volcanic eruptives in northeast Asia (Chun & Cheong, 2020; Sun et al. 2018). As illustrated in Figure 2, the proximal BC-T tephra in HSV is dispersed in composition between comenditic and trachytic, and is petrologically and geochemically similar to that of B-KY1 tephra in the Japan Sea. The composition of the BC-P tuff is also broadly consistent with that of B-KY1 but shows a wider dispersion. Furthermore, based on the LR04 benthic $\delta^{18}O$ timescale for the marine sediment core of ODP 794A, the depositional age of B-KY1 tephra was estimated to be around ~135 ka by Chun & Cheong (2020), overlapping with our $^{40}Ar/^{39}Ar$ ages of 137-124 ka for the BC eruptions. Taken together, these pieces of evidence indicate that B-KY1 tephra was most likely sourced from the CBS-TC volcano and thus represents the distal tephra deposit of the BC eruptions at locations about 600-900 km southeast of the summit caldera (Figure 1).

5.2. Climatic change as a possible trigger for the BC eruptions

There is a growing recognition that volcanism can be initiated and/or exacerbated by magma chamber depressurization at its overlying surface during glacier retreating and/or sea level drop (Albino et al., 2010; Cooper et al., 2018; Huybers & Langmuir, 2009; Rampino et al., 1979; Schmidt et al., 2013). For instance, the magmatism of mid-ocean ridges appears to keep pace with changing sea levels and Milankovitch glacial-interglacial cycles (Crowley et al., 2015; Lund & Asimow, 2011). Large variations and increase in eruption rate across Iceland over the past 10,000 years were likely caused by the last deglaciation through ice sheet removal-induced mantle melting

(Jull & McKenzie, 1996). Increased volcanic activities at Santorini, Greece have been associated with >40 m sea level drops over the past 360,000 years (Satow et al., 2021).

The Changbaishan Range consitutes the mountaneous terrains spanning the latitudes of 38°46'-47°30′N and longitudes of 121°08'-134°00'E in northeast China. As the highest peak of the mountain range, the CBS-TC crater is 25-30 km in diameter at its base and rises to an altitude of 2749 m on the caldera rim (Wei et al., 2013) (Figure 1). Regional climate is of temperate continental mountain type influenced by the North Pacific monsoons and the Siberian anticyclone, with mean annual temperature of -7.3°C and annual precipitation of 1342 mm measured near the summit caldera (Shi, 2005). The present-day theoretical snow line is estimated to be around 3380 ± 100 m (Zhang et al., 2008). Although thick snow accumulates during winters and springs, no modern glaciers have developed in the summit areas.

However, large-scale glaciers are known to have developed in the summit areas during the Last Glacial Maximum (LGM; 26-19 ka). Numerous glacial features are well preserved around the caldera and their formation was attributed to the LGM (Shi et al., 2005; Zhang et al., 2008). These include glacial cirques, trough valleys, and glacial striations both inside the caldera and on the crater slopes. The level of cirque floors defines the equilibrium line altitude (ELA) to 2000-2300 m during the LGM, about 1000-1200 m lower than that in the Tianshan Mountains of western China at the same latitude, suggesting that maritime temperate mountain glaciers have covered the crater areas due to increased winter monsoonal precipitation during the LGM (Shi et al., 2005).

During the PGM, the altitude of the CBS-TC crater before the BC eruptions is speculated to be considerably high around 3500-4000 m (Wei et al., 2013), well above the northern hemisphere glacial altitude of ~2300 m in the regions around 40-42°N latitudes (Evan & Cox, 2005). Therefore, the crater and its surrounding areas were likely heavily glaciated during the PGM. Since the PGM was much severer and more protracted than the LGM over Eurasia (Colleoni et al., 2016; Svendsen et al., 2004), the overlying glaciers and snow/ice cover on the pre-BC crater were presumably much thicker than during the LGM, imposing large gravitational load-induced pressure on the underlying magma chamber. Furthermore, seismic tomographic studies of the volcano (Zhao et al., 2009; Zhu et al., 2019) indicate that its formation is related to the upwelling of hot and wet asthenospheric materials in the big mantle wedge above the stagnant Pacific slab and was likely caused by plate tectonic processes in the upper mantle. The crustal magma chamber of the volcano, about 5-15 km below the ground surface (Xu et al., 2012), accumulated highly-evolved and volatile-rich magma and thus attained an excessively high pressure condition during the terminal phase of the PGM. Following the onset of the PDG at ~137-138 ka (Clark et al., 2020) (Figure 3c) and as an early response to the deglacial climate change due to the crater's relatively lower latitude (42°N), mountain glaciers and snow/ice cover were rapidly reduced or completely removed from the pre-BC crater and surrounding regions, which likely induced depressurization of the crustal magma chamber. The deglaciation also led to increased melting in the upper mantle which supplied the more primitive basaltic melts to the shallow reservoirs for imminent eruptions (Cooper et al., 2018; Iacovino et al., 2016; Pan et al., 2017). Such a glacial/interglacial climatic transition is speculated to serve as a possible trigger for the BC eruptions.

Evidence from the marine sediment cores in the Japan Sea appears to support this scenario. During the terminal phase of the PGM, the global sea level dropped below -90 to -120 m (Bintanja et al., 2005; Grant et al., 2014; Menviel et al., 2019) (Figure 3b), which caused the near closure of the Tsushima Strait (TSS) and the cessation of Tsushima Warm Current (TWC) into the Japan Sea (Gorbarenko & Southon, 2000; Khim et al., 2007; Tada & Irino, 1999; Tada et al., 2018) (Figure 1a). As a result, the Japan Sea became a large isolated and stratified water body facilitating the condition of bottom water anoxia (Khim et al., 2007; Tada et al., 2018). In the ODP 794A, 20EEZ-1 and other marine sediment cores, the deposition of the stratigraphically lower DLM layer reflects bottom water anoxia during the terminal phase of the PGM (Chun & Cheong, 2020; Khim et al., 2007; Tada et al., 2018). An upward transition to the LBM layer reflects bottom water oxygenation generated by restored oceanic circulations through the reopening of the Japan Sea to the Pacific during the PDG (Chun & Cheong, 2020; Khim et al., 2007; Tada et al., 2018). The B-KY1 tephra layer in the marine sediment cores was deposited between the underlying DLM and the overlying LBM layers (Figure 3d, e), suggesting that the BC eruptions were concurrent with and therefore likely triggered by the glacial/interglacial climatic transition.

5.3. Implication for the peak timing and duration of the PGM

The PGM often refers to the maximum advance of the Eurasian ice sheet around ~160-140 ka (Colleoni et al., 2016; Svendsen et al., 2004). In the LR04 benthic $\delta^{18}O$ stack record, the peak phase of the PGM is characterized by the deepest trough of the $\delta^{18}O$ curve interpreted to represent the interval of maximum global sea level drop and (inversely) global ice volume during MIS 6

(Grant et al., 2014; Lisiecki & Raymo, 2005; Menviel et al., 2019). Based on the LR04 age model, the peak timing of the PGM is centered at 140 ka, with a duration of 6 kyr from 143 to 137 ka (Figure 3c). U/Th dating of Tahitian fossil corals (Thomas et al., 2009) indicates sea level rise to -85 m and an inception of the PDG by 137 ka. Transient climate simulations (Clark et al., 2020) further show that both the Greenland and the Antarctic Ice Sheets start to deglaciate from their PGM extents at ~137.5 ka. These age data are consistent with the LR04-based chronology of the PGM (Figure 3c). ^{40}Ar/^{39}Ar dating of BC/B-KY1 tephra from this study yields new age constraints on the peak timing and duration of the PGM that substantiate the LR04-based chronology, as discussed below.

In the Japan Sea, the DLM layer overlain by the ^{40}Ar/^{39}Ar dated BC/B-KY1 tephra at the ODP 794A site was deposited at the depth interval of 606.2 to 587.2 cmbsf, with a sedimentation rate of ~3.5 cm/kyr estimated for the top core section of the hole (0-2550 cmbsf) (Tamaki et al., 1990). This sedimentation rate is however too crude to be used for accurate age estimating of marker layers in the core due to its large temporal variations (Chun & Cheong, 2020; Tamaki et al., 1990). During IODP Expedition 346, hole U1424A was dilled at a site about 600 m east of the 794A site. The DLM layer identified as marker layer "2-1" at the depth interval of 607.2-587.2 cmbsf is stratigraphically correlated with the DLM layer at the 794A site, and their deposition was interpretated to reflect a period of bottom water anoxia associated with the terminal phase of the PGM when the global sea level dropped below -90 m (Chun & Cheong, 2020; Tada et al., 2018).

Based on the LR04-tuned high-resolution age model of hole U1424A, the linear sedimentation rate (LSR) of the core section (607.2-485 cmbsf) that contains DLM layer "2-1" is 3.759 cm/kyr (Tada et al., 2018). Given the short distance of ~600 m between the two sites, the same sedimentation rate of 3.759 cm/kyr is thus assumed for the deposition of the DLM layer at the 794A site. Assigning the ^{40}Ar/^{39}Ar age of 137.7 ka to the top of this DLM layer (19 cm in thickness), we estimate an age of 142.7 ka for its base. These new age constraints bracket a depositional time interval of 5 kyr for the DLM layer, corresponding to the duration of the peak phase of the PGM from 142.7 to 137.7 ka recorded in the marine sediments. The mean age of 140.2 ka for the DLM layer is closely tied to the peak timing of the PGM at 140 ka (Lisiecki & Raymo, 2005) (Figure 3c). The 5-6 kyr duration of the peak phase of the PGM is also comparable to the 6-7 kyr duration of the LGM (26.5-19 to 20 ka) (Clark et al., 2009), which may yield new insights into the ice-sheet formation and dynamics during past glacial-interglacial cycles (Clark et al., 2020; Colleoni et al., 2016; Hughes & Gibbard, 2019; Rohling et al., 2017).

6. Conclusion

The BC eruptive episode of the CBS-TC volcano took place in the terminal middle Pleistocene around 137.7-124.2 ka. The distal tephra deposits of these eruptions are linked to the previously-identified B-KY1 tephra in the marine sediment cores from the Japan Sea, which marks the MIS 6/5 boundary associated with the glacial/interglacial climatic transition. Our findings suggest that the BC eruptions were likely triggered by depressurization of the magma reservoirs of the volcano due to glacial melting and retreat during the early phase of the PDG. In addition, this study provides new absolutely dated age constraints of 142.7-137.7 ka for the peak timing and duration of the PGM recorded as DLM layers in the marine sediments. Since the BC tephra is widely dispersed in marine sediments in the Japan Sea, it will serve as a new well-dated stratigraphic marker for the region.

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Data Availability Statement

The geochemical and geochronological raw data of the BC eruptions are available at the following data repository: https://doi.org/10.5281/zenodo.6658808.

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Figure Captions

Figure 1. Spatial distribution of BC eruption deposits in Changbaishan-Tianchi (CBS-TC) volcanic field. (a) Location map showing the CBS-TC volcano and marine sediment core sites of 20EEZ-1 and ODP 794A in the Japan Sea. Also shown are the isopach of the Millennium Eruption (ME) tephra (B-Tm) (Horn & Schmincke, 2000) and the thicknesses of BC/B-KY1 tephra (numbers in red) (Chun & Cheong, 2020). (b) Distribution of BC tephra in HSV and pyroclastic flows in EBV. (c) Inset photo showing the modern Tianchi caldera (view west). TSS: Tsushima Strait, deepest point at -130 m. TWC: Tsushima Warm Current. The cessation of TWC into the Japan Sea occurred when global sea level dropped below -90 m during past glacial-interglacial cycles (Tada et al., 2018).

Figure 2. Plots of major element compositions of glass by EPMA in wt% (normalized to 100% anhydrous), with known ranges of compositions from CBS-TC and nearby volcanic systems (Sun et al., 2018). Note that glass compositions of BC-T/BC-P and ME (Pan et al., 2017, 2020; this study) closely match that of B-KY1 and B-Tm in the Japan Sea (Chen et al., 2016; Chun & Cheong, 2020; Chun et al., 2006; McLean et al., 2018), respectively, confirming their shared origin from the CBS-TC volcano. The probe data are given in Table S1.

Figure 3. Proxies of global climate changes and sea-level fluctuations compared with the BC eruptions during the penultimate glacial/interglacial climatic transition. (a) Local summer insolation at 65°N & 65°S (Laskar et al., 2004). (b) Global sea-level reconstructions from ice sheet model and Red Sea relative sea level data (Bintanjia et al., 2005; Menviel et al., 2019). (c) LR04 benthic $\delta^{18}O$ stack curve (Lisiecki & Raymo, 2005). (d, e) X-ray radiographs of cores 20EEZ-1 & ODP 794A showing B-KY1 tephra layer between the underlying dark laminated mud (DLM) and the overlying light bioturbated mud (LBM). Radiographs are taken from Chun & Cheong (2020).

Table Captions

Table 1. $^{40}Ar/^{39}Ar$ ages of BC-T and BC-P deposits from the BC eruptions.