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Tephrostratigraphy of Changbaishan volcano, northeast China, since the mid-Holocene

Chunqing Sun [a, b, *], Jiaqi Liu [a], Haitao You [c], Karoly Nemeth [d]

[a] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Key Laboratory of Computational Geodynamics of Chinese Academy of Sciences, College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Institute of Agriculture and Environment, Massey University, Palmerston North, New Zealand

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A B S T R A C T

A detailed tephrostratigraphy of an active volcano is essential for evaluating its eruptive history, forecasting future eruptions and correlation with distal tephra records. Changbaishan volcano is known for its Millennium eruption (ME, AD 940s; VEI 7) and the ME tephra has been detected in Greenland ice cores ~9000 km from the vent. However, the pre-Millennium (pre-ME) and post-Millennium (post-ME) eruptions are still poorly characterized. In this study, we present a detailed late Holocene eruptive sequence of Changbaishan volcano based on single glass shard compositions from tephra samples collected from around the caldera rim and flanks. Tephra ages are constrained by optically stimulated luminescence (OSL) and AMS ^{14}C dates. Tephra from the mid-Holocene pre-ME eruption can be divided into two pyroclastic fall subunits, and it cannot be correlated with any known Changbaishan-sourced tephra recorded in the Japan Sea based on major element composition of glass shards, such as the B-J (Baegdusan-Japan Basin) and B-V (Baegdusan-Vladivostok-oki) tephras. ME pyroclastic fall deposits from the caldera rims and volcanic flanks can be correlated to the juvenile pumice lapilli or blocks within the pyroclastic density current (PDC) deposits deposited in the valleys around the volcano based on glass shard compositions. Our results indicate that the glass shard compositions of proximal ME tephra are more varied than previously thought and can be correlated with distal ME tephra. In addition, widely-dispersed mafic scoria was ejected by the ME Plinian column and deposited on the western and southern summits and the eastern flank of the volcano. Data for glass from post-ME eruptions, such as the historically-documented AD 1403, AD 1668 and AD 1702 eruptions, are reported here for the first time. Except for the ME, other Holocene eruptions, including pre-ME and post-ME eruptions, had the potential to form widely-distributed tephra layers around northeast Asia, and our dataset provides a proximal reference for tephra and cryptotephra studies in surrounding areas.

1. Introduction

The comprehensive construction of a stratigraphic framework and dating of the deposits of past volcanic eruptions is important for understanding past volcanic activity and for assessing future eruptions and associated volcanic hazards (Fontijn et al., 2014, 2015; Gertisser and Keller, 2003; Miyabuchi, 2009; Naranjo et al., 2016). Changbaishan volcano is an intraplate stratovolcano on the border between China and North Korea. The summit of the volcanic cone may have experienced several collapses due to the rapid evacuation of magma, and thus a complex, large caldera has formed (e.g., Nakada et al., 2005). The ~5 km-wide Changbaishan caldera might have been formed in a single collapse event by the Millennium eruption (ME), at around the AD 940s, which ejected about 100 km^3 of tephra (DRE ~25 km^3) (Horn and Schmincke, 2000; Sun et al., 2014a; Wei et al., 2003; Zou et al., 2010). Changbaishan has experienced several other explosive eruptions during the Holocene, such as the pre-Millennium eruption (e.g., the ~4–5 ka eruption), and the post-Millennium historically documented eruptions (e.g.,

* Corresponding author. Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.
E-mail address: suncq@mail.iggcas.ac.cn (C. Sun).

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the AD 1702 and 1668 eruptions) (Cui et al., 1995; Liu et al., 1998; Yang et al., 2014). Recent monitoring of the volcano, based on measurement of the geochemical characteristics of springs and seismic inversions on the underlying magma chamber, indicate an increasing potential for eruptive activity (Ri et al., 2016; Wei et al., 2013). However, the lack of detailed knowledge of the stratigraphy of the most recent eruptions has hindered studies of their eruptive processes and hence of predictions of future volcanic activity.

Here, we present an integrated and detailed stratigraphic framework for the young tephras deposited since the mid-Holocene around the caldera rim of Changbaishan volcano and its surrounding volcanic edifice forming a proximal-to-medial tephra record of the volcano. From previously published results and our new geochronological data, the eruptive sequence of Changbaishan volcano since the mid-Holocene was established by geochemical fingerprinting of tephra layers from the caldera rim to the volcanic flanks. This detailed Holocene stratigraphy offers a relatively precise framework for elucidating the volcanic history of Changbaishan and provides a basis for assessing future eruptive hazards and the areas that may potentially be affected. Additionally, this study provides a reference for comparison of proximal tephra for future correlations of the tephras sourced from this volcano since the mid- Holocene.

2. Geological background and eruptive history

Changbaishan is the highest volcano in northeast China (Fig. 1). It is located on a trachybasalt shield (the Gaima Basaltic Plateau) and covers an area of ~7200 km^2. Changbaishan formed from the Miocene to the early Pleistocene (during three main eruptive intervals: 22.64–15.6 Ma, 5.02–2.35 Ma, and 1.66–1.48 Ma), and covered the basement of Archean-Proterozoic metamorphic rocks; with up to 150 m of shield basalt (Liu et al., 2001; Wei et al., 2003, 2007, 2013; Zou et al., 2010). The cone of Changbaishan volcano was mainly constructed by eruptions of trachytic lava, and most of the uppermost parts of the cone have been removed by late-stage explosive eruptions (Liu et al., 2015; Wei et al., 2013). These explosive eruptions can be divided into three clusters: the pre-ME eruptions, the ME in the AD 940s, and the post-ME eruptions.

The best studied pre-ME event is the eruption that produced the pyroclastic fall deposits (NS-1 and NS-2) exposed on the Tianwenfeng (TWF) peak of the northern summit (Fig. 1). Tephra from this eruption consists of two subunits: the lower grey fall deposit (NS-1) and the upper yellow fall deposit (NS-2) (Fig. 2A). ^{40}Ar-^{39}Ar, uranium series disequilibrium, ^{14}C and optically stimulated luminescence (OSL) methods, have dated this tephra to ~1 to ~5 ka, while fission track (FT) dating on zircons gave an age of around 74 ka (Ji et al., 1999; Liu et al., 1998; Wan and Zheng, 2000; Wang et al., 1999; Yang et al., 2014). However, in contrast, other workers have suggested that this tephra was a syn-eruptive phase of the ME (Yin and Fan, 2012). Most of the aforementioned studies were concentrated on one of the subunits of the pre-ME tephra, the upper yellow fall (NS-2, 2A, 3), while no detailed geochronological and geochemical studies have been conducted on the lower grey fall (subunit NS-1, Figs. 2A and 3).

The most prominent eruption in the eruptive history of Changbaishan is the so called "Millennium eruption" (ME) which was one of two largest explosive eruptions in the past 2000 years. The Volcanic Explosivity Index (VEI) of this eruption was up to 7 and it can be compared with the great Tambora eruption of AD 1815; consequently, it has received a great deal of research attention (Horn and Schmincke, 2000; Liu et al., 1998; Oppenheimer, 2003; Stone, 2011, 2013). Over the past few decades, many dating methods, such as ^{14}C wiggle matching and ^{40}Ar-^{39}Ar dating, have been used to try to constrain the precise timing of this eruption; however, these efforts have not yielded a consensus regarding its age (Liu, 1999; Liu et al., 1998; Wang, 2012; Yang et al., 2014). Analysis of the ash from this eruption recorded in Greenland ice cores assigned an age of AD 940–941 (GICC05, or 946–947 by NS1-2011) or 945 ± 4 (GISP2) (Sigl et al., 2015; Sun et al., 2014a). In addition, the age of the eruption has been constrained to AD 946 by counting proximal tree rings, on the basis of an abnormal cosmogenic radiocarbon signal at around AD 775 (Oppenheimer et al., 2017). The occurrence of this tephra in Greenland ice cores, and associated acidity records, also resolves the controversy regarding its climatic impacts as a result of discrepancies in the datings of the timing of the eruption (e.g., Xu et al., 2013; Yin et al., 2012).

The ME can be divided into a first phase producing widespread pyroclastic fall deposits on the eastern flank of the volcano and non-welded pyroclastic density current (PDC) deposits around the volcanic vent; and a late phase producing welded PDC deposits along the valleys surrounding the volcano (such as the Jinjiang valley and Yalujiang valley) (Horn and Schmincke, 2000). Many pyroclastic fall and PDC deposits have been detected on the eastern flank of Changbaishan, and the grey pyroclastic fall deposits can be readily traced and correlated with the fall deposits (grey unit of NS-3, Fig. 2A and B and 3) on TWF summit (Liu et al., 2006; Machida et al., 1990) and NS-3 was deposited by the ME. However, the origin of the pyroclastic fall deposit (subunits NS-4, dark grey in color; and NS-5, black in color; Fig. 2B and C and 3) covering NS-3 is still controversial. Several studies have proposed that NS-4 and NS-5 on the summit of TWF were also derived from the ME; however, chronological results have assigned relatively young ages to them, i.e., post-MEs (Chen et al., 2016; Ji et al., 1999; Sun et al., 2016; Wang et al., 1999, 2001). In addition, if they were derived from the ME, questions arise regarding the relationship between these fall deposits and the PDC deposits that are present in the surrounding valleys, and if such pyroclastic fall deposits are also present on the flanks of Changbaishan.

Historical records from surrounding areas demonstrate that Changbaishan may have experienced several relatively minor eruptions (with an estimated VEI<5) since the ME, the most recent being in AD 1903 (Cui et al., 1995; Yun, 2013). Historical documents indicate that the AD 1702 eruption produced a ~3 cm thick fallout ash layer deposited ~70 km east of Changbaishan (Wei et al., 2013; Yun, 2013), but no confirmed field exposures can be precisely correlated to this. OSL dating of the cone formation trachyte of the inner caldera of the volcano indicates that the most recent eruption has an age of around 400 to 600 a, which may be compatible with the historical record (Li and Yin, 2001; Yin and Li, 2000). The AD 1903 eruption was a small phreatomagmatic eruption and the affected areas were limited to the inner caldera, while the geochemical compositions of the products of other post-MEs, and the areas affected, are unclear.

3. Sampling, field characteristics and analytical methods

3.1. Exposures and sampling

3.1.1. Summits around the caldera

Tianwenfeng peak (TWF, the northern slope summit of Changbaishan, Fig. 1) is an excellent site for tracing the late-stage explosive eruptions of the volcano since several clear and well-exposed fall deposits can be observed (Fig. 2A, B, C). A ~30 m thick pre-ME pyroclastic fall unit consisting of two subunits (NS-1, grey in color; NS-2, yellow in color) directly overlies the trachytic cone. Pumice blocks from these two subunits were collected for analysis. In addition, there are many mafic blocks up to ~50 cm in diameter within this fall deposit. This fall unit is exposed only on the TWF peak of the northern summit. The overlying NS-3 is a