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REVIEW ARTICLE

Distribution, geochemistry and age of the Millennium eruptives of Changbaishan volcano, Northeast China – A review

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Abstract Large explosive volcanic eruptions generate extensive regional tephra deposits that provide favorable conditions for identifying the source of volcanoes, comparing the sedimentary strata of a region and determining their ages. The tephra layer, referred to as B-Tm, generated by the Millennium eruption of Changbaishan volcano, is widely distributed in Northeast China, Japan, D.P.R. Korea, and the nearby coastal area of Russia. It forms part of the widespread northeast Asian strata and is significant for establishing an isochronal stratigraphic framework. However, research on the temporal characterization and stratigraphic correlation of associated strata using this tephra layer is mainly concentrated in and near Japan. In northeastern China, this tephra layer is seldom seen and its application in stratigraphic correlations is even rarer. More importantly, the determination of accurate ages for both distal and proximal tephras has been debated, leading to controversy in discussions of its environmental impacts. Stratigraphic records from both distal and proximal Changbaishan ash show that this eruption generally occurred between 1,012 and 1,004 cal yr BP. Geochemical comparison between Changbaishan ash and the Quaternary widespread ash around Japan illustrates that Changbaishan ash is a continuous composition from rhyolitic to trachytic and its ratio of FeO_T to CaO is usually greater than 4, which can be used as a distinguishing identifier among worldwide contemporary eruptions.

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1 Introduction

Tephra generated from a large explosive volcanic eruption may spread thousands of kilometers away from a vent in a very short time. As it takes only a few hours or days for tephras to fall to the ground or settle on the seabed and other sedimentary environments, the chronology of tephra layers can provide a forceful isochronous stratigraphic framework for extensive regional stratigraphic correlations (Shane, 2000; Turney and Lowe, 2001; Kuehn et al., 2011; Lowe, 2011; Óladóttir et al., 2011). The age of a source tephra must first be determined before it can provide an accurate key bed and age scale for stratigraphic correlation (Lowe, 2011). In addition, that age may be transferred from one location to another (Lowe, 2011; Tomlinson et al., 2012). Tephra layers may also provide a record of the eruption frequency of source volcanoes and the geochemical properties of the eruption products, which provides a forecast volcanic hazard and establishes the temporal-spatial relationships of volcanic eruption sequences (Shane, 2000, 2005; Shane et al., 2008; Moebis et al., 2011; Sohn et al., 2012).

Changbaishan volcano (also referred to as Tianchi, Baitoushan, Baegdusan or Paekdusan) is a huge intraplate stratovolcano, located on the border between China and D.P.R. Korea, which has experienced three evolutionary stages (Wei et al., 2003). The early lava shield of the volcano grew on the 5–2 Ma early-stage trachybasalt Gaima Plateau. The age of the volcanic cones in the middle stage, which mostly consist of trachyte, is less than 1 Ma. These middle-stage cones were mostly destroyed by the later-stage so-called Millennium eruption that formed the 5-km-wide Tianchi caldera (Liu and Wang, 1982; Wei et al., 2003, 2007; Zou et al., 2010). The Millennium eruption is considered the most violent eruption in the last two thousand years with a volcanic explosivity index up to 7 based on an estimation of 25 to 35 km high eruption column and a volume of 100 km^3 as loose tephra (Machida and Arai, 1983; Horn and Schmincke, 2000; Liu and Taniguchi, 2001; Guo et al., 2002; Wei et al., 2003). The main products, alkaline rhyolite pumice and volcanic ash, produced from this eruption were transported as far away as Hokkaido, Japan, 1,200 km away from the vent, where up to 4 cm of tephra thickness has been found (Fig. 1) (Machida and Arai, 1983). The eruptions of Changbaishan volcano not only pose a potential harmful threat to hundreds of thousands of residents living nearby, but may also greatly impact the neighboring countries of Japan, R.O. Korea, and eastern Russia. Moreover, investigations in recent years indicate that the volcano experiences numerous microearthquakes, hot springs, and other volcanic activities, thus the possibility of a future volcanic eruption is of great concern (Stone, 2010, 2011; Wei et al., 2013; Xu et al., 2013).

Studies on the Millennium eruption play a vital role for gathering data on historical eruptions and forecasting possible future volcanic activities. Field descriptions, age determinations, and geochemical analyses of the distal and proximal tephras have been widely reported over past several decades (e.g., Machida et al., 1990; Horn and Schmincke, 2000; Jwa et al., 2003; Kamite et al., 2010; Yin et al., 2012; Wei et al., 2013; Xu et al., 2013). Even so, many unknowns still exist regarding this eruption. For example, numerous dating techniques have been applied to constrain the age of the eruption, while no consensus has been achieved on its precise age (refer to the section on "dating of tephra"). No systematic works hitherto have been carried out to correlate the westward, eastward, and proximal tephras from this eruption. In this paper, the details of the field stratigraphic characteristics, geochemical data, and dating results for the Changbaishan Millennium eruption are presented and compared. Through sorting proximal and distal tephra and historical records, we believe that this eruption generally occurred between 1,012 and 1,004 cal yr BP, and that its tephra has a high total alkali and ratio of FeO_T to CaO in its constituent glass compared with that of other contemporary eruptions.

2 Field characteristics

The Millennium eruption resulted in numerous geomorphologic landscapes in China and D.P.R. Korea, including the Grand Yalu River Canyon, the Grand Jinjiang Canyon, and the Pumice Forest. The thickness of the eruptives (up to 100 m) suggests a large-scale eruption emplaced them. Eruption products have been found in northeastern China, Japan, and the coastal areas of Russia. Researches on the distal tephra have been concentrated in Japan and its surrounding areas, whereas research on the sequence of proximal tephras is relatively limited (e.g., Machida and Arai, 1983; Guo et al., 2005).

2.1 Distal tephra

Distal tephra of the eruption was first found in Hokkaido, Japan (Machida and Arai, 1983), and later in the boreholes in the Japan Sea, the Kuril Island Arc, and in the sediments of maar lakes in northeastern China (Furuta et al., 1986; Nanayama et al., 2003; Guo et al., 2005). Japanese scholars named it the B-Tm tephra based on the source volcano (Baegdusan, i.e., Changbaishan) and its location (Tomakomai) (Fig. 1(b), right) (Machida and Arai, 1983).

Data from numerous boreholes in the Japan Sea indicate that the B-Tm tephra is usually present in the top layer of sediment and that it gets thinner from west to east towards Hokkaido (Fig. 1) (Machida and Arai, 1983; Furuta et al., 1986; Machida et al., 1990; Ikehara, 2003). In peat sediment records from the northern part of the island of Honshu, two tephra layers with similar thickness and grain-size characteristics are commonly observed. Analyses of tephra petrography and glass geochemical features confirm that the top layer is the B-Tm tephra from the Millennium eruption and the bottom layer is the Towada-a (To-a) tephra from the AD 915 eruption of Towada caldera (Machida and Arai, 1983). These two tephra layers are also found in the sediment from a number of lakes on Honshu, specifically Ogawara Lake, Ichi-no-Megata Lake, Ni-no-Megata Lake, and San-no-Megata Lake (Fukusawa et al., 1998; Kamite et al., 2010; Yamada et al., 2010; Okuno et al., 2011). However, the stratigraphy in the peat sediment of coastal eastern Hokkaido and western Honshu differ somewhat. Although the B-Tm tephra also exists in these areas, it does not appear as the top layer of the sediment and no To-a tephra is found in the underlying layers (Hughes et al., 2013). Furthermore, the tsunami sediment at Suijin-numa on Honshu only has a To-a ash bed and no coexisting B-Tm tephra is found (Sawai et al., 2008). Therefore, Suijin-numa may represent the southeastern extent of tephras from the Changbaishan Millennium eruption.

Likewise, one layer of fine-grained white volcanic ash originating from the Changbaishan Millennium eruption is found in the tsunami sediments at Asahidake volcano in the middle of Hokkaido, on the east side of Kutcharo caldera, in the coastal areas of eastern Hokkaido, and in the area of Tyatya volcano in the southwestern Kuril Island Arc (Wada et al., 2001; Nakagawa et al., 2002; Nanayama et al., 2003, 2007; Hasegawa et al., 2009; Sawai et al., 2009).

Multiple concomitant layers of volcanic ash provide a

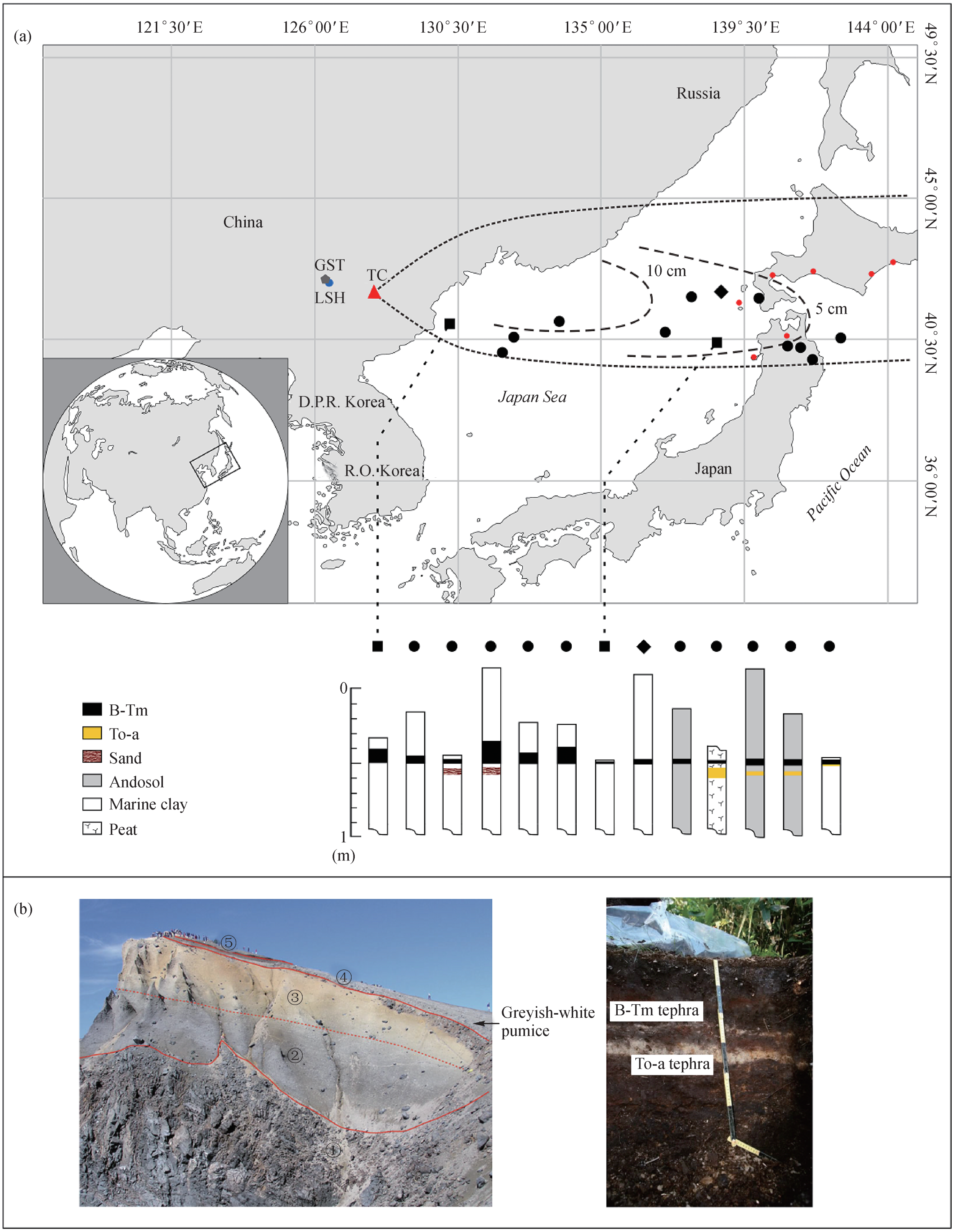

Fig. 1 (a) The distribution map of distal tephra of the Millennium eruption and the localities where the marker-tephras occurred. (b) The proximal and distal tephra from Millennium eruption and coexisting tephras. Left is the profile of Tianwen peak near the Tianchi Crater and right is the strata where the B-Tm occurred (Aomori Prefecture, Hokkaido, Japan). TC: Changbaishan Tianchi volcano; GST: Gushantun peat; LSH: Lake Sihailongwan. Red solid circles in (a) are the other reported sites where the B-Tm tephra occurred. Distribution and thickness information of distal tephra are from Machida and Arai, (1983). The left picture in (b) was modified from Yu et al. (2013) and the right is from the website of Tohoku University: http://www.museum.tohoku.ac.jp/past_kikaku/paekdusan/index.html.

set of well-constrained marker horizons for regional strata, which can be used to study the timing of volcanic eruptions, volcanic eruption histories, tsunamis, and other events (Nakagawa et al., 2002; Nanayama et al., 2003, 2007; Sawai et al., 2009).

The Longgang volcanic field in northeastern China, about 200 km northwest of Changbaishan volcano, contains nine maar lakes of various sizes. Little research on the tephra from the Millennium eruption has been undertaken in these maars. It is also worth noting that although it has been previously proposed that the products of the Millennium eruption could not be transported to Longgang volcanic field (Cheng et al., 2008), a cross section of the sediment in Sihailongwan maar lake in the Longgang volcanic field contains the products of the Changbaishan Millennium eruption as fresh and discontinued tephra (Guo et al., 2005). In addition, a small quantity of protogenetic tephra particles with irregular shapes has been found in Gushantun peat and it has been proposed that they were the product of the AD 1702, 1668, and 1597 eruptions of Changbaishan volcano based on its rhyolitic composition and ^{14}C age (260–420 cal yr BP) (Zhao and Liu, 2012). It is possible that the Longgang volcanic field might be the northwestern boundary of deposits from the Changbaishan Millennium eruption and therefore, these distal tephras are worth further identification and research.

2.2 Proximal tephra

The proximal tephra produced by the Millennium eruption can be divided into two phases (Fig. 2) (Horn and Schmincke, 2000). Phase 1 consists of the alkaline rhyolitic pumice fallout distributed in a sheet shape that dominates this eruption. The thickness of this fallout pumice deposit can be up to 70 m around the crater and decreases towards the east. The deposits are well bedded

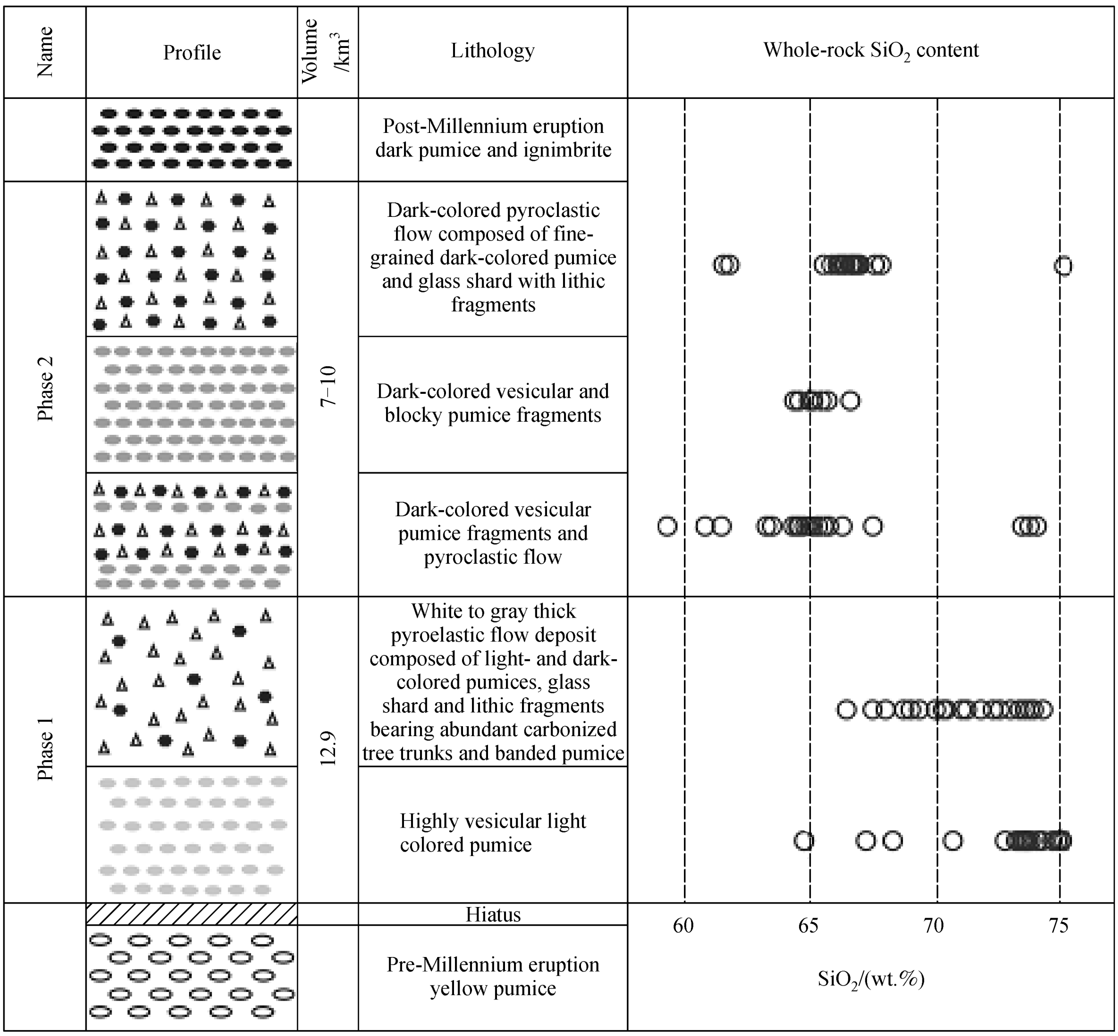

Fig. 2 Simplified lithological column of the proximal tephra sequence (Modified from Machida et al. (1990) and Nishimoto et al. (2010)).

and sorted in the area>15 km east of the crater, where the particle size of pumice was also found to decrease (Liu et al., 1998b). The pumice in this phase is mainly distributed on the eastern and southern slopes of Changbaishan volcano which is dominated by pumice fallout, while the northern slope is predominantly composed of unsolidified light-colored ignimbrite. The second phase consists of trachytic pyroclastic flow materials (up to 70–80 m thick) that are mainly distributed along ravines and other low-lying areas (Liu et al., 1998b) such as in the Grand Jinjiang and Grand Yalu River canyons. These pyroclastic deposits usually have column joint structure. There is no obvious discontinuity surface between the two phases, so the eruption interval between them is not considered to be long.

The stratigraphy of the proximal tephra is only recorded at a few locations. Because of its high elevation, Tianwen Peak only retains the phase-1 pumice fallout (Fig. 1(b), left), whereas the Grand Jinjiang and Grand Yalu River canyons, in addition to other ravine areas, perfectly preserve the phase-2 pyroclastic deposits. These two phases were also found at the site of Yunachi profile (Fig. 2) or Diaoyutai of Richeng JIN, on the eastern slope of Changbaishan volcano. The B-Tm tephra found in the Japan Sea and Japan Island can be correlated with the later phases 1 and 2 based on their glass compositions and petrographic characteristics (see section on glass geochemistry) (Machida et al., 1990; Nishimoto et al., 2010).

The greyish-white alkaline rhyolitic pumice layer of the Millennium eruption profiled at Tianwen Peak (Layer ④, Fig. 1(b), left) overlies an orange-colored alkaline rhyolitic pumice layer (Layer ③ , Fig. 1(b), left) which was produced by another large eruption (Liu et al., 1998b). Again, even though there is not an obvious discontinuity surface between the two pumice layers, the boreholes in the Yuchi-Chifeng area indicate that a clayey mud layer, about 20 cm thick, is interbedded between the two pumice layers; ^{14}C dating of the mud layer gives an age of 2,040±90 cal yr BP (Liu et al. 1998b). The absence of this mud discontinuity surface in the Tianwen Peak profile is most likely associated with the terrain, whereas the swampy environment in the Yuanchi-Chifeng area is suitable for the storage of sediment; thus the expected discontinuity surface was preserved.

2.3 Correlating proximal and distal tephra

On the whole, studies are consistent regarding the various horizons of the distal tephra from the Changbaishan Millennium eruption. However, uncertainty remains over the accuracy of their ages. Detailed tephra identifications and correlations may not only identify the source volcano of an individual tephra layer, but may also help determine an accurate age for a single tephra layer. However, only through the analysis of key field layers, mineral assemblage, composition, grainsize, shape of the shards, and thickness of the deposits, which accurately establish a proximal tephra sequence and determine the distal tephra layer to which it corresponds, can confident identifications and correlations of tephra layers be achieved. Future research should focus on relationships between the proximal tephra sequence and the distal tephra layers.

3 Glass geochemistry

Identification and correlation to a source volcano are mainly based on the geochemical characteristics of glass, glass morphology, mineral assemblages, and tephra ages, as described below.

3.1 Morphology and mineralogy of glass

The tephra of the Changbaishan Millennium eruption is dominated by grey and white pumice. The grey pumice is composed of trachyte and the white pumice is composed of alkaline rhyolite. These two types of pumice contain different amounts of phenocryst, i.e., 10%–20% for trachytic pumice, and approximately 3% for alkaline rhyolitic pumice (Horn and Schmincke, 2000; Guo et al., 2002; Fan et al., 2005; Nishimoto et al., 2010), with very low amounts of quartz phenocrysts. Rather, they predominantly consist of sanidine and plagioclase phenocrysts, with smaller amounts of fayalite and calcium titanaugite.

An obvious feature of the distal B-Tm tephra is the enrichment of alkaline feldspar, which can readily be compared with the tephras found in and around Japan. The B-Tm tephra mainly consists of fine-grained pumice with a higher content of pumiceous glass than bubble wall type glass (Machida and Arai, 1983). The average content of volcanic glass is about 62%, light minerals are 14%, heavy minerals are 4%, lithic fragments are 16%, with phenocrysts mainly comprised of potassium feldspar (Okuno et al., 2011).

SEM observations indicate that the cryptotephra found in the Gushantun peats is irregularly shaped with a bubble, thin-plate or sharp-angle structure (Zhao and Liu, 2012). Likewise, the research on the tephra of Changbaishan Millennium eruption identified in the Lake Sihailongwan deposits also indicated that this layer is generally found in the form of multi-bubble type or fiber-type glass (Guo et al., 2005).

3.2 Glass composition

The B-Tm tephra can be distinguished by its high content of total alkali (8%–12%) and FeO_T (3.7%–5%) from other contemporary eruptions which occurred in the regions around Japan. The Aso-4 tephra has a similar characteristic, but when adding the TiO_2 and CaO indexes, the B-Tm tephra can be recognized among the Quaternary tephras around Japan (Aoki and Machida, 2006). For example, the ratio of B-Tm tephra of FeO_T to CaO is greater than 4, which may be robustly incorporated as a useful index. In the following section, the data on glass compositions are reported as normalized values.

As for peralkaline magmas, fractional crystallization may complicate the differentiation trends, and the peralkalinity index (PI) can be used to assess the degree of magma evolution (Rooney et al., 2012). A strong positive correlation between PI and SiO_2 (Fig. 3) of glass from proximal and distal Millennium eruption tephras suggests that SiO_2 remains an appropriate choice to establish the differentiation trends.

According to the SiO_2 content, glass compositions of the distal and proximal tephras of the Changbaishan Millennium eruption are broadly divided into trachytic and rhyolitic members (Furuta et al., 1986; Machida et al., 1990). The SiO_2 content is 66%–69% or 74%–79% and the corresponding K_2O, Al_2O_3, FeO_T, TiO_2 and CaO all have two similar end members (Fig. 3 and Table 1). According to the Harker diagrams of major elements, following an increase in SiO_2 content, all major elements tend to decline and illustrate a good linear relationship; hence, it is deduced that these two end members are genetically related. Based on the above two end members, Furuta et al. (1986) proposed two different types of volcanics in the distal B-Tm tephra layer that correspond to the products of different evolutionary stages with similar petrogenesis. When Tokui (1989) performed his later research on the tephra in Hokkaido, Japan, he also characterized the B-Tm tephra layer as having a bimodal population composition and thought it to be consistent with proximal rhyolitic and trachytic tephra. Such bimodal end members have been confirmed by others (e.g., Machida et al., 1990; Okuno et al., 2011). However, the integration of past geochemical data will reveal there is a continuous compositional transition between the two end members (Fig. 3), so it may be deduced that these two end members might have been caused by magma mixing before the eruption. Trace element systematics within both comendites and trachytes also demonstrate mixing, with some more mafic than the other (Gill et al. 2013). Field evidence may also prove that the tephra of the Changbaishan Millennium eruption contains this transitional component, such as the inclusion relationship between gray and dark pumice, a disequilibrium mineral assemblage (coexistence of quartz and olivine) in the pumice clasts (Fan et al., 2005; Shimano et al., 2005; Fan, 2008; Gill et al., 2013; Nakagawa et al., 2013).

Distal B-Tm tephra discovered in the sediment of the Japan Sea also contains the two end members of rhyolite and trachyte. It also exhibits a transition in the intermediate components (Furuta et al., 1986; Machida et al., 1990). Considering the B-Tm tephra discovered in lakes and peat sediment on Honshu, analyses of the average value of its major elements show that it also contains the two end members (Fukusawa et al., 1998; Okuno et al., 2011; Hughes et al., 2013). However, the B-Tm tephra discovered in the vicinity of Tyatya Volcano in the southwestern part of the Kuril Island Arc contains only the rhyolitic member and lacks the trachytic member and intermediate transition components. Similarly, deposits at the Asahidake volcano in central Hokkaido also lack the trachytic member (Wada et al., 2001; Nakagawa et al., 2002). The average composition of the B-Tm tephra discovered in tsunami-emplaced sediments along the east coast of Hokkaido falls between the rhyolitic end member and the transition components; no trachytic member is observed (Nanayama et al., 2003).

Even though whole-rock geochemistry of tephra does not adequately fingerprint a tephra deposit, given the glass and crystal components of tephra can be fractionated with distance from vent during transport and depositional processes, glass data from the same eruption can also be heterogeneous due to multiple magmas, magma-mingling, or syn-eruptive changes in dispersal patterns (Lowe et al., 2008; Shane et al., 2008). Such heterogeneity was also verified by the tephra from the Millennium eruption. By separating out the geochemical data of the B-Tm tephra found in the tsunami deposits and other sediments in the Japan Sea, Honshu, eastern Hokkaido, and the Longgang volcanic field, i.e., Lake Sihailongwan and the Gushantun peat located west of the Changbaishan volcano, both rhyolitic and trachytic members were recognized in the east, while only a rhyolitic member was identified in the west. These two members and corresponding field evidence may have resulted from magma mingling, while the tephra dispersal difference between west and east of Changbaishan volcano may mainly be due to the change in wind direction during this eruption.

According to available geochemical data from the analysis of glass shards of the Changbaishan Millennium eruption, similarity coefficients for major elements with concentrations$>1\%$ in distal and proximal tephra were found to be similar. The two end members, trachyte and rhyolite, were calculated separately (Borchardt et al., 1972), and the results indicated a good correlation between distal and proximal tephra (Table 2). The similarity coefficient of the rhyolitic end member is as high as 0.99, whereas that of the trachyte is 0.98. When the similarity coefficients are$\geqslant 0.95$, the units may be considered correlatives. The interpretation of the B-Tm tephra as the product of Changbaishan Millennium eruption is therefore quite reasonable. In addition, the Changbaishan and B-Tm tephra are calculated separately for the major-element characterizations of the rhyolitic tephra layer in the Sihailongwan, Gushantun sediments. The results support a similarity coefficient for the major elements of the Sihailongwan tephra above 0.95 with both proximal tephra and distal B-Tm tephra. The major

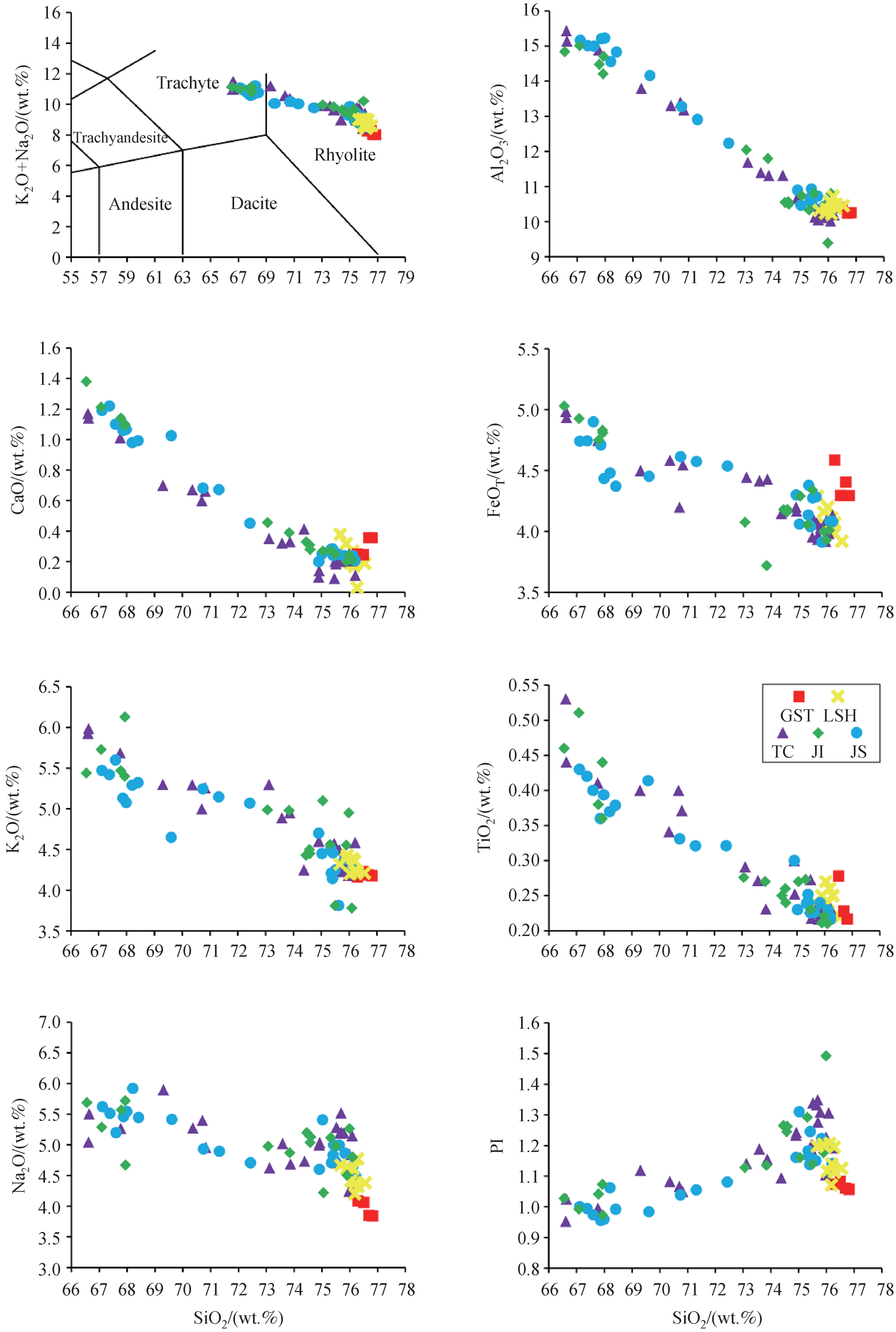

Fig. 3 Total alkalis versus silica (TAS) and major oxide biplots (wt.%) of geochemical characterizations of glass shards from the proximal and distal tephra of Changbaishan volcano. All data have been normalized to 100% for presentation. The peralkalinity index (PI) is calculated as (mol. (($Na_2O + K_2O$)/Al_2O_3)). TAS diagram is from Le Maitre et al. (1989), TC: proximal tephra (data from Machida et al. (1990), Machida and Arai (2003), Guo et al. (2002) and Zou et al. (2010)), JS: distal tephra from the Sea of Japan (data from Furuta et al. (1986), Machida et al. (1990) and Machida and Arai (2003)), JI: distal tephra from Japan (data from Machida et al. (1990), Nakagawa et al. (2002), Nanayama et al. (2003), Aoki and Machida (2006), Okuno et al. (2011) and Hughes et al. (2013)), GST: distal tephra from Gushantun peat (data from Zhao and Liu (2012)), and LSH: distal tephra from Lake Sihailongwan (data from Guo et al. (2005)).

Table 1 Main oxide composition of volcanic glass from the Changbaishan Millennium eruption compared with that of glass in tephra from Lake Sihailongwan and Gushantun Peat

	LSH	GST	TCr	TCt	B-Tmr	B-Tmt
SiO_2	76.12 ± 0.25	76.58 ± 0.23	74.51 ± 1.88	67.58 ± 1.27	74.84 ± 1.45	67.80 ± 0.74
TiO_2	0.24 ± 0.02	0.22 ± 0.05	0.26 ± 0.06	0.45 ± 0.06	0.25 ± 0.03	0.41 ± 0.04
Al_2O_3	10.42 ± 0.15	10.34 ± 0.10	10.99 ± 1.11	14.82 ± 0.72	10.91 ± 0.86	14.80 ± 0.36
FeO	4.09 ± 0.11	4.40 ± 0.14	4.17 ± 0.21	4.79 ± 0.22	4.17 ± 0.21	4.71 ± 0.21
MnO	0.07 ± 0.02	–	0.08±0.04	0.10±0.05	0.07±0.03	0.13±0.02
MgO	0.02±0.01	0.02±0.02	0.06±0.05	0.10±0.07	0.05±0.05	0.13±0.04
CaO	0.22±0.09	0.30±0.06	0.29±0.18	1.01±0.22	0.31±0.13	1.12±0.11
Na_2O	4.50±0.18	3.96±0.13	4.96±0.34	5.43±0.37	4.85±0.27	5.47±0.30
K_2O	4.30±0.09	4.19±0.03	4.61±0.38	5.73±0.31	4.51±0.42	5.39±0.35
n	10	4	20	4	26	13

Errors are 1σ; *n* is the number of glass shards; TCr: Changbaishan Tianchi rhyolitic members, TCt: Changbaishan Tianchi trachytic members, B-Tmr: distal rhyolitic members, B-Tmt: distal trachytic members. Data are from Furuta et al. (1986), Machida et al. (1990), Machida and Arai (2003), Guo et al. (2002), Nakagawa et al. (2002), Nanayama et al. (2003), Guo et al. (2005), Aoki and Machida (2006), Zou et al. (2010), Okuno et al. (2011), Zhao and Liu (2012) and Hughes et al. (2013).

Table 2 Similarity coefficients of major elements from analyses of glass shards from the distal and proximal tephra of the Changbaishan Millennium eruption and distal tephra from the Gushantun peat and Lake Sihailongwan

	LSH	GST	TCr	TCt	B-Tmr	B-Tmt
LSH	1.00					
GST	0.95	1.00				
TCr	0.95	0.91	1.00			
TCt	0.80	0.79	0.85	1.00		
B-Tmr	0.96	0.93	0.99	0.84	1.00	
B-Tmt	0.82	0.80	0.86	0.98	0.85	1.00

TCr: Changbaishan Tianchi rhyolitic members, TCt: Changbaishan Tianchi trachytic members, B-Tmr: distal rhyolitic members, B-Tmt: distal trachytic members.

compositions of glass shards of the Sihailongwan tephra are consistent with those of distal and proximal Changbaishan rhyolitic end member tephra, where alternatively, the major elements of the glass shards of the Gushantun cryptotephra show a relatively poor agreement.

From tephra composition studies and analyses of the strata where the B-Tm tephra occurred, distal B-Tm tephra was shown as the product of the Changbaishan Millennium eruption. In regard to the tephra identified in Sihailongwan maar lake in the Longgang Volcanic field, the major elements observed were generally consistent with the major elements of the distal and proximal rhyolitic end members of the Changbaishan ash while the trachytic end member is absent. Even though, the chronological results bear some resemblance to those of the Millennium eruption elsewhere (refer to Section 3); the supposition that these tephras are from the Millennium eruption still needs further verification. When identifying and correlating tephra from the Millennium eruption, if both similar rhyolitic and trachytic end members are found at the same time, then to a large extent, this suggests that the tephra is indeed a product of this eruption; however, if only one similar end member is observed, then further verification will be needed.

4 Dating of tephra

4.1 Historical records of this eruption

The large amount of carbonized wood in the pumice around Changbaishan volcano indicates that the Millennium eruption had a huge impact on the vegetation. However, no direct historical record of this huge eruption has been found to date in China leaving only indirect records from neighboring regions to be used in historical studies of this event (Machida et al., 1990; Machida and Okumura, 2007; Chu et al., 2011). Cui et al. (2000, 2008) and Cui and Liu (2006) evaluated historical documentation of the event in Korea, including Goryeosa, the Miscellaneous Record of Haidong, Samguk Sagi and the Historical Materials of the Korean Li Dynasty, discovering that the timing of this massive Millennium eruption was concentrated during the period of AD 1200 and AD 1014–1019. Records indicate that a loud sound was heard immediately followed by the eruption with a dense black and strange gas from the direction of Changbaishan volcano. Dust falls subsequently became common during AD 1199–1201. However, during the period of AD 1014–1019, a large number of abnormal red gas and volcanic ash eruptions were recorded. All of these abnormal phenomena are considered to be the result of Changbaishan eruptions. Additional events, as recorded in Goryeosa, the History of Korea, and other historical documents document the occurrence of similar natural phenomena in AD 946. The Japanese Hungguk Temple Chronicle also noted the event of white and grey snow, likely white rhyolitic tephra in the atmosphere during the winter of AD 946 (Hayakawa and Koyama, 1998). Similar abnormal weather phenomena, also attributed to the Millennium eruption, occurred during AD 929–944.

Historical records have been shown as the most accurate way of dating large volcanic events in this region; yet when compared with the dating results (Sections 4.2 and 4.3), they are often inconsistent, which may be ascribed to the following two reasons. First, these indirect historical records may have reliably recorded for the Millennium eruption, but not every abnormal phenomenon occurred in the sky corresponds to an individual volcanic eruption event, while may have instead been caused by other natural phenomena. Second, even though numerous eruptions correspond to these abnormal phenomena, uncertainty remains concerning the largest of these eruptions.

4.2 Dating of distal tephra

Distal B-Tm tephra was first discovered during archaeological studies of the Heian Period in northern Honshu. Detailed research involving stratigraphic correlations suggests that the B-Tm tephra was deposited in the early to middle 10th century (Machida and Arai, 1983; Machida, 1999).

Techniques applied to constrain the age of this eruption by distal B-Tm tephra have been documented by Okuno (2002), including varve chronology, dendrochronology, ^{14}C wiggle-matching and historical records (e.g., Table 3).

The widely distributed lakes of Japan provide a rich sedimentary record of regional volcanic eruptions. From research on the sediments of Ogaware Lake in northeast Japan, Fukusawa et al. (1998) discovered annual sedimentary laminations (varves) between the B-Tm and To-a tephras. According to historical records, the To-a tephra was deposited in AD 915 and can be considered as an age marker. By counting the varves between the two tephra layers, the age of the B-Tm tephra can be placed at AD 937–938. The same method has been utilized in other lakes. For example, between the two tephra layers in Ni-no-Megata and San-no-Megata lakes, there are 14.5 varves, thereby supporting a date of AD 929 for the B-Tm tephra (Kamite et al., 2010; Yamada et al., 2010). Additionally, analysis under a microscope of organic material caught up in the tephra deposit indicates that the B-Tm tephra was caused by either one or multiple eruptions in spring or summer (Kamite et al., 2010; Yamada et al., 2010), whereas microscopic studies on the outermost layer of trunks buried in the Changbaishan ignimbrite indicate that the Millennium eruption took place in autumn or winter (Machida and Mitsutani, 1994; Yin et al., 2012). Although the resolution of lake varves is as short as a year or season, the age of the To-a unit as recorded in historical writings may have errors and lake sedimentary records can have “missing laminations”. Therefore, the deduction of tephra age by varve counting is uncertain. When considering the geographic environment and sediment properties around Ogaware Lake, we think the result by Fukusawa et al. (1998) may be closer to the real B-Tm age. In regard to the season of the volcanic eruptions, we also surmise autumn–winter to be correct because the pumice fallout was mostly distributed to the east of Changbaishan volcano, which is consistent with the prevailing northwesterly winds in those seasons.

Dendrochronology provides another way to determine the age of B-Tm tephra. For example, pairs of tephra layers (i.e., the B-Tm tephra and the To-a tephra below) were discovered in the sediment of Tashiro Swamp in northeastern Honshu. A wooden house was found buried in the To-a tephra at Odate, and by using dendrochronology to date the wooden house, the youngest wood was dated to AD 912. This enables us to deduce that the B-Tm tephra must be younger than that date. In addition, the B-Tm tephra, found at an archaeological site in the town of Noheji, was cut by a channel and dated to AD 972 by collecting planks present in the channel. Therefore, the B-Tm tephra must have been deposited between AD 912 and AD 972 (Nakamura et al., 2007).

Among the published results from the Longgang volcanic field in northeastern China, ages for the tephras from the Changbaishan eruptions in Sihailongwan and Gushantun sediments were determined by AMS ^{14}C dating. By using such methods, Guo et al. (2005) deduced the age of the Millennium eruption tephra layer in Sihailongwan to lie between AD 1085 and AD 1630. In Gushantun peat, one rhyolitic tephra layer was found with an age of 420–260 cal yr BP (Zhao and Liu, 2012). The characteristics of its major elements are similar to the products of Changbaishan volcano; hence, Zhao and Liu (2012) assumed that the tephra was produced by the Changbaishan volcanic eruption of AD 1702. However, according to the calculations of similarity coefficients for the major elements (Table 2) and the deduced age result of this tephra layer, we think that the tephra layer in Gushantun peat was probably not part of the Millennium eruption. This non-correlation is also consistent with geochemical data from the volcanic ash.

Although the studies summarized here establish an age range which can be used to constrain the age of Millennium eruption, no consensus has been reached on its accurate dating. In addition, the tephras in the Japan Sea and in the maar lakes of northeastern China have inconsistent geochemical data. Therefore, further and more detailed studies are still needed to be carried out.

Table 3 Main dating results of Changbaishan Millennium eruption

Dating result	Dating method	Material	Sampling site	References
1190 – 990 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Northern slope of Changbaishan	Jwa et al. (2003)
1020 – 1007 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Northern slope of Changbaishan	Nakamura (2007); Nakamura et al. (2007)
1001 – 961 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Horn and Schmincke (2000)
929 – 893 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Dunlap (1996)
735±15 cal yr BP*	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Liu et al. (1998a)
1034 – 1014 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Machida and Okumura (2007)
1005 – 990 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Yatsuzuka et al. (2010)
1029 – 1009 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Eastern slope of Changbaishan	Yin et al. (2012)
1010 – 998 cal yr BP (95.4%)	^{14}C wiggle-matching	carbonized wood	Western slope of Changbaishan	Xu et al. (2013)
1128±120 yr	Ar-Ar	sanidine	–	Wang (2012)
1.0±0.65 ka	U-TIMS	–	Northern slop of Changbaishan	Wang et al. (2001); Wang et al. (1999)
1.18±0.11 ka	TL	–	Northern slop of Changbaishan	Ji et al. (1999)
1.54±0.98 ka	ESR	–	Northern slop of Changbaishan	Yin et al. (1999)
0.025 – 56 Ma	FT	–	Northern slop of Changbaishan	Wan and Zheng (2000)
AD 937 – 938	Varve chronology	Varve	Japan	Fukusawa et al. (1998)
AD 912 – 972	Dendrochronology	Tree ring	Japan	Nakamura et al. (2007)
AD 929	Varve chronology	Varve	Japan	Kamite et al. (2010); Yamada et al. (2010)
AD 1630 – 1085	Varve chronology	Varve	Northeastern China	Guo et al. (2005)

* The calibrated probability levels are unavailable.

4.3 Radiocarbon dating of proximal tephra

A large amount of carbonized wood has been found within the proximal tephra on the slopes of the Changbaishan volcano. Numerous studies have dated the wood (e.g., Liu et al., 1998a; Horn and Schmincke, 2000; Jwa et al., 2003; Machida and Okumura, 2007; Nakamura, 2007; Nakamura et al., 2007; Yatsuzuka et al., 2010; Yin et al., 2012; Xu et al., 2013), yielding ^{14}C wiggle-matching ages of 1,190–735 cal yr BP (Table 3).

Both ^{14}C dating of carbonized wood from Naitou Mountain on the northern slope of Changbaishan volcano, and a tephra profile along a roadside adjacent to the Songhua River on the west slope, show that the age of the Millennium eruption was 1,050±70 ^{14}C yr BP and 1,120±70 ^{14}C yr BP (Zhao, 1981). Carbonized wood collected from Hepingyingzi, Antu Shentanyao, Huangsongpu, Pumice Forest (Xiagu Fushilin), Erdaobaihe, in addition to other areas, give numerous single ^{14}C dating ages that range from 1,489 to 895 ^{14}C yr BP, with most within the range of 1,200–1,000 ^{14}C yr BP (Liu et al., 1998a; Liu, 1999; Liu and Taniguchi, 2001; Jwa et al., 2003; Yin et al., 2005). The carbonized wood samples collected from the pumice in Pumice Forest (Xiagu Fushilin) have a clear growth ring structure. A ^{14}C wiggle-matching method applied to heartwood and sapwood gives a date of 1,190–990 cal yr BP for the Millennium eruption (Jwa et al., 2003). Subsequently, Japanese researchers have twice collected carbonized woods from the pyroclastic flow in Huangsongpu on the northern slope of Changbaishan volcano. The samples collected the first time did not have bark, so the outermost growth ring could not be determined. In contrast, the samples obtained the second time have approximately 100 growth rings with bark. The date of 1,020–1,007 cal yr BP was obtained for the Millennium eruption with the ^{14}C wiggle-matching method, which is consistent with the age of the distal B-Tm tephra presented above (obtained using a relevant dendrochronology method) (Nakamura, 2007; Nakamura et al., 2007). Xu et al. (2013) found a piece of wood with 264 clear growth rings (the bark was slightly carbonized) in the Xiaoshahe pyroclastic flow on the northwestern slope of Changbaishan volcano. Based on the age data of 27 tree rings samples and the ^{14}C wiggle-matching method, it was finally determined that the Millennium eruption occurred in the winter of 1,004 cal yr BP, which is confirmed by historical climatic records from Japan and other areas (Hayakawa and Koyama, 1998).

D.P.R. Korea and the Yuanchi area of China, eastern slope of Changbaishan volcano, are the main regions that were covered by the greyish-white pumice of the Millennium eruption. Chichagov et al. (1989) first conducted ^{14}C dating of five carbonized wood samples from D.P.R. Korea resulting in the date of 830–640 ^{14}C yr BP, while simlarly, it was determined that the samples from China were deposited in 1,370–1,010 ^{14}C yr BP. By collecting dead tree material from pumice fallout in D.P.R. Korea, a date of 1,001–961 cal yr BP was determined by the ^{14}C wiggle-matching method (Horn and Schmincke, 2000). However, Dunlap (1996) obtained a ^{14}C wiggle-matching age (at the University of Arizona) and determined 929–893 cal yr BP to be the appropriate timing of the Millennium eruption. Carbonized wood was also found in the Yuanchi area. Through systematic ^{14}C measurements from the center to the edge of the wood, followed by fitting with a high-accuracy tree ring calibrating curve, the obtained age of the Millennium eruption was determined to be 735±15 cal yr BP (Liu et al., 1998a). Recently, Japanese researchers obtained two carbonized tree sections (302 growth rings and 59 growth rings) at Heishigou on the eastern slope of Changbaishan volcano. These samples were dated (at intervals of 10 and 2 growth rings, respectively) using the ^{14}C wiggle-matching method to obtain two ages for the Millennium eruption: 1,005–990 cal yr BP and 1,005–987 cal yr BP (with the most likely eruption time to be 997 or 1,008 cal yr BP) (Yatsuzuka et al., 2010).

Yin et al. (2012) collected 82 in-situ carbonized wood samples with intact bark from the white pumice fallout in the Hengshan Forest on the southern slope and Old House Hill (Laofangzi Xiaoshan) on the northeastern slope. Using the ^{14}C wiggle-matching method, a reliable age of 1,029–1,009 cal yr BP was obtained for the Millennium eruption, with the most probable occurrence in 1,012 or 1,011 cal yr BP, which is in agreement with the historical climate and other records from eastern Asia (Stothers, 1998; Fei et al., 2004; Fei and Zhou, 2006).

By using the ^{14}C wiggle-matching method, Yatsuzuka et al. (2010), Yin et al. (2012) and Xu et al. (2013) achieved the most accurate dating results for the Millennium eruption to date. This method not only avoids errors resulting from single sample ages, which may be collected from different tree growth rings, but may also make better systematic corrections to tree ring ages. These results are therefore more reliable than those from single carbonized wood samples. One precondition for the dating of tephra by the ^{14}C wiggle-matching method is that when enormous quantities of hot pumice fall to the ground, the trees must immediately be heated and killed. Generally, these specifications must be adhered to allow for an accurate age representation of tephra covering the bark of the in-situ carbonized woods (Yatsuzuka et al., 2010).

Note that most of the radiometric ^{14}C age data listed in Table 3, have a greater (older) age. Such age deviations may occur for the following three reasons:

1) There may be enormous fumarole activities and toxic gases, such as H_2S, SO_2, and CO_2, before volcanic eruptions, resulting in the death of trees and other plants. Thus the ages dated by carbonized wood collected from pumice fallout or pyroclastic flow could give an age that is older than the eruption.

2) During a volcanic eruption, pumice fallout and pyroclastic flows are very hot and the external growth rings of the trees may be burnt off, thus the collected tree ring samples may not stand for the real age of this eruption. What’s more, carbonized wood with intact bark may be protected from pumice fallout and not suffer the same severity of impact from pyroclastic flows (Yatsuzuka et al., 2010).

3) Dominant volcanic activities might release a large amount of carbon dioxide gas, affecting the ^{14}C level of atmosphere in the region. This would elevate the regional C level and affect the calibration age results. For example, the concentration of soil gas (CO_2) on the western slope of Changbaishan volcano may reach 500–1,000 ppm (unpublished data), thereby diluting the regional ^{14}C level.

4.4 Other radiometric methods for dating proximal tephra

In addition to ^{14}C dating methods, other dating methods have been utilized directly on the pumice of the Millennium eruption. Ji et al. (1999) dated the pumice samples on Tianwen Peak with the thermoluminescence method, thus obtaining a thermoluminescence age for the Millennium eruption of 1.18±0.11 ka. Yin et al. (1999) dated the grey pumice within the yellow pumice from the profile of Tianwen Peak by using the ESR dating method, thus obtaining an age of 1.54±0.98 ka. Wang et al. (1999, 2001) carried out high-accuracy U-series TIMS dating using the samples collected from the profile of Tianwen Peak-Qixiang Station-Volcano Station, obtaining an age for the grey pumice of 1.0±0.6 ka, similar to the result of ^{14}C dating. In addition, they established six eruption stages for Changbaishan according to a series of data in the profile. Zou et al. (2010) considered that AD 1000 is the timing for the Changbaishan Millennium eruption and by utilizing the U-Th dating of zircons selected from the pumice of the Millennium eruption, they also obtained a residence time of ~8 ka for the magma of the Millennium eruption in the magma chamber, the shortest yet discovered, while Gill et al. (2013) determined that the comendite magma was 10–20 ka old at the time of eruption. Wan and Zheng (2000) dated the pumice from both the Millennium and the contemporary eruption of Baiyan Peak by fission track analysis, with the end result of 0.025–56 Ma. Such old age results are inconsistent with all other results obtained by the dating methods presented above, which shows that conventional fission track dating methods are not appropriate for dating the Changbaishan Millennium eruption. Wang (2012) collected sanidine samples from the pumice of Changbaishan Millennium eruption, treated and radiated them in three batches, and obtained a weighted average depositional date of AD 884±120, thereby obtaining the first Ar-Ar age for the Millennium eruption.

Overall, dating results from thermoluminescence, ESR, U-series disequilibrium, and fission track have a greater range than those from the Ar-Ar method for this eruption. Even so, the Ar-Ar dating result is closer to ^{14}C dating results and historical records. Although these geological radioactive dating methods are not as accurate as the ^{14}C dating method for an event as young as the Millennium eruption, when the eruption products of the Changbaishan volcano from the last thousand years do not contain carbonized wood or other organic samples, the mutual verification of these dating methods is still worth applying.

5 Conclusions

This paper presents a summary of the recent work on the Millennium eruption of Changbaishan volcano, including the field characteristics of distal and proximal tephra, tephra geochemistry and mineralogical assemblages, and dating results. This work has additionally highlighted a number of areas where further work is essential to better understand the eruption and environmental impact of such a large-scale eruption. These include the following:

1) Even though the precise timing of the Millennium eruption remains uncertain, an eruption date between 1012 and 1,004 cal yr BP (Yin et al., 2012; Xu et al., 2013) was favored in this paper. The westward boundary of the eruptives includes the Longgang volcanic field. Tephra from this eruption, with characteristics of high alkali and a ratio (>4) of FeO_T to CaO, can be clearly identified among contemporary eruptions.

2) The impact of the Millennium eruption on regional–or even global–environmental records needs further studies. Acidic spikes in ice cores from the Polar Regions alone cannot adequately determine the actual eruption event (Zielinski et al., 1994; Zielinski, 1995).

3) Consensus has not been achieved on the sequence of proximal tephras deposited from the Millennium eruption to the more recent eruptions.

4) Identification of distal tephra in sedimentary environments from the west of Changbaishan volcano is poor. The geochemical characteristics of the tephra units to the east and west of the volcano are obviously different; therefore, their identification in these respective sedimentary environments should be a target for further studies and should help to further our understanding of the scale and mode of the Millennium eruption. In addition, older tephra layers that originated from the Changbaishan volcano are found in the Janpan Sea and other areas (Lim et al., 2013), but proximal tephra corresponding to them and the fine details of the sequence are still not perfect. Therefore, elaborating on the proximal tephra sequence and mapping tephra/cryptotephra layers from the Japan Sea, maar lakes, and other sedimentary environments in northeast China should be a focus not only for the Millennium eruption, but also for other historical eruptions of Changbaishan volcano.

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