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A re-assessment of historical records pertaining to the activity of Mt. Baekdu (Paektu, Tianchi) volcano

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Abstract

This study re-assesses the historical records pertaining to the activity of Mt. Baekdu according to volcanic phenomena. We categorized volcanic phenomena into five categories: rumbling, atmospheric abnormality, ash rain, ash cloud and phenomenon sightings, and investigated historical records (in Chinese) for each phenomenon and identified their volcanological implications. Among the volcanic phenomena, ash rain had the most abundant records, and in particular, Goryeosa recorded the ash rain phenomenon 56 times. And more than 90 volcanic eruptions were discovered from the Millennium Eruption from November 3, 946 AD, to February 7, 947 AD, most of which were either Plinian or Vulcanian eruptions with volcanic ash dispersed into the regions surrounding the volcano creating fallout ash. Based on the historical eruptions, eruption precursors, and volcanic unrest of the volcano between 2002 and 2006, Mt. Baekdu is regarded as an active volcano that has the potential to erupt. Therefore, to mitigate the hazard caused by the eruption of Mt. Baekdu, it is necessary to analyze the historical eruption records of Mt. Baekdu and understand the characteristics of the eruptions through this analysis.

Keywords Historical eruption records, Mt. Baekdu volcano, Millennium eruption, Vulcanian eruption, Plinian eruption

Introduction

Investigating and analysing historical records that may indicate the nature and impacts of past volcanic eruptions is pivotal in assessing the future volcanic threat. Such investigation can be particularly fruitful when historical evidence is confronted with interpretations of natural proxy records, including the proximal geological record, tephrochronology, ice core glaciochemistry,

and tree-ring-based climate reconstructions. In this way, not only it is possible to establish the record of past volcanism but also it can identify the impacts and societal repercussions of eruptions (e.g., Oppenheimer 2011; Pyle 2017; Pyle et al. 2018; Pyle and Barclay 2020). The 1815 eruption of Tambora (Sigurdsson and Carey 1989; Oppenheimer 2003) and the 79 AD eruption of Vesuvius (Sigurdsson et al. 1982) would be the representative example of the approach. Oral traditions also describe well past volcanic activities, alerting geoscientists to the volcanoes that were not previously considered as sites of future eruptions. If the traditional knowledge of Aeta indigenous group who lived on the slopes of Mt. Pinatubo, Philippines, received volcanic risk management's attention sooner, the risk perception of volcanic hazards might be more recognizable through the depth study before it reached to the climatic phase of eruption in 1991 (Rodolfo and Umbal 2008).

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Since Mt. Baekdu (Figs. 1, 2, 3) is located on the border between China and DPR Korea, precise field geological survey research is very limited in reality. However, by investigating the past eruption interval and eruption characteristics, we can develop the rough prediction and understand eruption characteristics of the future eruption period. Therefore, studying the eruption characteristics of Mt. Baekdu volcano from the historical documents can enhance the overall understanding of the future behavior of Mt. Baekdu. There is an enduring debate concerning the activity of the volcano since the so-called Millennium Eruption of 946 AD (Horn and Schmincke 2000; Zou et al. 2010; Wei et al. 2013; Sun et al. 2017). This event was only recently securely dated, thanks to a combination of tree ring and ice core evidence (Oppenheimer et al. 2017; Hakozaiki et al. 2018). Some interpretations of historical sources suggest minor eruptions of the volcano occurred in AD 1265, 1403, 1668, 1702, and 1903 after the Millennium eruption (Soh and Yun 1999; Pak and Rim 2010; Miyamoto et al. 2010; Yun et al. 2013a; Ramos et al. 2016; Li 2017; Sun et al. 2017). However, Pan et al. (2020) state that no convincing direct physical evidence was discovered for any eruption that occurred since the Millennium Eruption. We returned to

the historical records to shed further light on this issue. Mt. Baekdu experienced an unrest episode characterized by uplift, increased seismicity, and changed in gas geochemistry between 2002 and 2005 (Xu et al. 2012), emphasizing the importance of understanding the history of the volcano.

Methods

Historical records about suggestive of eruptions of Mt. Baekdu have been previously discussed (Cui et al. 1995, 2000, 2008; Jin and Cui 1999; Yun and Cui 1996; Cui and Liu 2006; Yun et al. 2013b). The records were mostly derived from sources such as Nihongiryaku (“日本紀略”), a chronicle of Kofukuji Temple (“興福寺年代記”), Goryeosa (“高麗史”), Goryeosa Segwa (“高麗史世家”), Dongguk Munheon Bigo (“東國文獻備考”), Joseon Wangjo Sillok (“朝鮮王朝實錄”), Seungeongwon Ilgi (“承政院日記”), Haedongjamnok (“海東雜錄”), and Changbaishanjiaanggǎngzhilùe (“長白山江崗志略”).

Nihongiryaku describes a Japanese history compiled in the Heian period from 660 BC to 1036 AD. This book is kept in the National Diet Library Digital Collections. Goryeosa and Goryeosa Segwa are books describing the history of Goryeo and Noble Family from 918

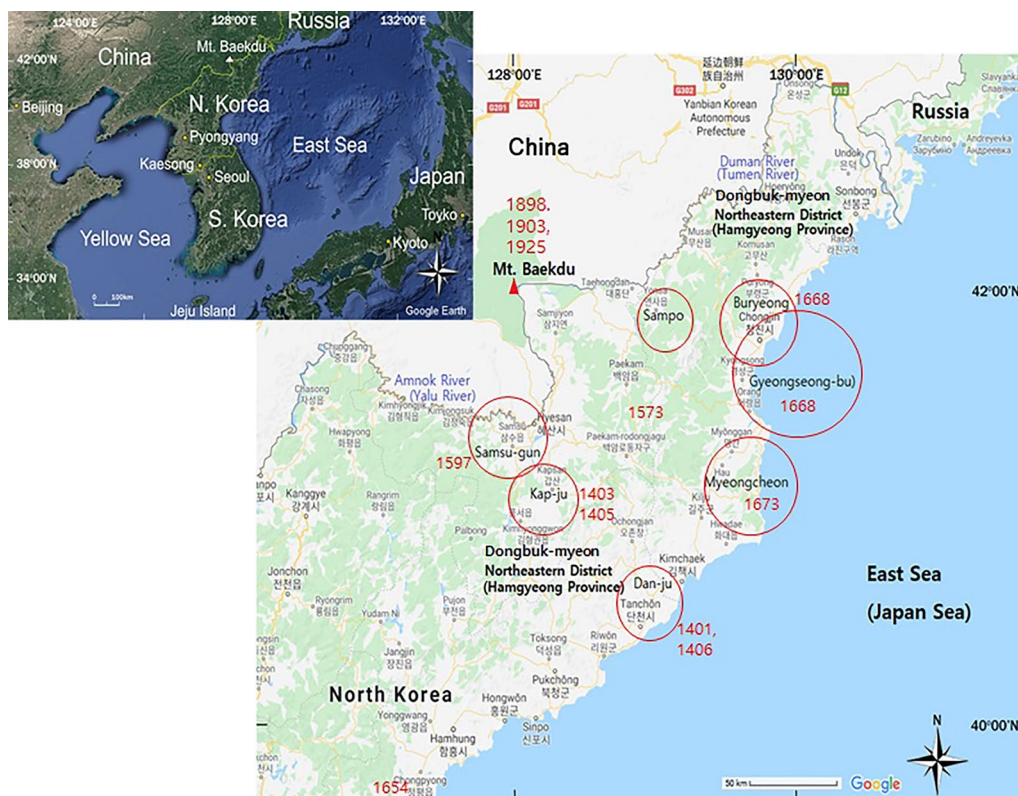


Fig. 1 Location of Mt. Baekdu volcano (also known as Paektu, Baitoushan, Changbaishan, and Tianchi) and localities where the volcanic phenomenon was observed in the DRPK (modified from Google Earth)

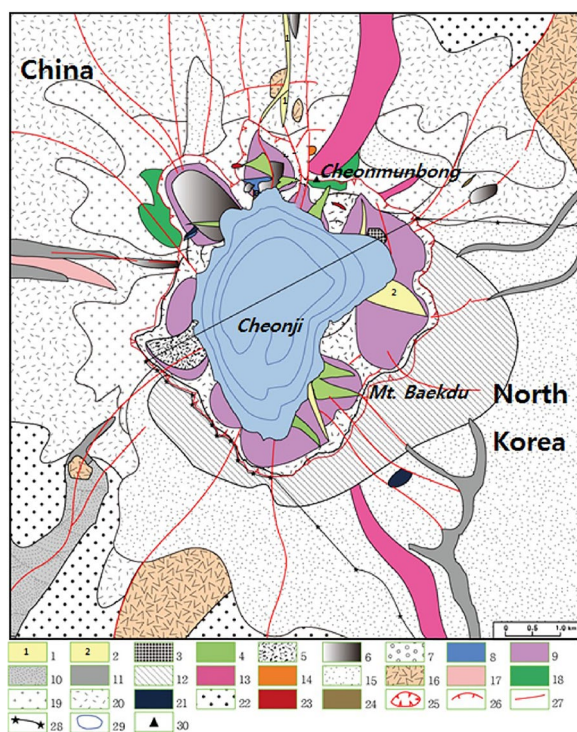


Fig. 2 Generalized geologic map of the summit area of Mt. Baekdu (modified from Wei et al. 2013). [1; alluvial sandstone and conglomerate bed of modern river-bed, 2; fan earth flow inside and outside the Cheonji caldera lake, 3; gray trachytic pumice and debris sedimentation on No. 6 boundary line monument (1903 AD), 4; mid-term fan earth flow inside the caldera, 5; black trachytic pumice around the Cheonji on No. 5 boundary line monument (AD 1702 eruption), 6; black trachytic welded tuff breccia of upper Palgoimyo (1668 AD), 7; black trachytic pumice of lower Palgoimyo (1668 AD), 8; early fan earth flow inside the caldera, 9; sedimentation side and top of caldera, 10; black and gray–black earth flow outside volcanic cone, 11; black and gray–black trachytic pyroclastic flow (AD 946 eruption), 12; gray–black pumice of the south-side Cheonji, 13; Gisangcheomgi clastic alkali rhyolite, obsidian, welded tuff, 14; light gray and gray–purple alkali rhyolitic cataclastic rock, 15; Baiyunfeng light gray alkali rhyolitic pumice, 16; shanti talus, 17; Bingchang gray–purple and dark grey welded breccia, tuff (erupt five thousand years ago), 18; Cheonmunbong gray–orange alkali rhyolitic pumice, 19; lower orange–yellow pumice, welded tuff breccia, upper trachyte, alkali rhyolite, obsidian, 21; Laohudong (plateau) basalt (0.32–0.35 Ma), 22; Baekdusan lower trachyte, 23; alkali rhyolitic dike, 24; trachytic dike, 25; collapse fault, 26; a paddle wheel fault, 27; fault, 28; border, 29; isobath of Cheonji caldera lake, 30; Cheonmunbong]. Cheonji: Tianchi in Chinese, Palgoimyo: Baguamiao in Chinese, Gisangcheomgi: Qixiangzham in Chinese, Cheonmunbong: Tianwenfeng in Chinese



Fig. 3 Photos of Cheonji (Tianchi in Chinese) caldera lake on the top of Mt. Baekdu (upper; summer season, lower; winter season)

until 1770, arranged with the historical method. Joseon Wangjo Sillok is the Annals of the Joseon Dynasty from 1392 to 1897. Seungeongwon Ilgi is the Diaries of the Royal Secretariat from 1623 to 1910 AD. Haedongjamnok is a book compiled by Kwon Byul (權黻) during Joseon Dynasty, which contains various historical stories extracted from many books. Kwon Byul wrote about the people’s history, categorizing the information according to the family names until the early Joseon Dynasty. Stories about royal families are written only until Goryeo. These books are kept in the Gyujanggak Library of Korea. Chángbáishānjiānggǎngzhìlüè is a report of an on-site survey of Mt. Baekdu. This book describes the eruption of Mt. Baekdu in 1903 and is kept in the Jilin Province Library. Figure 4 shows the list of the ancient references regarding the eruption records of Mt. Baekdu.

The original medieval and later Japanese and Korean documents and books written in Chinese were first translated into Korean by the Gyujanggak Library of Korea and scholar who is well versed in old Chinese characters, and then into English in this paper. After then, events that are closely related to volcanic eruption were classified and examined according to volcanic phenomena.

to 1392 AD. Dongguk Munheon Bigo is the reference book of compiled documents of the Eastern Kingdom (=Joseon Dynasty) from 2333 BC to 1994 AD. It is a sort of encyclopedia that contains information about the border of Korea, civilization, and the social system

Phenomena indicating a volcanic eruption

Rumbling

January 24, 939 AD The original text of Nihongiryaku says, “天慶二年正月二日甲辰春日大社鳴如擊”. It translates as follows: “The sound of a large drum was heard on

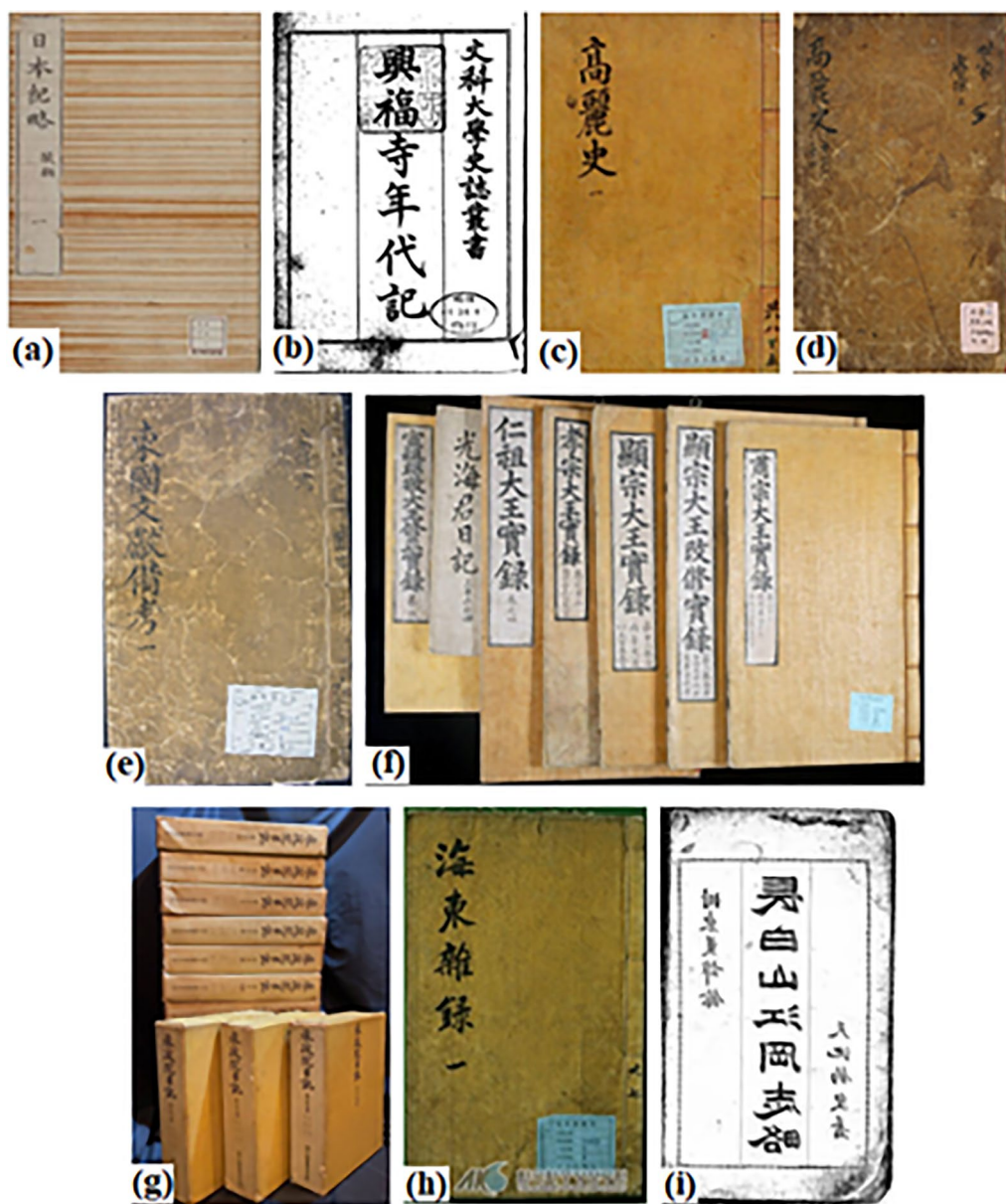


Fig. 4 The ancient references and other papers including the records on Mt. Baekdu eruptions. **a** Nihongiryaku (“日本紀略”), **b** a chronicle of Kofukuji Temple (“興福寺年代記”), **c** Goryeosa (“高麗史”), **d** Goryeosa Segwa (“高麗史世家”), **e** Dongguk Munheon Bigo (“東國文獻備考”), **f** Joseon Wangjo Sillok (“朝鮮王朝實錄”), **g** Seungjeongwon Ilgi (“承政院日記”), **h** Haedongjamnok (“海東雜錄”), **i** Changbáishánjiānggāngzhilüè (“長白山江崗志略”) (Yun 2013)

January 2 (January 24 by the solar calendar), 939 AD, the second year of the Tengyo era, which was in Kasuga-Taisha shrine, Nara”.

In the Japanese era, Tengyo (天慶) is the period from May 938 to April 947. This record is the rumbling by the explosive volcanic eruption from a long distance away and it is highly likely that this phenomenon was caused by the Mt. Baekdu eruption. Interestingly, the following event recorded (in 946 AD) also talks of a drumbeat sound, and the timing of the event does coincide with the

year of the Millennium Eruption. Conceivably, this event could be related to the precursory activity of Mt Baekdu but there is no other corroborating evidence. Based on the descriptions in Nihongiryaku, which is a Japanese history book, Akaishi et al. (2000) made assumptions that there had been resonance by the explosion from a long distance in January 939 AD and considered that it had been caused by the B-Tm (Baegdusan-Tomakomai tephra; Machida et al. 1981; Machida and Arai 1981, 1983) eruption. If the January 939 AD rumbling originated from Mt.

Baekdu and an explosive volcanic eruption had occurred at that time, the Ainu, who were the native people living in Aomori (i.e., a city located in NE Honshu, Japan) and further north in the region of Hokkaido, where both the B-Tm tephra distribution axis passed through, would have experienced volcanic ash falling just like rain. This would have resulted in severe economic damages such as unexpected cooler or colder weather changes and its impact on crop failure. Therefore, there are possibilities that the Ainu rebellion, which began in May 939 AD, could have been caused by the effects of the B-Tm tephra (Akaishi et al. 2000). Accordingly, it can be also expected that the AD 939 rumbling event, which was recorded in Nihongiryaku, could have been caused by the eruptions of Mt. Baekdu in 937 and 938 AD (Fukusawa et al. 1998).

November 3, 946, and February 7, 947 AD An original written record in the second scroll of Goryeosa Segae, which was written during the first year (946 AD) of King Jeongjong in the Goryeo Dynasty, mentions “是歲天鼓鳴赦” which can be translated as follows: “As the sound of beating was heard from the sky (a heavenly drum beating was heard) this year, the criminals were pardoned” (Fig. 5). The original text of chronicle of Kofukuji Temple

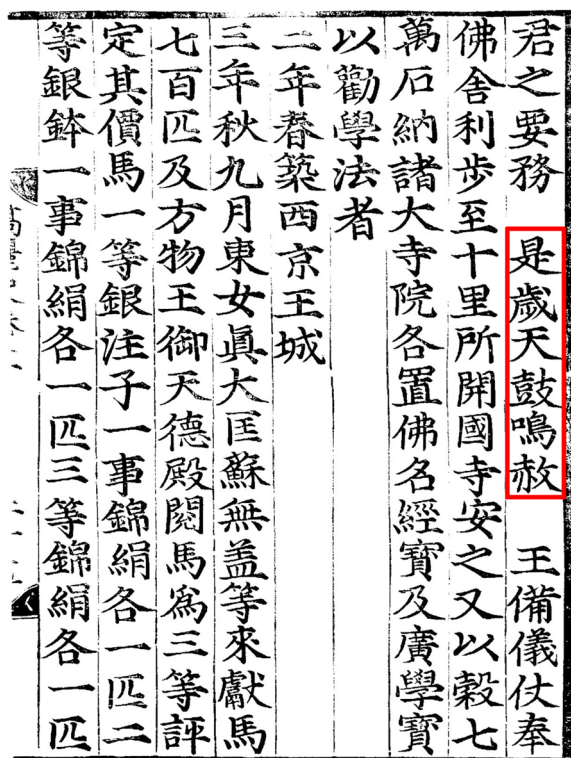


Fig. 5 The original text of the 946 eruption record (from Goryeosa Segae)

(“興福寺年代記”) also says, “天慶九年十月七日夜白灰散如雪” which can be translated as follows: “On the night of October 7 (November 3 by the solar calendar), 946, white ash fell like snow”.

It may be the eruption of volcanic ash that rained down on 3 November, 946 in Nara, Japan.

Also, the original text of Teishinkoki (“貞信公記”, a Japanese history and the journal of Fujiwara Tadahira, an early regent) says, “天曆元年正月十四日空中有聲如雷鳴”. It translates as follows: “In the region of Kyoto, “there was a sound from the sky on January 14 (February 7 by the solar calendar), 947, the first year of the Tenryaku, also Tenreki, era, and the sound was like thunder”.

The original text of Nihongiryaku says, “正月十四日庚子此日空中有聲如雷” which means, “There was a sound from the sky on 7 February 947 by the solar calendar, and it sounded like thunder”.

Goryeosa is the chronicle of the Goryeo Dynasty, which was written in the succeeding Joseon Dynasty. It was altered in texts several times after its first draft in the beginning of the Joseon Dynasty and finally compiled in 1451 AD. The original text of Goryeosa Ji (“高麗史志”), Volume 7, includes the record saying, “定宗元年天鼓鳴” which means “the sound of beating was heard from the sky at 946”, and the original text of Goryeosa Jeolyo (“高麗史節要”, Essentials of Goryeo History) also includes the following record which says, “是歲天鼓鳴赦” (Fig. 6).

The fact that the natural phenomenon was recorded on several different books proves that 946 rumbling event must have been not only recognized to the people of Goryeo dynasty as an important and serious phenomenon but also evoked fear and terror. We cannot determine whether these records indicate the explosive eruption of Mt. Baekdu in particular. At that time the territory of Goryeo was south of Euiju—Wonsan and it did not reach to the north where Mt. Baekdu was located in. Considering that the winter prevailing winds used to come out of the northwest, the Goryeo territory was beyond the coverage of ash fall. Therefore, even if the rumbling occurred in Mt. Baekdu, the writer would not be able to identify the cause of the rumbling.

The analysis of the tenth century eruption products around Mt. Baekdu through a geological field survey shows that pumice fall layers erupted before the huge pyroclastic flow deposits. It is speculated that, at the time of these Plinian and ignimbrite eruptions, the sound of the volcanic explosion was conveyed as resonance far to Gaeseong(Kaesong=The capital of Goryeo) which was about 465 km away from Mt. Baekdu and even to Japan which was more than 1,000 km away from Mt. Baekdu. Hayakawa and Koyama (1998) compared the

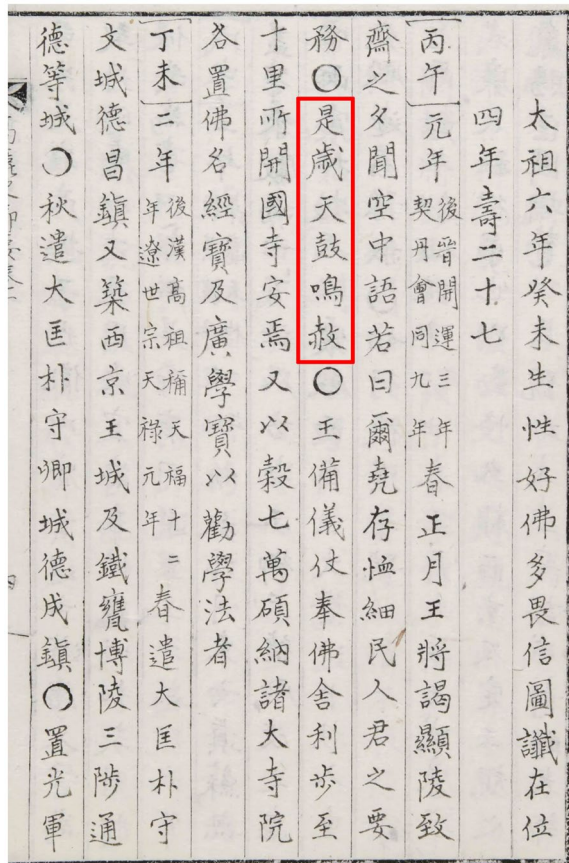


Fig. 6 Another original text of the 946 eruption record (from Goryeosa Jeolyu)

thunder recorded in Teishinkoki or Nihongiryaku with the Changbai pyroclastic flow (C-pfl) eruption (Machida et al. 1990) and speculated that the B-Tm tephra had also fallen at this time in Hokkaido or Tohoku region.

November 20, 1362 AD An original written record in Goryeosa which was written during the eleventh year (1362 AD) of King Gongmin in the Goryeo Dynasty mentions “恭愍王十一年十一月乙巳天鼓鳴” which can be translated as following: “As the sound of drumbeating was heard from the sky on November 4 (November 20 by the solar calendar), 1362 AD, the eleventh year of the King Gongmin”. It appears there was an explosive volcanic eruption and it caused the rumbling sound from the sky in the capital (Kaesong city) of Goryeo dynasty (Fig. 7).

Atmospheric abnormalities (= atmospheric red and white glowing)

1014, 1016, 1017, 1018 and 1019 AD The original text of the second volume (of a set of three) of Goryeosa (“高麗史(中)”) says, “顯宗五年三月庚寅夜四方赤氣, 七年十二月

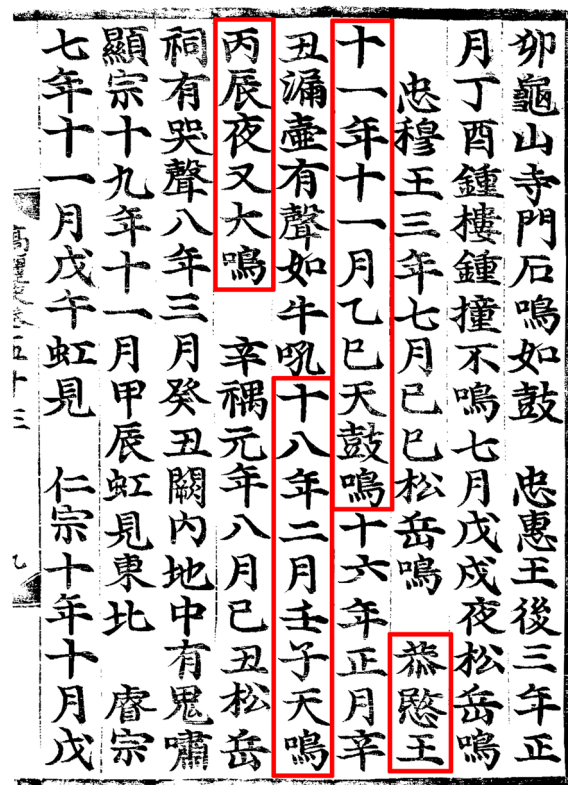


Fig. 7 The original text of the 1362 eruption record (from Goryeosa)

丁酉四方赤氣, 八年二月癸酉赤氣如火弥天, 十年正月乙酉赤氣意天”. It translates as follows: “One night in March of the 5th year of King Hyeonjong, Gyeongin, all over the place was tinged with red. In December of the 7th year, Jeongyu, all over the place was shrouded in a red tinge. In February of the 8th year, Gyeju, all over the place was shrouded in the red tinge like a fire in the sky. In October of the 10th year, Eulyu, all over the sky was tinged with red.”

Gyeongin is the 27th year of the sexagenary cycle. Jeongyu is the 34th year of the sexagenary cycle. Gyeju is the 10th year of the sexagenary cycle and also the Year of the Fowl in the Chinese zodiac cycle. Eulyu is the 2nd year of the sexagenary cycle.

The original text of the first volume of Dongguk Munheon Bigo says, “顯宗五年三月庚寅夜四方赤氣, 四月庚午白氣界天如匹布, 七年十二月丁酉四方赤氣, 八年二月癸酉赤氣如火弥天, 十一月己未夜白氣如練意天俄變爲赤氣, 九年正月癸亥白氣如帶亘天, 十年正月乙酉赤氣意天”. It translates as follows: “One night in March of the 5th year of King Hyeonjong, Gyeongin, all over the place was shrouded in the red tinge. In April, Gyeongin, a white smoke like a white cotton cloth spread in the sky. In December of the 7th year, Jeongyu, all over the place was tinged with red. In February of the 8th year, Gyeju,

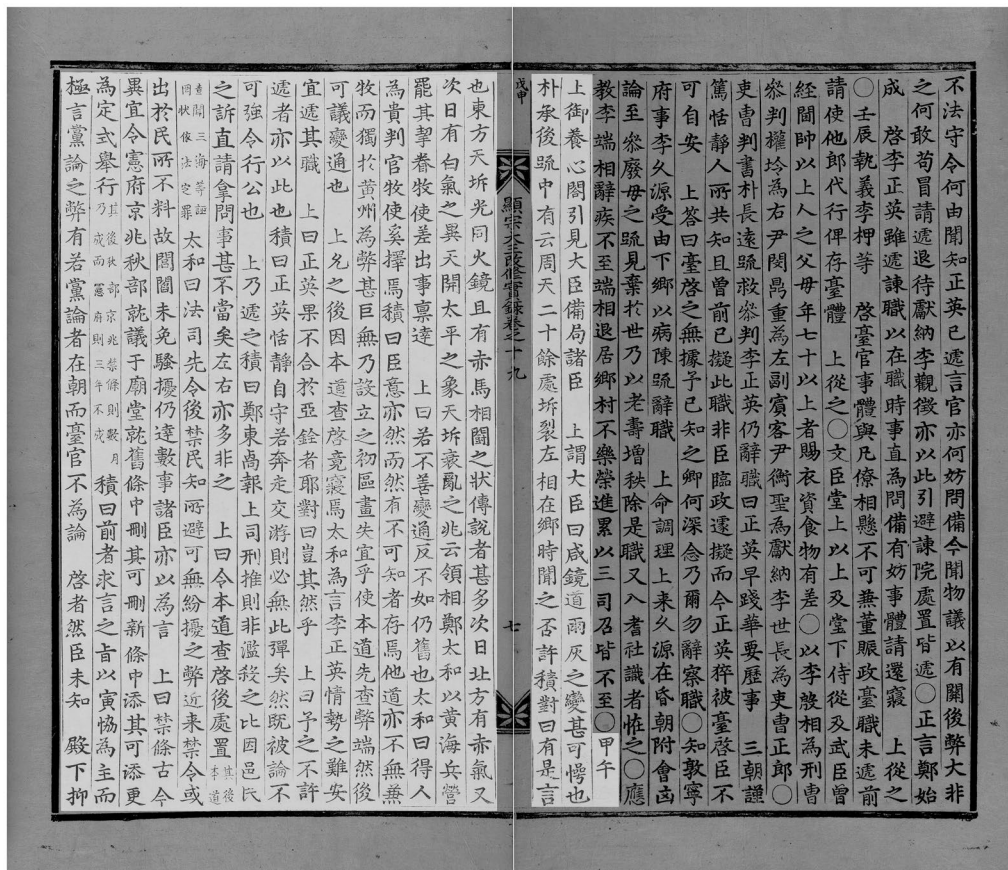


Fig. 8 The original text of the 1668 eruption record (Yun 2013)

the red tinge like a fire spread across the whole sky. One night in November, Gimi, the sky was tinged with white, just like covered by white silks, and then it became tinged with red. In January of the 9th year, Gyehae, a white-banded smoke reached the sky. In January of the 10th year, Eulyu, all over the sky was tinged with red”.

Gyeonggo is the 7th year of the sexagenary cycle and also the Year of the Horse in the Chinese zodiac cycle. Gimi is the 56th year of the sexagenary cycle. Gyehae is the 60th year of the sexagenary cycle and also the Year of the Swine in the Chinese zodiac cycle. The records of the 5th year (1014 AD), 7th year (1016 AD), 8th year (1017 AD) and 10th year (1019 AD) of King Hyeonjong, such as ‘a white smoke like a white cotton cloth spread in the sky’ and ‘at night, all over the place was shrouded in the red tinge’, describe the volcanic ash dispersion and the meteorologically unusual atmospheric phenomenon. Cui and Liu (2006) interpreted them as the atmospheric phenomenon caused by Mt. Baekdu super-volcanic eruption. The record of the 9th year of King Hyeonjong (1018 AD) saying ‘a white-banded smoke reached the sky’ can be interpreted in a way that the north or northeast winds flew

from the Mt. Baekdu region and the volcanic ash clouds moved to the lower altitudes and advanced southward. In other words, it implies the production of ash falls.

June 5, 1668 AD There is a record from the 14th volume of the Annals of the Joseon Dynasty, revised version of King Hyeonjong, April 26 (the day of Gapo; June 5 by the solar calendar) of the 9th year (1668 AD, the year of Mushin/the 7th year of Emperor Kangxi, Qing Dynasty) (Fig. 8). The first article of the book says: “甲午/上御養心閣, 引見大臣、備局諸臣。上謂大臣曰: “咸鏡道兩灰之變, 甚可愕也。朴承後疏中有云: ‘周天二十餘處坼裂, 左相在鄉時聞之否?’” “許積對曰: “有是言也。東方天坼, 光同火鏡, 且有赤馬相鬪之狀, 傳說者甚多。次日, 北方有赤氣, 又次日, 有白氣之異。天開, 太平之象, 天坼, 衰亂之兆云”。 It will be translated as follows: “The King said, I went to Yangshimhap and had a speech to the ministers and many officers from Biguk. I talked to the ministers, “I was surprised at the extraordinary phenomenon of the ash falling in Hamgeyong Province. Park Seunghu reported me, about 20 places around the skies were opened”. So, I asked to the first vice-premier, “Have you heard such a

thing when you were staying in the country?” Then, Heo Jeok replied, “I’ve heard about that. The eastern sky broke up and the light was like sun ray from a burning glass. I also heard that there had been the scenes looking like the red horses fighting against each other. Many people said the same thing. The next day, the north was tinged with red, and it was tinged with strange white the following day. People say that the opening of the sky is the sign of peace and its breaking up is that of uproar”.

Yangshimhap is one of the separate buildings of Daejojeon of the Changdeok Palace. Biguk is the synonym for Bibyeonsa, the Border Defense Council of the earlier Joseon Dynasty, and later it played the same role as Uijeongbu. Based on the record from the Annals of the Joseon Dynasty that about 20 places around the skies opened and the light was like sun ray from a burning glass, it can be inferred that there was an explosive magmatic eruption and the high-temperature eruption products were illustrated as the scene of red horses fighting against each other. From the record that the sky was later tinged with strange white and the volcanic ash rain fell in the Hamgyeong Province, it can be inferred in the same manner from the 1403 AD, 1405 AD and 1406 AD records that the volcanic ash erupted from Mt. Baekdu flew by the western winds, moved to east, and fell down to the Hamgyeong Province regions. In other words, the Plinian eruption following the explosive magmatic eruption caused the volcanic ash clouds to move eastward, and consequently, the ash falls fell down.

Ash rain (= dust rain)

March 25, 1124 AD The original text of the second volume (of a set of three) of Goryeosa says, “仁宗二年三月丙辰雨土三日”. It translates as follows: “March 8 (March 25 by the solar calendar), 1124 AD, the second year of King Injong, earth (= soil including volcanic ash) fell down like rain 3 days”.

We cannot determine exactly whether it was the volcanic ash caused by the eruption of Mt. Baekdu or the yellow sand (or Asian dust) (Chun et al. 2002). However, when we interpret this record with the other materials which will be mentioned later, it is very likely that this record indicated the ash fall event. According to the Seounkwanji (書雲觀志, 1818), 土雨 “某時某更四方昏濛若下塵”, it is described as “It is recorded that at some point in time, it’s dark and hazy everywhere, and the dust seems to fall like drizzle”. When Asian dust blows, it looks cloudy in the state of suspended dust in Korean peninsula, but as in this article, it fell like rain, which means that it was in the state of solid particles affected by gravity. Therefore, it is interpreted that the ash falls caused by Mt. Baekdu volcanic eruption.

1199, 1200 and 1201 AD The original text of the second volume (of a set of three) of Goryeosa says, “神宗二年五月南部北井水赤沸聲如牛鳴凡十餘日”. “神宗二年十月辛酉雷俄而有怪氣中黑辺赤從鵠峯出漸大弥滿京都遂雨雹黑氣下地咫尺不見人”. “神宗三年潤二月戊申四方昏溟雨土二日庚午雨土四方昏溟意日, 四年四月庚辰朔雨土”. It translates as follows: “In May of the second year of King Shinjong, the water in the well was turned into red and made the boiling sound just like a cow cry for 10 days. And “in October 2 (October 23 by the solar calendar) of the second year of King Shinjong, Shinyu, the thunder suddenly filled the air and the blackish-red gas arose in Gongnyeong (鵠嶺 = older name of Songaksan, Kaesong). It continued to fill the air and filled the capital (Kaesong city) with hail falling down. It was getting dark, so no one even an inch ahead was to be seen”. “In February (the leap month) 22 (April 7 by the solar calendar) of the third year of King Shinjong, Mushin, it was dark all around, a light rain fell, and a dust storm or yellow sand blew. And on March 15 (April 29 by the solar calendar), Gyeonggo, a dust storm blew. It was dark and drizzled all day long”. “In April 1 (May 4 by the solar calendar) of the fourth year of King Shinjong, Gyeongjin, on the first day by the lunar calendar, an earth fell down like rain”.

Shinyu is the 58th year of the sexagenary cycle. Mushin is the 45th year of the sexagenary cycle. Gyeonggo is the 7th year of the sexagenary cycle. Gyeongjin is the 17th year of the sexagenary cycle. This can be interpreted in a way that the explosive vibration caused by the explosive eruption from Mt. Baekdu (Cui et al. 2000; 2008) was transferred as a form of resonance, followed by the clouds of hot black volcanic ash flown to the south by the north or northeast winds, and then the volcanic gas and ash clouds which were produced from the crater by the Plinian eruption moved by the prevailing wind effects and finally fell as ash falls, in other words, a dust storm. This record has also been included in the first volume of Haedongjamnok (“海東雜錄(上)”).

April 15, 1265 AD The original text of the second volume (of a set of three) of Goryeosa says, “元宗六年三月丁亥微雨白如酒粉”. It translates as follows: “In March of the sixth year of King Wonjong, Jeonghae (April 15 by the solar calendar), some particles from fine solid materials like leaven powder fell down like fine rain”.

Jeonghae is the 24th year of the sexagenary cycle. That the fine particles of solid materials were falling like rain indicates that ash was falling down. As mentioned earlier, it can be interpreted in the way that the ash clouds which were produced from the Mt. Baekdu crater moved southward by the north or northeast winds and the fine ashes fell down from clouds.

June 24, 1373 AD The original text of the second volume (of a set of three) of Goryeosa says, “恭愍王二十二年四月丁酉雨土” “恭愍王二十二年四月丁酉夜天雨白毛長二寸或三四寸細如馬髮。戊寅夜雨白毛，壬午，癸未，丁亥，丙申亦如之” “恭愍王二十二年四月己卯大霧雨白毛遍國中庶人皆曰龍毛拾而視之乃白馬髮也，五月壬寅朔霧雨毛” It translates as follows: “In April of the 22nd year (1373 AD) of King Gongmin, Jeongyu (June 24 by the solar calendar), the earth fell down like rain”. “One night in April of the 22nd year (1373 AD) of King Gongmin, Jeongyu (June 24 by the solar calendar), something white like horsehair, 2 chon (= 6.06 cm) or 3–4 chon (= 9.1–12.1 cm) in length, fell from the sky. One night in Muin, something like white fur fell down. It did so in Imo, Gyeyu, Jeonghae, and Byeongshinil, too”. “In April of the 22nd year (1373 AD) of King Gongmin (June by the solar calendar), Gimyeoil, some things like pieces of white fur fell down like heavy fog and rain. All the people in the country mentioned that they looked as if the scales of the dragon were blowing like the hair of the white horse. On the first day of May, Iminil, hairs fell like fog and rain”.

Muin is the 15th year of the sexagenary cycle. White fur fell down depicts the long, flat pieces of pumice 6 to 12 cm in length, and the volcanic ash fell from the sky in June. It can be interpreted in a way that the scales of the dragon are the crushed and broken pieces of pumice and pieces of white fur, or the hairs of the white horse are Pele’s hair which were erupted from Mt. Baekdu moved southward by the north or northeast along with the volcanic ash clouds. It seems that they described the pieces of pumice as shaggy horsehair. As white horse’s fur is so thin and long, it resembles Pele’s hair. Considering the movement of the crushed pumice or Pele’s hair, we can infer that the Volcanic Explosivity Index (hereinafter “VEI”) was much higher than that of the time when the yellow sand blew.

May 8, 1401 The original text which was written on March (the leap month) 25 (Gapin) (May 8 by the solar calendar), the first year (1401 AD: Shinsa) of Taejong Sillok (太宗實錄, Annals of King Taejong) (Fig. 9) says, “兩炭于端州-東北面察理使報: “端州東北間，非烟非霧，渾天黑暗，有炭落地” 封數枚以上.” It translates as follows: “The coal-black rain fell in Danju (端州). The officer who had been sent to govern the Northeastern District, called Dongbukmyeon Challisa (東北面察理使), reported as follows: In Danju, something neither smoke nor fog covered and darkened the whole sky. Charcoal (black pumice or scoria) has been laid on the floor. So, I sealed a couple of pieces of the charcoal and I am sending them.”

The year 1401 is called Gapinnyeon. Gapin is the 51st year of the sexagenary cycle and the Year of the Tiger in the Chinese zodiac cycle. Danju is the old name of

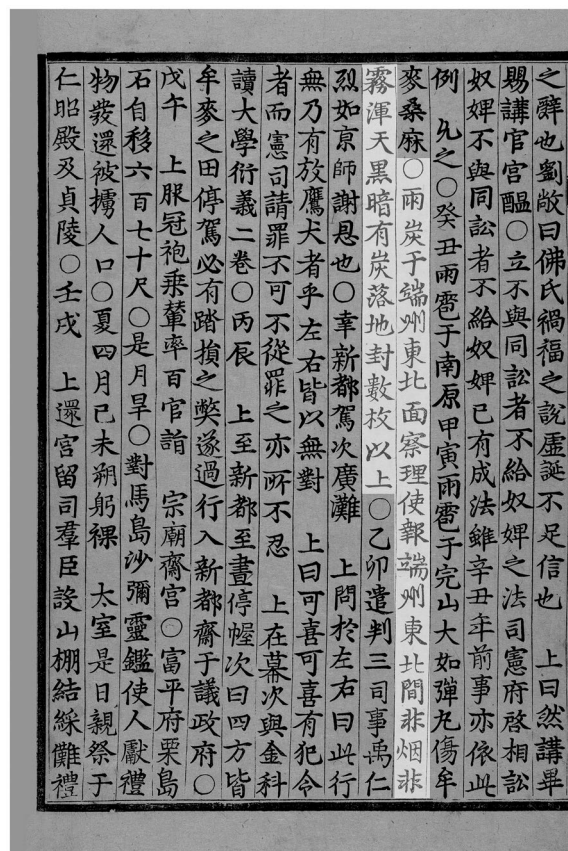


Fig. 9 The original text of the 1401 eruption record (Yun 2013)

Dancheonsi and Heocheongun in Hamgyeongnamdo, North Korea, during the Goryeo and early Joseon Dynasties. This can be interpreted as the volcanic ash fall in Hamgyeong Province and can be inferred that the ash clouds moved to the east by the Plinian eruption and the VEI was higher than that of the time when the Asian dust blew. It seems that the black pumice that erupted simultaneously was misunderstood as the charcoal, and the sample was taken. This record has also been included in the first volume of Dongguk Munheon Bigo (“東國文獻備考(上)”).

February 18 and April 13, 1403 AD The original text written on January 27 (Eulsail) (February 18 by the solar calendar), the third year of King Taejong (1403 AD) says, “乙巳 甲州地 寧怪. 伊羅 等處，兩半燒蕘灰，厚一寸 五日而消”. It translates as follows: “In Younggoe and Ira of Gapju (Gaju was renamed Gapsan), half burned and half dried ash fell like rain. A layer of ash on the ground was about 1 chon (= 3.03 cm). The falling ash continued for 5 days.”

The original text which was written on March 22 (Gihaeil) (April 13 by the solar calendar), Joseon

Wangjo Sillok Taejong Sillok (朝鮮王朝實錄 太宗實錄, Annals of King Taejong of the Annals of the Joseon Dynasty), the fifth volume, says, “己亥 東北面雨灰”. It translates as follows: “The ash fell down like rain in the Northeastern District”.

This record (the fifth volume of the Annals of King Taejong of the Annals of the Joseon Dynasty) indicates that the volcanic ash fell in Hamgyeong Province, east of Mt. Baekdu. It can be inferred from this record that the ash clouds moved to the east by the Plinian eruption, and the ash falls fell down. This record has also been included in the first volume of Dongguk Munheon Bigo.

March 23, 1405 AD The original text written on February 23 (Gichukil) (March 23 by the solar calendar), the fifth year of King Taejong, says, “己丑 雨色如灰”. It translates as follows: “The greyish rain fell”.

February 27, 1406 AD The original text written on February 9 (Gyeonggo) (February 27 by the solar calendar) of the sixth year of King Taejong (1406 AD: Byeongsul) says, “庚午 東北面端州, 雨土凡十四日”. It translates as follows: “The earth fell down like rain in Danju of the Northeastern District for 14 days”.

The 1405 record from the Annals of the Joseon Dynasty indicates that the volcanic ash fell in Hamgyeong Province, east of Mt. Baekdu. It can be inferred from this record that the ash clouds moved to the east by the Plinian eruption, and the ash falls fell down. This record has also been included in the first volume of Dongguk Munheon Bigo.

The 1406 record indicates that the volcanic ash fell in Hamgyeong Province, east of Mt. Baekdu. It can be inferred from this record that the ash clouds moved to the east by the Plinian eruption, and the ash falls fell down for 14 days. This record can be the one indicating that the volcanic activities lasted for 2 weeks.

March 4, 1573 AD The original text written on February 1 (March 4 by the solar calendar) of the sixth year of King Seonjo (1573 AD) says, “雨土”. It translates as follows: “The earth fell down like rain”.

This record from the Annals of the Joseon Dynasty, like the 1403, 1405, and 1406 records, indicates that the volcanic ash fell in Hamgyeong Province, east of Mt. Baekdu. It can be inferred from this record that the ash clouds moved to the east by the Plinian eruption, and the ash falls fell down. This record has also been included in the first volume of Dongguk Munheon Bigo.

June 5, 1668 AD The record of 1668 AD (the 9th year of King Hyeonjong, Joseon Dynasty, the year called Mushin, and the 7th year of Emperor Kangxi, Qing Dynasty) indi-

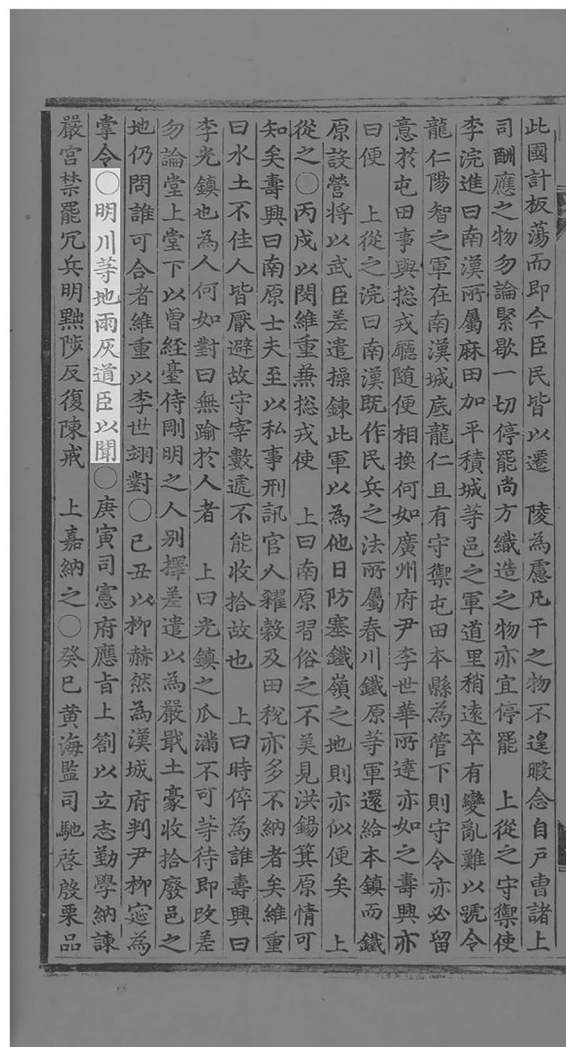


Fig. 10 The original text of the 1673 eruption record (Yun 2013)

cates that volcanic ash fell like rain throughout Gyeongseongbu and Buryeong in Hamgyeong Province (Fig. 5).

The original text written in the 14th volume of the Annals of Great King Hyeonjong of the 37th volume of the Annals of the Joseon Dynasty says, “咸鏡道 鏡城府 雨灰, 富寧 同日 雨灰”. It translates as follows: “The volcanic ash rain fell in Gyeongseongbu, Hamgyeong Province. On the same day, the volcanic ash rain fell in Buryeong, too”.

May 20, 1673 AD The original text written in 1673 AD, the 14th year of King Hyeonjong, Joseon Dynasty (Fig. 10) says, “明川等地 雨灰”. It translates as follows: “The volcanic ash fell down like rain in Myeongcheon, Hamgyeong Province”.

The April 28 (May 20 by the solar calendar), 1673 AD record written in the Annals of the Joseon Dynasty, just

like 1403, 1405, 1406, and 1668 AD records, indicates that the volcanic ash fell in the Hamgyeong Province, which was located on the east of Mt. Baekdu. From this record, it can be inferred that the Plinian eruption caused the volcanic ash clouds to move eastward by the eruptive event of the Cheonji Volcano, and consequently, the ash falls fell.

Except for the aforementioned, there are records of ash rain as follows; the ash rain continued for 3 days in Sakju in 1417 AD (“朔州土雨凡三日”). And it is recorded that on February 5 (March 7 by the solar calendar), 1470 AD, ash rain fell in Jeolla Province and Gyeongsang Province (“全羅, 慶尙兩道土雨”). On April 21 (May 21 by the solar calendar), 1470 AD, ash rain also fell in Gyeongsang Province, Jeolla Province, and Chungcheong Province (“聞下三道土雨”). In 1528 ash rain and hail fell two times; on March 14 (April 2 by the solar calendar), ash rain and hail fell at night (“夜, 土雨, 雨雹”) and on May 13 (May 30 by the solar calendar), in Danyang, ash rain and hail fell (“丹陽雨雹, 土雨”). Therefore in Goryeosa, a total of 56 times, including those mentioned above, were written about ‘ash rain(雨土)—1412, 1417, 1419, 1421, 1425, 1470, 1475, 1478, 1480, 1494, 1496, 1501, 1502, 1516, 1518, 1520, 1523, 1524, 1525, 1527, 1528, 1529, 1530, 1531, 1538, 1544, 1548, 1550, 1551, 1555, 1558, 1563, 1565, 1575, 1609, 1619, 1640, 1643, 1662, 1675, 1681, 1695, and 1724 AD.

Ash cloud

1199, 1200 and 1201 AD The original text of the second volume (of a set of three) of Goryeosa says, “神宗二年五月南部北井水赤沸聲如牛鳴凡十餘日: “神宗二年十月辛酉雷俄而有怪氣中黑辺赤從鵠峯出漸大弥滿京都遂雨雹黑氣下地咫尺不見人: “神宗三年潤二月戊申四方昏溟雨土二日庚午雨土四方昏溟意日, 四年四月庚辰朔雨土”. It translates as follows: “In May of the second year of King Shinjong, the water in the well was turned into red and made the boiling sound just like a cow cry for 10 days. And “in October 2 (October 23 by the solar calendar) of the second year of King Shinjong, Shinyu, the thunder suddenly filled the air and the blackish-red gas arose in Gongnyeong(鵠嶺; older name of Songaksan, Gaeseong). It continued to fill the air and filled the capital (Gaeseong City) with hail falling. It was getting dark, so no one even an inch ahead was to be seen”. “In February (the leap month) 22 (April 7 by the solar calendar) of the third year of King Shinjong, Mushin, it was dark all around, light rain fell, a dust storm or yellow sand blew. And on March 15 (April 29 by the solar calendar), in Gyeonggo, a dust storm blew. It was dark and drizzled all day long”. “On April 1 (May 4 by the solar calendar) of the fourth

year of King Shinjong, Gyeongjin, on the first day by the lunar calendar, an earth fell down like rain”.

Shinyu is the 58th year of the sexagenary cycle. Mushin is the 45th year of the sexagenary cycle. Gyeonggo is the 7th year of the sexagenary cycle. Gyeongjin is the 17th year of the sexagenary cycle. This can be interpreted in a way that the explosive vibration caused by the explosive eruption from Mt. Baekdu (Cui et al. 2000; 2008) was transferred as a form of resonance, followed by the clouds of hot black volcanic ash flown to the south by the north or northeast winds. Then the volcanic gas and ash clouds which were created from the crater by the Plinian eruption were moved by the prevailing wind effects and finally fell as ash falls, in other words, a dust storm. This record has also been included in the first volume of Hae-dongjamnok (“海東雜錄(上)”).

March 15 and April 8, 1550 AD The original text written on February 27 (March 15 by the solar calendar), the fifth year of King Myeonjong (1550 AD) says, “京師雨土”. It translates as follows: “The earth fell down like rain in the capital (= Seoul)”. And another original text written on March 22 (April 8 by the solar calendar) says, “京城雨土, 全羅道全州, 南原, 灑雨後, 烟霧四色, 屋瓦草樹, 皆有黃白之色, 掃之飛散. 至二十五日, 傳不快開”. It translates as follows: “The earth fell like rain in the capital. In Jeonju and Namwon, Jeollado, everywhere was filled with fog like smoke after rain, and tiles, grass, and trees were all yellow and white when swept, they became dust, and when shaken, they flew away. It was not clear until the 25th”.

November 18, 1654 AD The original text written in the 13th volume of the Annals of King Hyojong of the 35th volume of the Annals of the Joseon Dynasty says, “至於黑氣, 則臣所目見也. 其氣若雨非雨, 若烟非烟, 自北而來, 聲若風驅, 臭若腥臊, 轉頭之頃, 彌滿山谷, 掩翳三光, 咫尺不辨牛馬, 吁亦異哉! 近則積城, 長湍之間, 遠則咸鏡南道之界, 無處不然云”. It translates as follows: “I saw the air tinged with black myself. It was something that looked like rain, but it wasn’t rain. It was something like smoke, but it wasn’t. It came from the north. It sounded like the gusting wind and smelled fishy. It filled the air in the valley within a short time and shaded light, so not a cow nor a horse even an inch ahead could not be distinguishable. Oh, what a strange thing it is! I’ve heard that it happened in places as close as Jeokseong (40 km north of Seoul) and Jang-dan (40 km northeast of Seoul) and as far away as the southern border of Hamgyeong Province as well”.

It can be inferred from this record that the volcanic ash and volcanic gases which were erupted from Mt. Baekdu in October, were flown by the north or northeast winds, and transferred southward, having lower altitudes. In other words, it can be interpreted as the production of a

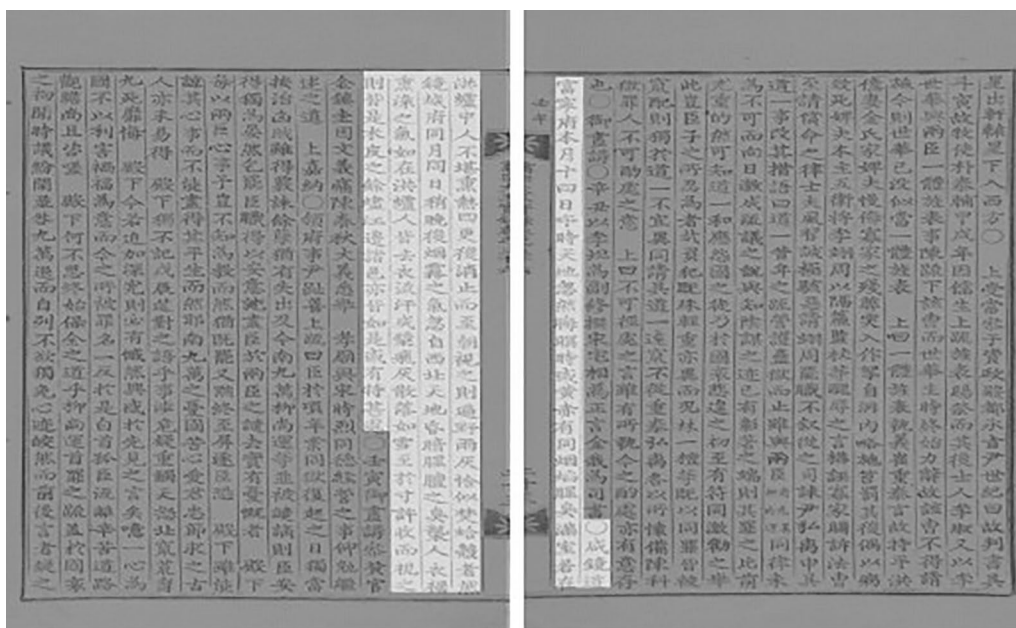


Fig. 11 The original text of the 1702 eruption record (Yun 2013)

wind-modified fall. The fact that the affected area ranged as far as to the south borderline of Hamgyeong Province can confirm that the wind-modified fall was pushed southward from the north, namely, Mt. Baekdu (Yun et al. 2013b; Yun 2018).

June 9, 1702 AD The original text written in 1702 AD (Fig. 11) says, “咸鏡道宣寧府, 本月十四日午時, 天地忽然晦暝, 時或黃赤, 有同烟焰, 腥臭滿室, 若在洪爐中, 人不堪熏熱, 四更後消止, 而至朝視之, 則遍野雨灰, 恰似焚蛤殼者然 鏡城府同月同日稍晚後, 烟霧之氣, 忽自西北, 天地昏暗, 腥膻之臭, 襲人衣裾, 熏染之氣, 如在洪爐, 人皆去衣, 流汗成漿, 飛灰散落如雪, 至於寸許, 收而視之, 則皆是木皮之餘燼. 江邊諸邑, 亦皆如是, 或有特甚處”. It translates as follows: “In the Buryeongbu, Hamgyeong Province, on the 14th day of the month, between 11 a.m. and 1 p.m., called “Oshi”; the sky and the earth suddenly became dark. It was sometimes tinged with yellow and it seemed that smoke went up and flames were burst into, and also something fishy filled the air in the room. The people could not stand the heat as if they were staying inside a furnace. The heat did not cool down around the 4th Gyeong, called “Chukshi (between 1 a.m. and 3 a.m.)”. The next morning, I saw the whole field covered and piled with ash and it looked like the shells burned. Later on the same day of the same month in Gyeongseongbu, something like smoke and fog suddenly came from the north-west, and the sky and the earth became dark. The people’s clothes were saturated with the smell of fish and the heat was severe, as if sitting inside a furnace. Therefore, all the

people took off and threw their clothes and they were sticky with sweat. The wind-blown ash was falling like snow in all directions. The thickness of the ash piled was about 1 chon (= 3.03 cm). Walking through and watching, I thought it looked like charred tree bark. Many towns along the riverside were in the same situation and some of the towns were worse”.

AD 1702 was the 28th year of King Sukjong, Joseon Dynasty, and the record was written in the 36th volume of the Annals of Great King Sukjong of the 280th volume of the Annals of the Joseon Dynasty (the record written on the day of Shinchuk, May 1702, the 28th year of King Sukjong; May 20 (June 15 by the solar calendar)). Based on this record, the volcanic eruption occurred on May 14 (June 9 by the solar calendar).

This is the 1702 AD record which is presumed to be the eruption from the Cheonji, Mt. Baekdu volcano. It was a large Plinian eruption with VEI 5 by setting up an ash fall isopach at the location 140 km away from Mt. Baekdu, the location of the eruption, and using empirical formulae. The minimum amount of eruption products calculated by the empirical formula was 1.2 km³ and this 1702 AD eruption from Mt. Baekdu was a large eruption corresponding to VEI 5 (Yun and Lee 2011). The record describes well that the high-temperature volcanic ash by the Plinian eruption was transferred to the lower altitudes by the winds, namely, the wind-modified fall was produced and deposited.

Phenomenon sighting

October 6, 1597 AD 1597 AD is the 30th year of King Seonjo of the Joseon Dynasty, Jeongunyeon, and it is equivalent to the 25th year of King Shin of the Ming Dynasty, the Wanli era of China. This year's record included realistic descriptions regarding the earthquakes and volcanic eruptions throughout Samsugun in Hamgyeong Province, which is also the volcanic field of Mt. Baekdu.

This record describes the volcanic activities which occurred in the region of Samsugun, south of the Amnokgang (Amnok River) which was the southern end of the Mt. Baekdu volcanic field and it indicates that the earthquakes preceded the small explosive eruptions (Li et al. 2012; Li 2013).

The original text written on October 2 (Gimiil) (November 10 by the solar calendar), the 30th year of King Seonjo, Jeongunyeon (the 93rd volume of the Annals of Great King Seonjong (Seonjo) of the 29th volume of the Annals of the Joseon Dynasty) says, “咸鏡道觀察使宋言慎書狀去八月二十六日辰時, 三水郡境地震, 暫時而止 二十七日未時, 又爲地震, 城子二處頽圮, 而郡越邊甌巖, 半片崩頽, 同巖底三水洞中川水色變爲白, 二十八日更變爲黃 仁遮外堡東距五里許, 赤色土水湧出, 數日乃止 八月二十六日辰時, 小農堡越邊北德者耳遷絕壁人不接足處, 再度有放砲之聲, 仰見則烟氣漲天, 大如數抱之石, 隨烟拆出, 飛過大山後, 不知去處 二十七日酉時, 地震, 同絕壁, 更爲拆落, 同日亥時子時, 地震事”. It translates as follows: “Hamgyeong provincial governor Mr. Song Eon-shin wrote a letter. On August 26 (October 6 by the solar calendar), between 7 a.m. and 9 a.m., called “Jinshi”, an earthquake occurred in Samsu-gun (county) and it stopped shortly afterward. On the 27th (October 7 by the solar calendar), between 1 p.m. and 3 p.m., called “Mishi”, when another earthquake hit, two places of the castle collapsed, and half of Steamer Rock across town crumbled. The stream, called Samsudong Jungcheon, running beneath the Rock, turned white, and it turned yellow on the 28th (October 8 by the solar calendar). Where the red muddy water was bubbling up five li (about 2.1 km. According to the Korean traditional standard measurement, 1 li (里) is about 420 m) at east of Inchaebo (仁遮外堡, one of the small castles in Samsu-gun, which was built to defend the border) and it stopped in a few days. On August 26 (October 6 by the solar calendar), during Jin-shi (between 7 a.m. and 9 a.m.), I heard cannon firing twice from Deokjaicheon Cliff (德者耳遷絕壁), which was located across Sonongbo (小農堡, another castle in Samsugun) and where there was no place a person can keep his/her feet on and looked up to it. Smoke was going up into the sky and the rocks (volcanic blocks) which can be the size of several arms' stretches were blown and ejected along with the smoke.

Having their tracks covered up, the ejected rocks crossed a large mountain. On the 27th (October 7 by the solar calendar), during Yushi (between 5 p.m. and 7 p.m.), an earthquake occurred and the Cliff collapsed again. On the same day, there were earthquakes during Haeshi (between 9 p.m. and 11 p.m.) and during Jashi (between 11 p.m. and 1 a.m.) as well”.

The Annals of the Joseon Dynasty include the records of a series of volcanic activities that occurred in the region of Samsu, Hamgyeong Province, in the vicinity of Mt. Baekdu, for three consecutive days from October 6 to 8, 1597 AD. The records of the Samsu earthquakes also included presumptive activities related to volcanic explosions. Therefore, the series of earthquakes in this region can be interpreted as volcanic earthquakes. It may be the eruption from Wantiane of the southern part of Baekdusan Volcanic Field. The major earthquakes around Mt. Baekdu caused the change in the dynamic stress and the movement of magma, and it consequently became more active. It is presumed that the triggered earthquake created the favorable conditions to occur the volcanic eruption of Mt. Baekdu. It should be explained that the eruption style could have been Vulcanian if the eruption produced such large volcanic blocks with cannon-firing noises.

June 5, 1668 AD The record of June 2, 1668 AD, contains not only atmospheric abnormalities but also phenomenon sightings. In the 14th volume of the Annals of the Joseon Dynasty, the first article of the book says: “甲午/上御養心閣, 引見大臣、備局諸臣. 上謂大臣曰: “咸鏡道雨灰之變, 甚可愕也. 朴承後疏中有云: ‘周天二十餘處坼裂, 左相在鄉時聞之否?’ “許積對曰: “有是言也. 東方天坼, 光同火鏡, 且有赤馬相關之狀, 傳說者甚多. 次日, 北方有赤氣, 又次日, 有白氣之異. 天開, 太平之象, 天坼, 衰亂之兆云”. It translates as follows: “The King said, “I went to Yangshimhap and gave a speech to the ministers and many officers from Biguk. I mentioned to the ministers, “I was surprised at the extraordinary phenomenon of the ash falling in Hamgyeong Province. In the appeal submitted by Park Seunghu, he said, ‘About 20 places around the skies opened.’ So, I asked to the first vice-premier, “Have you heard such a thing when you were staying in the country?”. Then, Heo Jeok replied, “I’ve heard about that. The eastern sky broke up and the light was like sun ray from a burning glass. Besides, I’ve heard that there had been scenes looking like the red horses fighting against each other. Many people talked about the same thing. The next day, the north was tinged with red, and it was tinged with strange white the following day. People assumed that the opening of the sky is the sign of peace, and its breaking up is that of uproar”.

At the end of the translation, there is a part about what people witnessed and observed regarding the volcanic phenomena.

May or June 1903 AD The 1903 AD (the 29th year of Guangxu, Qing Dynasty) record of the Cheonji Volcano eruptive process has been described in *Chángbáishānjiānggǎngzhìliè* written by 天池鈞搜 Jian-feng Liu as follows: “据引路人徐永順云, 光緒二十九年五月 其弟復順, 隨玉讓 俞復等人在沮石坡下杜坡口 忽見兩鹿登坡—(中略)—六人坐臥池沿 至夜半 寒風透骨 餓不能寢 共餐糙糧 而盡 未幾 天微明而霧仍如故—(中略)—霧時雷雨交加 眾皆器不成聲 旋又入夜 見池中三 五明星忽起忽落 條而 潑刺一聲 自空中落一火球大如 輪. 水面萬千燈火直同白晝—砲聲轟降 宛如霹靂 波浪 涌起直衝斗牛 六人戰慄不敢動—(中略)—半鍾余 雹落 如雨 大者寸許 六人各避石下 俞與復順頭骨血出 用濕 衣 裹之 又兩鍾余 東方曉亮 雲淡風清 微霧峰尖. 徐永 順言之叢叢故志之”. It translates as follows: “Seo Young-soon, the guide, said that his siblings Boksoon, Okliang, and Yubok and a couple of others saw two deer going up to the mountain from Du-pa-goo beneath JeoSeokpa in May of the 29th year of Guangxu. (Omitted). These six people were lying or sitting around the lake. When the night came, the icy wind pierced their bones and they felt hungry. So they could not easily fall asleep. They ate up their grains. When some time went by, the sky was lightened and it was still foggy. (Omitted). All of a sudden, the lightning flashed, and it began to rain. People were crying in terror. When the night grew older, three to five stars came up and went down to the lake. When there was a sudden explosion sound, fireballs as big as a wheel fell from the air, and a shower of sparks on the surface of the lake looked as bright as the light of the day. The sound of cannon firing filled the air with the roll of thunder, and the waves rose as high as the sky. These six people could not move in trembling. (Omitted). At midnight, the six people took shelter under rocks. Yu and Boksoon got hit on the head, had bleeding, and pressed/wrapped their head

with wet clothes. After two hours, the sun came out in the east. The clouds cleared away, the winds died down and the mists were hovering only around the mountain peak. Seo Youngsoon’s words are true and that is why I write down here”.

The eruption record of the Cheonji Volcano (a small phreatomagmatic eruption) realistically describes the volcanic eruption which occurred within Cheonji, a caldera on the top of Mt. Baekdu. The fireballs as big as a wheel can be interpreted as volcanic bombs, and from this record, it can be inferred that a lot of hot volcanic ash and eruption products were emitted over the lake and then sank. The 1903 AD eruption products could be identified on the northern side of the Cheonji caldera. It indicates that there was small Vulcanian or phreatomagmatic eruptions.

1898 AD and 1925 AD According to the field trip logs of a Russian explorer, there is a record that an eruption occurred in the caldera of the volcano when he reached the summit of Mt. Baekdu in 1898. The volcano began to erupt in front of his eyes, and smoke and volcanic ash rose (Garin 1949). The eruption was small and momentary, and the eruption products did not cross the somma of the caldera. Another record that indicates an eruption occurred in Mt. Baekdu in 1925 AD has been also found in the book, titled *Volcanic Belts of Eastern Asia*, which was written by the Far East branch of the former Soviet Union Academy of Sciences and published by Nauka publishing company in 1984 AD.

Discussion

After the Millennium Eruption, there have been more than 90 intermittent eruptions on small and medium scales at the Mt. Baekdu volcano (Fig. 12). Although some have been observed in the Hamgyeongdo region, shock waves from explosive eruptions have reached far more than 500 km away from Mt. Baekdu and fallout

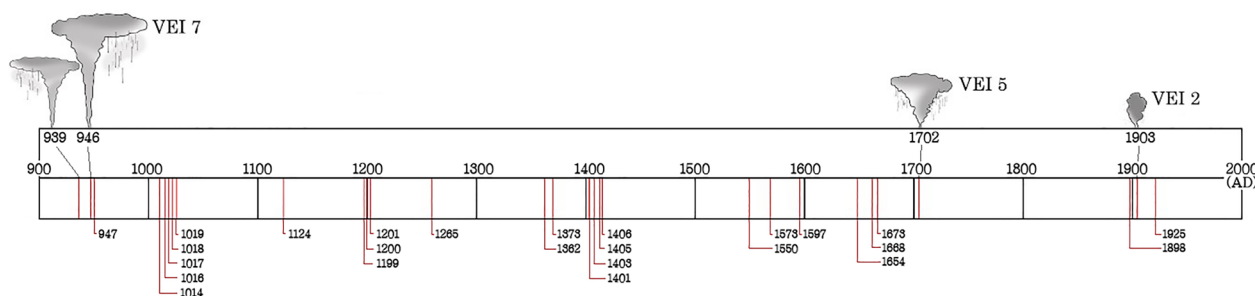


Fig. 12 The eruption records of Mt. Baekdu. The figure shows three eruptions which is represented their VEI. These VEIs are the estimated values by our previous and this research

Table 1 A chronological table for the historical records of Mt. Baekdu volcanic activities

No.	Date(s) (AD)	Eruption type(s)	Records of volcanic activities	References
1	January 24, 939	Explosive eruption	The sound of a large drum was heard The rumbling phenomenon by the volcanic eruption	Nihongiryaku
2	November 3, 946 the 1st year of King Jeongjong of the Goryeo Dynasty	Explosive eruption	The sound of beating was heard from the sky. (Tokyo, Japan)	Goryeosa Sega Teishinkoki Nihongiryaku
3	February 7, 947 the 2nd year of King Jeongjong of the Goryeo Dynasty March and April 1014 the 5th year of King Hyeonjong of the Goryeo Dynasty	Explosive eruption Vulcanian eruption + Plinian eruption	There was a sound from the sky... it sounded like thunder One night ... all over the place was tinged with red	Nihongiryaku Nihongiryaku Goryeosa (the second volume), Dongguk Munheon Bigo (the first volume)
	December 1016 the 7th year of King Hyeonjong of the Goryeo Dynasty February and November 1017 the 8th year of King Hyeonjong of the Goryeo Dynasty January 1018 the 9th year of King Hyeonjong of the Goryeo Dynasty		All over the place was shrouded in a red tinge The phenomenon of volcanic ash dispersion The whole sky was tinged with red like fire A white-banded smoke reached the sky	
4	January and October 1019 the 10th year of King Hyeonjong of the Goryeo Dynasty March 25, 1124 the 2nd year of King Injong of the Goryeo Dynasty	Plinian eruption	Ash fall A dust storm has blown for the last three days Ash fall phenomenon	Goryeosa (the second volume)
5	May and October 23, 1199 the 2nd year of King Shinjong of the Goryeo Dynasty	Plinian eruption	In the South, the water in the well was turned red and made the sound of boiling like a lowing cry for ten days The thunder... filled the air and the blackish-red gas arose in Gongnyeong. It continued to fill the air and filled the capital with hail falling down. It was getting dark, so no one even an inch ahead was to be seen ... a dust storm blew. It was dark and drizzled all day long A dust storm blew...	Haedongjapgi (海東雜記) (the first volume)
6	April 7, 1200 the 3rd year of King Shinjong of the Goryeo Dynasty May 4, 1201 the 4th year of King Shinjong of the Goryeo Dynasty	Plinian eruption Plinian eruption	Volcanic gases, volcanic clouds, ash falls Some particles from fine solid materials like leaven powder fell like fine rain. (Ash falls)	Goryeosa (the second volume)
7	April 15, 1265 the 6th year of King Wonjong of the Goryeo Dynasty November 20, 1362 the 11th year of King Gongmin	Plinian eruption Explosive eruption	The sound of beating was heard from the sky	Goryeosa

Table 1 (continued)

No.	Date(s) (AD)	Eruption type(s)	Records of volcanic activities	References
8	June 24, 1373 the 22nd year of King Gongmin	Plinian eruption	A dust storm (Ash falls) blew. Some things like pieces of white fur fell down like fog and rain. It looked as if the scales of the dragon were blowing like the hair of the white horse	Goryeosa (the second volume)
9	May 8, 1401 (the leap month), the first year of King Taejong of the Joseon Dynasty	Plinian eruption	These records depict the long, flat pieces of pumice 6 to 10 cm in length and the volcanic ash fell from the sky The coal-black rain fell in Dan-ju (based on the report by Dongbuk-myeon Challisa) The volcanic ash fell in Dan-cheon, Hamgyeong Province	Annals of King Taejong Dongguk Munheon Bigo (the first volume)
10	February 18 and April 13, 1403 the 3rd year of King Taejong of the Joseon Dynasty	Plinian eruption	In Gap-ju, half burned, half dried ash fell like rain for five days and a layer of ash on the ground was about 1 chon (3.03 cm)	Dongguk Munheon Bigo (the first volume)
11	March 23, 1405 the 5th year of King Taejong of the Joseon Dynasty	Plinian eruption	The ash fell like rain in Dongbuk-myeon (Hamgyeong Province) The greyish rain fell. (Dongbuk-myeon)	The 5th volume of the Annals of Great King Taejong of the Annals of the Joseon Dynasty Dongguk Munheon Bigo (the first volume)
12	February 27, 1406 the 6th year of King Taejong of the Joseon Dynasty	Plinian eruption	The dust storm blew in Dan-ju, Dongbuk-myeon for 14 days (The volcanic activities lasted for 2 weeks)	Goryeosa
13	1417	Plinian eruption	The ash rain was continued during three days in Sakju	Goryeosa
	March 7 and May 21, 1470	Plinian eruption	The ash rain fell in Jeolla and Gyeongsang Provinces	Goryeosa
	April 2 and May 30, 1528	Plinian eruption	The ash rain also fell in Gyeongsang, Jeolla and Chungcheong Provinces	Goryeosa
14	March 15 and April 8, 1550 the 5th year of King Myeongjong	Plinian eruption	The ash rain and hail fell at night In Danyang, ash rain and hail fell	Annals of the Joseon Dynasty
15	March 4, 1573 the 6th year of King Seonjo of the Joseon Dynasty	Plinian eruption	The earth fell down like rain in capital The dust storm blew. (Ash falls)	Annals of the Joseon Dynasty
16	October 6, 1597 the 30th year of King Seonjo of the Joseon Dynasty	Phreatic eruption + Explosive eruption + Volcanic earthquake	The dust storm blew in Hamgyeong Province Earthquakes and small eruptions occurred throughout Samsu-gun (Hamgyeong provincial governor Mr. Song Eon-shin)	Dongguk Munheon Bigo The 29th volume of the Annals of the Joseon Dynasty

Table 1 (continued)

No.	Date(s) (AD)	Eruption type(s)	Records of volcanic activities	References
17	November 18, 1654 the 5th year of King Hyeonjong of the Joseon Dynasty	Plinian eruption	Throughout Hanyeong Province, Jeok-seong and Jang-dan, the air was tinged with black, it rained, smoke rose and the fishy smell filled the air in the valley, it became dark and nothing an inch ahead could be distinguished	The 93rd volume of the Annals of Great King Seonjo The 35th volume of the Annals of the Joseon Dynasty
18	June 5, 1668 the 9th year of King Hyeonjong of the Joseon Dynasty	Strombolian eruption + Vulcanian eruption + Plinian eruption	The volcanic ash fell like rain in Gyeongseongbu and Buryeong in Hamgyeong Province	The 13th volume of the Annals of Great King Hyeonjong The 37th volume of the Annals of the Joseon Dynasty
19	May 20, 1673 the 14th year of King Hyeonjong of the Joseon Dynasty	Plinian eruption	The volcanic ash fell down like rain in Myeongcheon, Hamgyeong Province	The 14th volume of the Annals of Great King Hyeonjong Annals of the Joseon Dynasty, written in the 14th year of King Hyeonjong
20	June 9, 1702 the 28th year of King Sukjong of the Joseon Dynasty	Plinian eruption	In the Buryeong-bu, Hamgyeong Province, the sky and the earth became dark. Smoke went up, flames were burst into and something fishy filled the air in the room. The people could not stand the heat. The thickness of the ash piled was about 1 chon (3.03 cm)	The 280th volume of the Annals of the Joseon Dynasty
21	1898	Cheonji volcanic eruption	A Russian explorer reached the summit of Mt. Baekdu and wrote his field trip logs that described the occurrence of an eruption from the caldera of the volcano	The 36th volume of the Annals of Great King Sukjong
22	May or June 1903	Small phreatomagmatic eruption	When the explosion was heard, fireballs as big as a wheel fell from the air and a shower of sparks on the surface of the lake looked as bright as the light of day	Changbaishanjiaanggangzhilüe
23	1925	Small Strombolian eruption Phreatic eruption Phreatomagmatic eruption	The existence of the record in the book written by the Far East branch of the former Soviet Union Academy of Sciences in 1984	Volcanic belts of Eastern Asia (1984)

volcanic ash has fallen like rain about 1000 km away, indicating that there were mainly Plinian eruptions.

After the Millennium Eruption formed the Cheonji caldera, a caldera lake was created at Mt. Baekdu, storing freshwater. It is assumed that this water flowed underground and met with rising magma, facilitating the cataclysmic action and further enhancing the explosive power of magma. The historical eruptions on record mainly describe the fallout volcanic ash caused by the Plinian eruption.

The pyroclastic flows and lavas that historically erupted are distributed in the area around the Cheonji caldera of Mt. Baekdu, as verified by geological field surveys. The pyroclastic flows are widely distributed over the trachytic or the basaltic lavas. On the stratovolcano outside the Cheonji caldera rim of Mt. Baekdu, the trachyte and alkali rhyolite lava and pyroclastic rocks slope steeply, developing a V-shaped valley. The upper part of these mountain slopes and valleys is composed of fallout volcanic ash, pumice layers, and pyroclastic deposits of historic eruptions; moreover, vegetation development is sparse.

In addition, the prediction characteristics on the advection and diffusion of volcanic tephra from the explosive eruption in Mt. Baekdu (Lee et al. 2012) were already examined. The movement of volcanic ash was analyzed for 48 h after its release from the synoptic observation site on October 21, 2010 AD (Lee et al. 2012). From this study, it was determined that it is mainly composed of particles with an emission altitude of 2 km or less, which can move to the south and deposit on the ground of the Korean peninsula. However, volcanic ash mainly moves to the east. Some of these can change their diffusion path when the northeast air flows into the Mt. Baekdu area, causing volcanic ash to fall and deposit on the southern part of the Korean peninsula (Lee and Yun 2011).

In this case, the size of the fallout volcanic ash flowing into the Korean peninsula is less than 0.05 mm (or 50 μm), and larger particles are less likely to flow into the peninsula as its migration is not significantly affected by diffusion (Lee et al. 2012). When the volcanic ash from Mt. Baekdu eruptions advances and spreads towards Hamgyeongdo or South Korea due to the inflow of the northeast air flow, volcanic disasters may occur. Such disasters are caused by the fall of volcanic ash and dust storms in the area along the volcanic ash cloud movement path, as recorded in historical records.

Many scholars conducted research to identify volcanological characteristics and the existence of a magma chamber beneath Mt. Baekdu. Zhang et al. (2002) studied the magma system of the Changbaishan-Tianchi Volcanic region with the 3D deep seismic sounding (DSS) technique. According to the results, the magma system

of BVF, mainly characterized by the low velocity of P waves, can be divided into four parts in terms of depth. Song et al. (2006) present velocity models determined by inverting refracted and reflected arrivals along two active source lines in the BVF (Changbaishan volcanic region). They interpret the low-velocity zone (LVZ) beneath Mt. Baekdu, which locates about 30–60 km to the north of the summit of the Mt. Baekdu volcano (the most recently active volcano in the region), about 30–75 km in north–south extent, at most 35 km in east–west extent, and to the depth of around 10–25 km below the surface. They suggest that the LVZ indicates a residual crustal magma chamber. The recent study by Ri et al. (2016) presents receiver function results from an unprecedented seismic deployment in the DPRK. These are the first estimates of the crustal structure on the DPRK side of the Mt. Baekdu volcano and, indeed, anywhere beneath the DPRK. The results show high values of VP/VS, which suggest that partial melt is present in the crust beneath Mt. Baekdu. They suggest that the region of melt represents a potential source of magma erupted in the last few thousand years and may be associated with an episode of volcanic unrest observed between 2002 and 2005.

According to the results of seismic and geophysical studies on Mt. Baekdu, Mt. Baekdu is an active volcano that has magma chambers under the volcanic edifice, and there is a possibility that Mt. Baekdu might erupt in the future. Therefore, it is necessary to find and analyze the historical eruption records of Mt. Baekdu and recognize the characteristics of eruptions to prepare the future eruptions and reduce potential hazards.

Conclusion

In addition to the current study, for the better understanding of the historical eruptions of Mt. Baekdu, further volcanic studies can be conducted through discovering and analyzing records that infer the eruptive events from the Korean historical documents.

These historical records could provide data to help understand the volcanic characteristics of Mt. Baekdu during the Quaternary period, with a geological survey on the volcanic tephra of the historical era around the Cheonji caldera. Table 1 shows a comprehensive summary of the historical eruptions by year.

The volcanic ash diffusion to the eastern side of Mt. Baekdu appears to be caused by the volcanic ash which was sprayed like rain as volcanic ash clouds. Ash plumes formed by explosive Vulcanian or Plinian eruptions which was moved to the east by the westerlies. If each of these 90 volcanic activities is considered an independent event, the average eruption interval is 45 ± 72 years. When the period of frequent volcanic activity is grouped into eight (939–347, 1014–1124, 1199–1201, 1265–1373,

1401–1406, 1573–1597, 1654–1702, 1903–1925 AD), the eruption interval of Mt. Baekdu is calculated as 138 ± 70 years.

If the eruption period is divided into five groups, 10–11th, 13th, 15th, 16–18th, and twentieth centuries, the eruption interval can be calculated as 230 ± 24 years. Therefore, the last small-scale eruption occurred in 1925, and a geophysical investigation has identified that magma chamber exists 10 km below the ground, that is, below the average sea level of the Cheonji caldera of Mt. Baekdu (Zhang et al. 2002). It has also been confirmed that there is a magma chamber 5 km below the ground from the top of the Cheonji caldera of Mt. Baekdu (Chae et al. 2013). Therefore, there is a possibility of an eruption at Mt. Baekdu in the future; thus, close monitoring will be required.

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Author contributions

S-HY: Conceptualization, Methodology, Investigation, Writing–Original draft preparation. JL: Investigation, Writing–Reviewing and Editing, Visualization. CC: Investigation, Visualization. CO: Writing–Reviewing and Editing.

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Declarations

Competing interests

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

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