2013 IAVCEI Field Trip Guide

B8: Changbaishan volcano, the magnificent gift from the nature

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1. Introduction

Changbaishan volcano (also known as Baekdusan) is located in the border area between China and North Korea (42°01'N, 128°03'E), with its caldera occupied by a 3.4-4.5 km in diameter and 373 m deep Lake Tianchi at the altitude of 2749 m a.s.l. The most recent large Plinian eruption (VEI 7) of the volcano occurred in AD 946 (Xu *et al*., 2013). It ejected a huge plume estimated to be as high as ~ 25 km (Liu *et al*. 1998), producing a massive amount of pyroclastic flows and pumice ash that spread over the Sea of Japan, passed through the northern Japan Islands, and reached as far as the Kuril trench, more than 2000 km from the volcano (Nanayama *et al*., 2003) (**Fig.1**). This millennium eruption has been speculated as one of the largest volcanic eruptions on Earth over the past 2,000 years. At least three small-scale eruptive activities of the volcano were historically documented in AD 1668, 1702 and 1903 after the Millennium eruption. In recent years, Changbaishan volcano appears to have waked up and resumed its activities (Xu *et al*., 2012). During 2002 to 2006, the frequency of volcanic earthquakes increased by about 2 orders of magnitude compared to that of the background in other time. The active period was also accompanied by ground inflation, high values of CO_2, He, H_2, and high ratios of N_2/O_2 and $^3He/^4He$ in volcanic gases released from three hot springs near the caldera rim. The above monitoring evidence implies pressurization of the magma chamber, possibly caused by incremental magma recharge. This has attracted great attention from both the international scientific community and the general public of China and Korea (Stone, 2010, 2011).

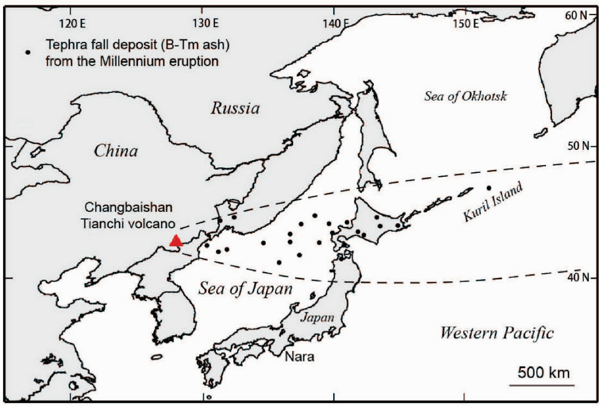

Figure 1. Schematic map showing the geographic location of Changbaishan volcano in northeast China and the distribution of distal tephra from the Millennium eruption

2. Tectonic setting and volcanic geology

As a potentially hazardous intraplate stratovolcano about 1200 km west of the west Pacific subduction zone, the volcanism of Changbaishan volcano is not well understood. Recent studies from seismic wave tomography, magnetotelluric soundings, and volcanic rock geochemistry have yielded new evidence to support a subduction-related model that explains the geological origin of Changbaishan volcano (e.g. Tang *et al*., 2006; Zhao *et al*., 2009; Wei, 2010; Kuritani *et al*., 2011). In this model, the west Pacific

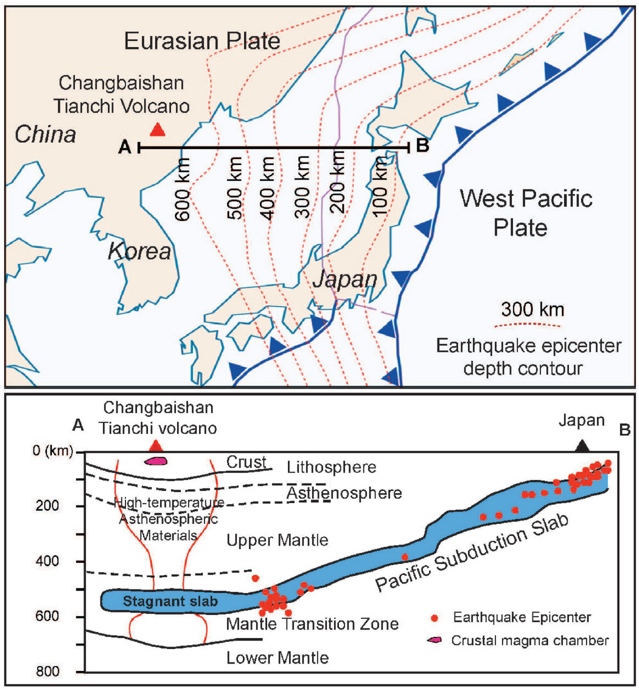

Figure 2. Tectonic location of Changbaishan volcano; A-B profile showing the west Pacific plate subduction, the Wadat-Benioff seismic zone, and the magmatic system

plate subducts underneath the Eurasian plate along the Japan arc island at a dip angle of 20° to the west to reach to the mantle transition zone at a depth of ~ 600 km, where the subducting slab becomes stagnant (**Fig. 2**). Deep dehydration of the slab and convective circulation in the mantle wedge cause upwellings of high-temperature asthenospheric materials, leading to the formation of Changbaishan volcano.

Geologically, Changbaishan volcano is located on Archean and Mesozoic basement within a major rift zone of NE China, which first developed in the early Cenozoic. There are some large-scale rift zone faults, with mainly NE-, NW- and NNE-trends, in the Changbaishan area (Dostal *et al*., 1988; 1991; Basu *et al*., 1991; Liu *et al*., 1994). The early-middle Cenozoic structures delineate NE-ENE-trending extensional zones. NE-trending faults and basalt fissures suggest volcanism in an intercontinental rift environment (Bailey, 1974; Liu, 1987; Jin and Zhang, 1994; Wang *et al*., 1999; Jilin Bureau of Geology and Mineral Resources, 1988; Zhao, 1988). Cenozoic volcanism formed the Gaima Plateau lavas (29-2.1 Ma) from scattered centres over a large area, including where Tianchi caldera and its neighbouring volcanoes eventually developed (**Fig. 3, Table 1**). The Cenozoic rift zone is marked by the NE extension of the Tanlu faults with many Cenozoic and Quaternary volcanic centres within the grabens.

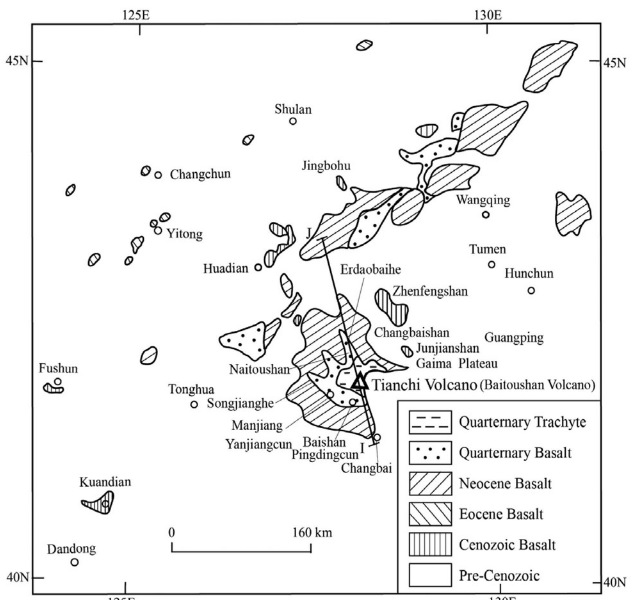

Figure 3. Cenozoic volcanic rocks in Changbaishan area. (modified from Jin and Zhang (1994)).

From the late Pliocene, new structures formed due to a change of regional tectonic conditions. Chronological evidence for fault activity during the Quaternary indicates that most of the NE- and NW-trending faults had not been active since 0.1 Ma (Wang *et al*., 2003). "X-shaped" shear joints cut through comendite and basaltic lavas in Changbaishan volcano in a nearly E-W direction. Thus, since the Pleistocene (or the late Pliocene), the Changbaishan area has been in a state of E-W crustal compression; the area also regional uplift, with rates up to 2.7 mm/year on the eastern margin of Korea. The crustal uplift rate decreases from east to west (Lee 1991).

Tianchi caldera and neighbouring Holocene volcanoes define a WNW-ESE volcanic belt after 1.6-1.4 Ma **(Fig. 3**). The Tianchi caldera and its neighbours are located about 120 km to the west of the deep seismicity at 600 km depth related to the subduction of the west Pacific plate beneath Japan and NE China. The Cenozoic and Quaternary magmatism in this area might be related to disturbance of the mantle due to subduction, although the mechanisms are not understood. There is evidence that thick Archean mantle lithosphere was removed by the early Cenozoic (Griffin *et al*., 1998) and so the onset of Cenozoic volcanism might also be related to the upwelling of hot mantle during delamination.

The volcano has experienced three main evolutionary stages; construction of a trachybasalt shield, formation of a trachyte composite cone and explosive eruption to form an apron of comenditic and trachytic pyroclastic deposits around the volcano **(Fig. 4**). Although the predominant evolution of the volcano is from mafic to felsic magmas, satellite intermediate and basaltic lavas have been erupted on the flanks throughout the evolution. In addition minor trachyte was erupted in the shield stage (**Table1**).

Shield-forming stage

The lava shield was constructed on the Gaima plateau (Liu, 1983; 1987; Liu and Wang, 1984; Machida *et al*., 1990; Qiu *et al*., 1991) and is composed mostly of alkali trachybasalts. The lavas are known as the Baishan Formation (Jin and Zhang, 1994) and are also known as the Manjiang Formation (Jilin Bureau of Geology and Mineral Resource, 2000). In North Korea trachybasalts belong to the shield are known as the Pochon Series. Over 380 craters or vents have been found around Changbaishan volcano in North Korea (Jin and

Zhang, 1994). There are also many associated co-genetic radial basaltic dykes and dyke swarms surrounding Changbaishan volcano, which the ages were determined in the range 1.1-1.66 Ma (Liu, 1999; Liu *et al*., 1998). The shield basalts vary in morphology, texture and composition, including basaltic brecciated lava, trachybasalt, and basalt. The lava shield extends over distances of `tens of kilometres and covers on an area of about 6800 km^2 with an average thickness 55 m, yielding an approximate volume for the shield of 370 km^3 produced over about 0.5 Ma, giving an average magma production rate of 0.74 km^3 per 1000 years.

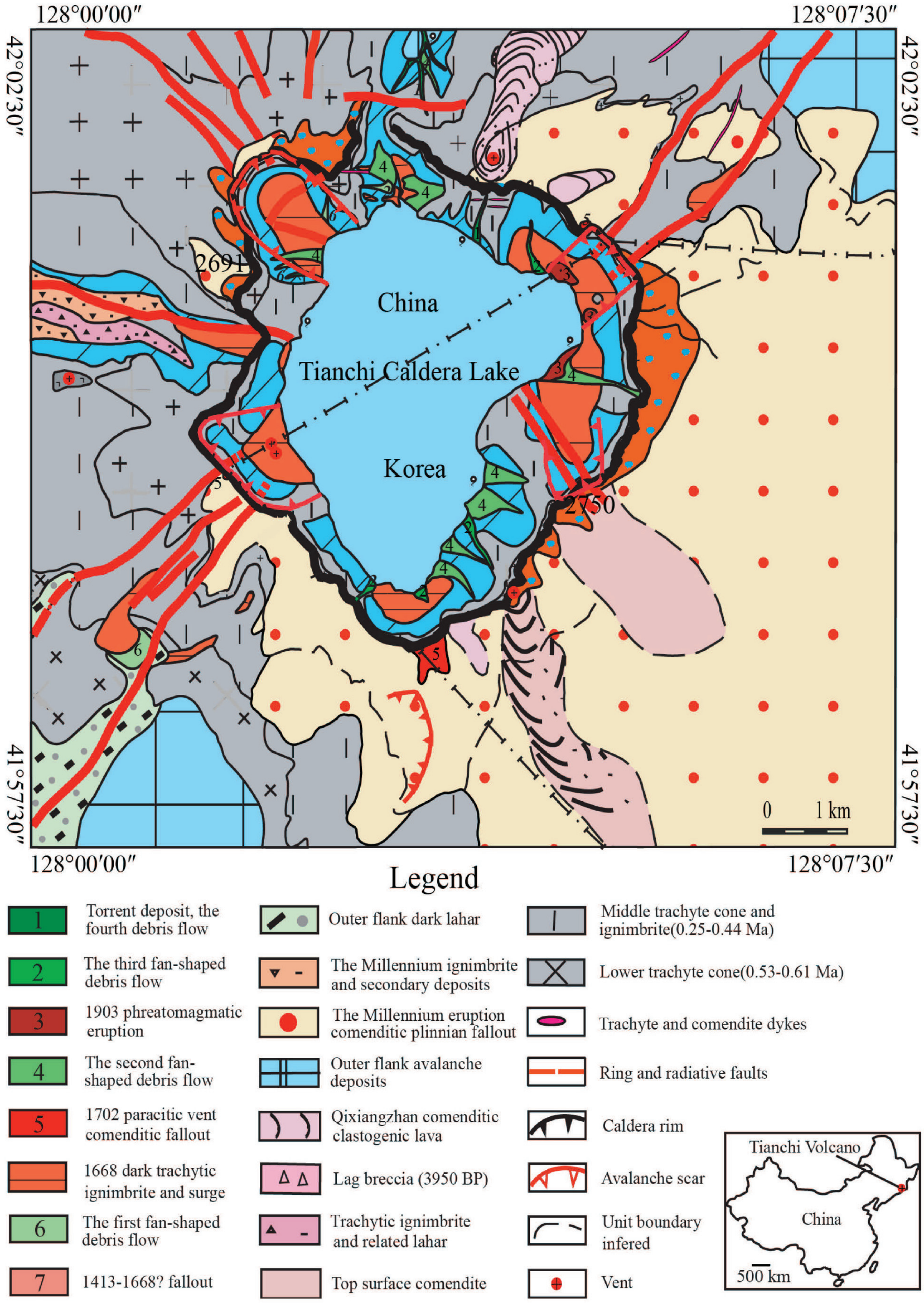

Figure 4. Geological map of the top area of Tianchi caldera from Wei et al. (2013)

Composite-cone construction

The formation of the composite cone took place in the Pleistocene (Jin and Zhang, 1994; Liu *et al*., 1998) when magma composition changed from basalt and trachybasalt to trachyte and comendite. The early-erupted magma was trachyandesite and trachyte but comendite products were erupted in the latest episode. Composite cone development can be divided into four stratigraphic units each of which started with explosive activity and were followed by lavas (**Table 1**). Trachyandesitic deposits of the first unit (~ 1 Ma) are mostly covered by younger trachytes and are only exposed at a few places on the north and south flanks of the cone at elevations between 1700-2000 m asl. The trachytic deposits of the second unit (0.55-0.61 Ma) are situated at the foot of Tianchi composite cone where they often have dips of over 30^{o}. This is the main geomorphological boundary separating the cone from the shield. The composite cone has a base elevation varying between 1600-1900 m. Products of the third unit (0.25-0.44 Ma) rest on the middle and upper part of the composite cone with elevation from 1700-2200 m on the outer flanks and from 2200-2600 m on the inner wall of the caldera (**Fig. 5**). Comendite erupted as well as trachyte. Comendite co-erupted with trachyte magma in the fourth unit (0.2- 0.04 Ma) and deposits of this unit make up the peaks along the crater rim. These deposits reach down to elevations of 2200-2600 m on the outer flanks and make up the highest points on the crater rim.

Satellite (or parasitic) volcanism and dyke intrusions accompanied the construction of the composite-cone. Examples of the parasitic volcanism are the Laohudong basalt (0.34±0.02 Ma), which covered the second unit trachytes. Dykes are a common component of the composite cone. Four sets of lava-like and tuffaceous ring intrusions related to the Tianchi caldera were emplaced. A few dykes with mainly NE trends were found on the NE flank of the cone. There are also ring dykes with compositions that evolved from trachyte to comendite with time. Comenditic pyroclastic dykes show typical textures of welding and emplacement deformation, such as vertical foliation and lineation of fiamme.

In North Korea, the equivalent composite cone-forming deposits are made up of four units, which are, in stratigraphic order: the Pukphothaesan, Taephyong, Mudubong and Chonji Formations. All of them belong to Paektusan Series (Ri, 1993). The Chonji Formation correlates with the fourth unit identified by Chinese workers with thickness in the range 80-150 m and with age determination of 0.087 Ma and 0.101 Ma (Liu *et al*. 1998). The Chonji Formation is divided into a lower member of trachydacite and an upper member (alternatively known as Janggunbong Formation) of trachyrhyolite. Some parts of the upper member were produced by comenditic satellite volcanism (like the Qixiangzhan satellite volcano in China).

The stratocone has an estimated volume of 70 km^3 erupted over about 1 Ma (Jin and Zhang, 1994). This is a minimum volume as significant volumes of pyroclastic material must have been eroded from the flanks or dispersed beyond the cone. We assume here that the volume of pyroclastic material is comparable to the cone volume and assign an erupted magma volume of order 140 km^3 to this period. This volume gives a magma production rate of 0.14 km^3 per 1000 years, a rate 5 times less than estimated for the shield stage. This lower rate is expected if the trachyte magmas of the shield are derived as residual melts from intruded crystallization of basalt.

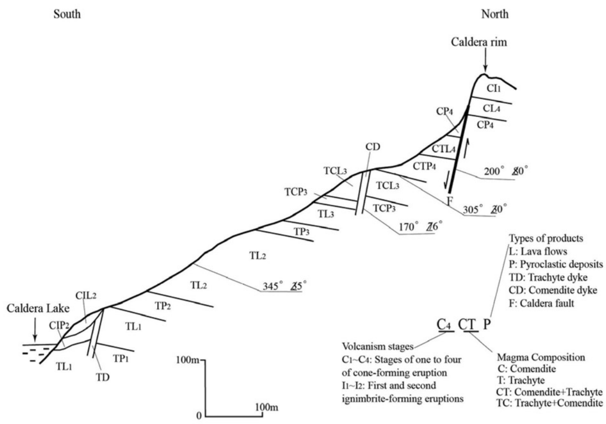

Figure 5. Inner wall profile of north frank of Tianchi caldera. (modified from Jin and Zhang (1994)

Holocene volcanism

Holocene volcanism at Changbaishan volcano is represented by at least two major explosive eruptions that formed ignimbrites and tephra fall deposits.

The deposits of an early ignimbrite-forming eruption are only sparsely preserved. The thickness and widespread distribution of these deposits indicate that this early ignimbrite-forming eruption had a magnitude comparable to the younger eruption at 1000 years BP. Comendite pumice fallout deposits and ignimbrite occur at Tianwenfeng and Wuhaojie (Fifth Boundary Marker) along the crater rim, Heifengkou on the north flank and Yuanchi (Circular Pool) or Dixiasenlin (Forest Below Ground) on top of the basaltic plateau. Lag breccias, about 2 m thick, outcrop on the north flank of the main cone and are equivalent of the pumice deposits on the crater rim, and yielded a ^{14}C age of 3950 ±120 BP (Wei *et al*., 2004). U series and TL dating on these deposits yielded ages of around four or five thousand years (Li *et al*., 2000 a; b; Wang *et al*., 2000). Manchurian legends from the 4000-5000 years ago (Wei *et al*., 2001) also indicate a major eruption at this time. Yellowish pumice fallout deposits (25 m thick) are overlain by the white-grey pumice of the 1000 year BP eruption on the crater rim. The deposits are partially welded and contain blocks of trachyte. The averaged maximum lithic grain size (average of 3 or 5 largest clasts, ML) is 1.8 m while the maximum pumice (MP) is 44 cm. A welded ignimbrite fills in the Erdaobaihe River with variable thickness in the range 5-30 m. Reddish pumice fiammes show reverse grading but lithics are normally graded. There is a brown or yellow pumice-rich fallout deposit and ignimbrite east of the volcano, which is correlated to this event. A widespread black soil layer with a radiocarbon age of 2040 ± 70 BP covers these deposits.

An ash fall layer from Changbaishan in Hokkaido, Japan has an age of 2130 ± 80 BP (Horn and Schmincke, 2000), but an equivalent deposit has not yet been identified on the cone or on the flanks of Tianchi caldera.

The youngest explosive eruption occurred about one thousand years ago, informally so-called the *Millennium* eruption. In the past three decades, a great deal of research has been carried out in order to date the Millennium eruption. Conventional ^{14}C dating of charcoal pieces recovered from the volcanic deposits produced a rather scattering age distribution from AD 550 to AD 1150, with a modal age around AD 1000 (Liu *et al*., 1998). The wiggle-match (WM) of sequences of ^{14}C ages, which were obtained using AMS technique of charred trees (with bark) killed during the eruption, yielded four well-dated ages of AD 921-941, AD 935 +8/-5, AD 953 +7/-8, and AD 969 +15/-24 (all reported at the 95.4% confidence level or 2σ age range) (Horn and Schmincke, 2000; Nakamura *et al*., 2007; Yatsuzuka *et al*., 2010; Yin *et al*., 2012). Although these previously reported ^{14}C ages place the eruption tentatively in the mid 10th century AD, they do not yet offer any unambiguous and consensus age for this eruption. Recently, Xu *et al*. (2013) reported a new high-precision ^{14}C wiggle-match age of AD 946 ± 3 which was obtained from a 264-year old tree trunk (with bark) killed during the eruption, by using the OxCal's Bayesian modeling approach with 27 sequentially sampled annual rings of decadal intervals. This new chronology conforms well to the calendar date of AD 946 for the eruption inferred from the historical evidences.

The Millennium deposits are distributed widely around Tianchi caldera. There are three main facies: plinian fallout, pyroclastic flow deposits in valleys and an ignimbrite sheet that covers the shield. The Millennium pyroclastic deposits consist mostly of white grey highly vesicular comenditic pumice (> 40% vesicles) and lesser amounts of late-stage trachyte pumice (Dunlap, 1996; Shi *et a*l., 2005). The comendite pumice is crystal poor (3 vol% anorthoclase, hedenbergite, fayalite, Fe-Ti oxide, quartz and apatite). Some of the pumice lapilli contain trachyandesite streaks. A late stage dark-grey trachytic pumice deposit mantles the cone and is attributed to a final event of the eruption.

The equivalent deposits of the ignimbrite-forming eruption in North Korea are called the Pumice Formation and covered Taehongdan plain to the east, Mt. Pukphothae to the southeast and Rimyongsu to the south. Ri (1993) stated that the greatest deposit thickness is 25 m at the foot of the inner wall of the caldera and recognised three types of deposits on the basis of pumice colour. White grey pumice represents fallout deposits and dark and pink pumice occur in ignimbrite.

Parasitic comendite volcanism also developed in the Holocene near the central part of the stratocone. The best example of satellite volcanism is Qixiangzhan volcano (see **Fig. 4**). The pyroclastic flows or clastogenic lava fed by a strombolian eruption was deposited on the ctratocone flanks remaining different flowing structures.

Recent historical activity

Wei *et al*. (1999) recognized a young thin fallout deposit of dark and semi-vesicular trachytic pumice covering the Millennium deposits on the crater rim. They found also some youngest pumiceous deposits by the lake and on the caldera rim. Some historical records (Cui *et al*., 1995; Wei *et al*., 2003) mention eruptions of Changbaishan volcano after the cataclysmic caldera- forming Millennium eruption. One occurred in 1668 and others are possible (e.g., in 1702 and 1903 AD).

Table 1 Summary of geochronological data on Changbaishan volcan

Volcanism	Formations	Deposits	Maximum thickness (m)	Time dating	Equivalence in Korea	Further data and description
Ignimbrite forming eruption	Millennium	White grey pumice	70	AD 946 ±3 (Xu *et al*., 2013) AD 935+8/-5 (Nakamura *et al*., 2007) AD 953 +7/-8 (Yatsuzuka *et al*., 2010) AD 969 +15/-24 (Horn and Schmincke, 2000) AD 921-941 (Yin et al., 2012)	Pumice Formation, white grey, grey in colour, black tuff is the latest deposit, volume 5-15 km^3, pink pumice interbedded with obsidian, ^{14}C date 840±40 BP, caldera volume is 40 km^3 (Ri 1993).	Post-ignimbrite eruptions in 1668, 1702 and 1903 AD, tuff ring dyke, 0.75±0.43 ka, 0.34 ~ 0.39 ± 0.04 ka 1.0±0.6 ka, 1.18±0.11 ka 1.54±0.98 ka (Li et al., 2000c)
	4000-5000 BP or 25000 BP?	Yellow pumice	30	4105±80 BP (Liu et al 1998) > 2130±80 BP (Horn and Schmincke 2000) > 2040±90 BP (Liu et al 1998) 24500 (Machida and Arai 1992)		Qixiangzhan comenditic satellite volcano, ring dyke intrusion, 3.2 ka, 3.93 ka, 4.3±0.367 ka, 5.3±1.2 ka (Li et al 2000 c)
Composite cone eruption	Baitoushan	Comendite and trachyte (Stage 4)	214	0.04 - 0.20 Ma (Dunlap 1996, Liu 1983)	Chonji Formation, around Tianchi 80-150 m thick, 0.087, 0.101 Ma (Ri 1993), lower part trachydacite 0.10-0.13 Ma (Ri 1993), upper trachyrhyolite 0.05-0.08 Ma (Ri 1993).	Basaltic satellite volcano 0.18±0.02 Ma, the upper trachydacite in Korea equivalent, the comenditic satellite volcano in China, ring dyke 20.9 ka, 21.9-24.4 ka, (Li et al 2000c)
		Trachyte and comendite (Stage 3)	221	0.25-0.44 Ma (Liu 1983)	Pukphothaesan Formation, covers 60 km^2, 370 m thick, 0.61, 0.39, 0.28 Ma (Ri 1993), Taephyong Formation equivalence of lower part of Laohudong basalt, Mudubong Formation equivalence of upper part of Laohudong scoria.	Laohudong basaltic satellite volcano 0.34±0.02 Ma. In Korea, Pukphothaesan, Taephyong, Mudubong and Chonji Formation compose Paektusan Series. 40-210 ka (Li et al 2000c)
		Trachyte (Stage 2)	207	0.55 ± 0.024 - 0.61 ± 0.015 Ma (Liu 1983)		Once accepted time dating for beginning of the cone, 281-551 ka (Li et al 2000c)
		Trachyte (Stage 1 or pre-cone?)	300	1.00±0.03 Ma 1.01±0.03 Ma (Liu et al 1998)	Not found yet	1010-1120 ka (Li et al 2000c)
Shield forming eruption	Baishan	Baishan (or Manjiang) Basalt	150	1.12±0.03 Ma, 1.3-1.6 Ma 1.48±0.10 Ma, 1.49±0.03 Ma 1.59±0.06 Ma, 1.66 Ma (Liu et al 1998)	Pochon Series that covers on 5400 km^2, thickness 166 m, two eruption interruption, pollen and magnet ages of Pliocene and lower Pleistocene (Ri 1993).	Fissure eruptions also occurred, basaltic dykes radiated from the shield
Plateau forming eruption	Junjianshan	Junjianshan Basalt	188	2.1-4.5 Ma (Jin and Zhang 1994)	Quaternary polycentric basalt plateau distributed in China and Korea on a total about 20000 km^2. No available data collected from Korea.	Once put into the shield-forming eruptions
	Songhuajiang	Songhuajiang Basalt	No available	4.9-5.3 Ma (Jin and Zhang 1994)		High level basalt
	Chuandishan	Chuandishan Basalt	No available	7-11 Ma (Jin and Zhang 1994)		
	Naitoushan	Naitoushan Basalt	400	12.0-16.7 Ma (Jin and Zhang 1994)		Rich in mantle xenoliths
	Zhenfengshan	Zhenfengshan Basalt, phonolite	495	19-24 Ma (Jin and Zhang 1994)		
	Maanshan	Maanshan Basalt	204	29 Ma (Jin and Zhang 1994)		

Felsic magma production

The magma volume for the Millennium eruption is estimated to be 24 km^3 by Horn and Schmincke (2000). If this is doubled to 50 km^3 to take account of the comparable magnitude earlier ignimbrite then a rate of 5.2 km^3 per 1000 years is calculated for the 9000 years between the start of the Holocene and the Millennium eruption. A more conservative view is that the felsic magma was produced over 40,000 years since the end of the stratocone phase, a time-scale consistent with U series data discussed below. In this case, the rate is 1.2 km^3 per 1000 years. Alternatively, if evolved magma is generated at the rate of 0.14 km^3 per 1000 years calculated for the cone stage, then the Millennium chamber would have taken 170,000 years to accumulate. Although these estimates have large uncertainties, they indicate that the generation of evolved felsic magma in the Holocene seems to be much larger than the time-averaged rates for the shield and stratocone. The formation of the magma body for the caldera forming eruption is discussed further below.

3. Petrology and Geochemistry

Basalts in the lava shield

The shield-forming stage (Baishan Formation) is mostly composed of trachybasalts, but there are also alkali trachytes, tholeiitic basalts and basaltic andesite using the classification of Le Bas *et al.* (1986). The chemical composition of volcanic rocks erupted during shield- and cone-forming stage or the Holocene can be grouped as trachybasalt with 49-51% SiO_2 , trachyte with 51-65% SiO_2 , and comendite with 65-77.5% SiO_2 (Le Bas *et al.*, 1986; Liu *et al.*, 1998). Their common feature is high K_2O (**Fig. 6**).

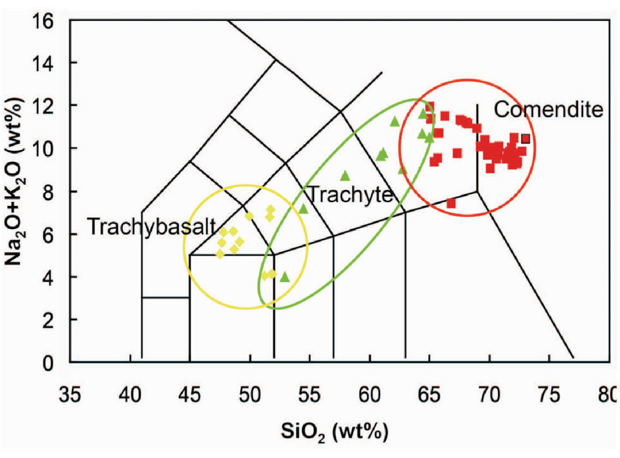

Figure 6. TAS plot of volcanic rock of Changbaishan volcano (modified from Liu , 1999)

Magma composition of the composite cone

The composite cone is mainly composed of aegirine trachyte or aegirine-quartz trachyte. Riebeckite- bearing comendite is found in the fourth unit. The parasitic eruptions of trachybasalts are similar to shield-forming lavas in composition. The phenocrysts in the trachytes at the lower part of the cone are sanidine or anorthoclase, plagioclase and pyroxene, sometimes with small amounts of amphibole and fayalite. The pyroxene phenocrysts in the trachytes are aegirine augite or hedenbergite. There are minor amounts of fayalite and arfvedsonite. The matrix mainly consists of plagioclase and alkaline feldspar, with minor quartz, amphibole and scaly metabiotite. Sometimes rounded plagioclase is included in other minerals. Accessory minerals in the trachyte are titano-magnetite and apatite. Phenocrysts in the comendite are mainly anorthoclase and aegirine with minor arfvedsonite, fayalite and quartz. The matrix of comendite is mostly glassy with fibrous crystalline aggregate. A few rounded small inclusions of fine-grained gabbro have been found at the upper part of the cone.

The Holocene deposits

The comendite pumices in the Holocene ignimbrites have similar lithological features, although the pumice in the earlier ignimbrite has high H_2O^+ content. The pumices are mostly glassy, and contain anorthoclase and aegirine phenocrysts with rare fayalite phenocrysts. The comendite pumices contain SiO_2 mostly between 70% and 74%, and is rich in K_2O but poor in CaO and MgO. The Qixiangzhan Holocene satellite deposits consist of comenditic pyroclastic rocks, clastogenic lava and obsidian-like densely welded tuff. The phenocrysts in the satellite comendite are anorthoclase, aegirine and fayalite, similar to those seen in the pumice, with 70-73% SiO_2, high K_2O and low CaO, MgO. Chevkinite is a minor phase. Trachytic pumice from post-Millennium deposits is rich in phenocrysts (10-20 vol%), comprising anorthoclase, hedenbergite, Fe-Ti oxide and rare olivine.

Trace elements

Cr, Ni, Co in the trachybasalts and the parasitic Laohudong trachybasalts of the cone-forming stage are significantly lower than those in other basalts in eastern China and indicate some differentiation (Liu *et al*., 1998). ∑REE, REE patterns and La/Sm ratio of the trachybasaltic rocks are very similar. This implies that they share the same magma evolution trend. ∑REE increases from trachybasaltic rocks to trachyte and comendite while the REE patterns for these rocks still remain similar. The trachytes and comendites have strong negative Eu anomaly while all the trachybasaltic rocks have positive Eu anomaly. The former feature implies the trachyte and comendite magmas have fractionated plagioclase or have involved partial melting of rocks with residual plagioclase. The positive anomaly of Eu in trachybasalts may also reflect accumulation of plagioclase (labradorite) crystals in the magma reservoir.

Sr, Nd, Pb isotope features

Liu *et al*. (1998) provided data for six samples on Sr-Nd isotopes of shield-forming trachybasalts and for six samples on Sr-Nd isotopes of cone-forming trachyte. From ^{143}Nd/^{144}Nd - ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd - ^{206}Pb/^{204}Pb data almost all of the Changbaishan volcanic rocks have Sr-Nd isotope ratios close to Bulk Earth. The ^{87}Sr/^{86}Sr value of a few pre-Holocene trachytes is higher than those of the trachybasalts and might be explained by some crustal contamination.

U-Series data

All pumice clasts from the Millennium eruption have excess ^{230}Th, a characteristic of most intraplate alkali basalts and their differentiates. The trachyte clasts have slightly higher (^{230}Th)/(^{232}Th) than the comendites, suggesting derivation of the comendites over a few tens of thousands of years from a trachytic parent (Dunlap 1996). In addition, the comendites are in radioactive equilibrium between (^{226}Ra) and (^{230}Th) despite extremely low Ba/Th ratios due to extensive fractionation of alkali feldspar, whereas the trachytes have (^{226}Ra) deficits (Dunlap, 1996). This requires that much of the comendite melt was >8000 years old at the time of eruption and that the trachytes entered the magmatic system more recently. Chevkinite-bearing mineral separates from the Millennium pumice give a well-defined linear array that, if treated as an isochron, gives an apparent crystallization age of 23 ka (Dunlap, 1996). Such an array might date a short crystallization event or result from incorporating old chevkinite seeds in younger mineral hosts. The latter interpretation is preferred and is consistent with accumulation and continuous crystallization of felsic magmas in a crustal chamber for a few tens of thousands of years before the large Holocene explosive caldera-forming eruptions. For a time of 23 ka and volume of 24 km^3 of felsic magma the rate of production would be 1 km^3 per 1000 years which is still significantly higher than the rate of production of the shield and strato-cone stages.

4. Geophysical Survey of the Magma System

There have been a number of geophysical studies in the region and on Tianchi caldera using a variety of techniques. Magnetotelluric soundings recognized a high conductivity zone at depths of 15-25 km beneath Tianchi caldera over an area of 20 km^2 that has a footprint equivalent to area of the caldera (as shown by the 1.5-1.7 Ω/m encounter line in **Fig. 7**). The high conductive and low resistance zone extends upwards in the NE direction. This may represent a zone of partial melt or small magma bodies (Zhao *et al*., 2000; Tang *et al*., 2001).

Seismic surveys show a low P wave velocity layer in Changbaishan area at depth of 40-65 km (Guo *et al*., 1996) and a low P wave velocity zone at

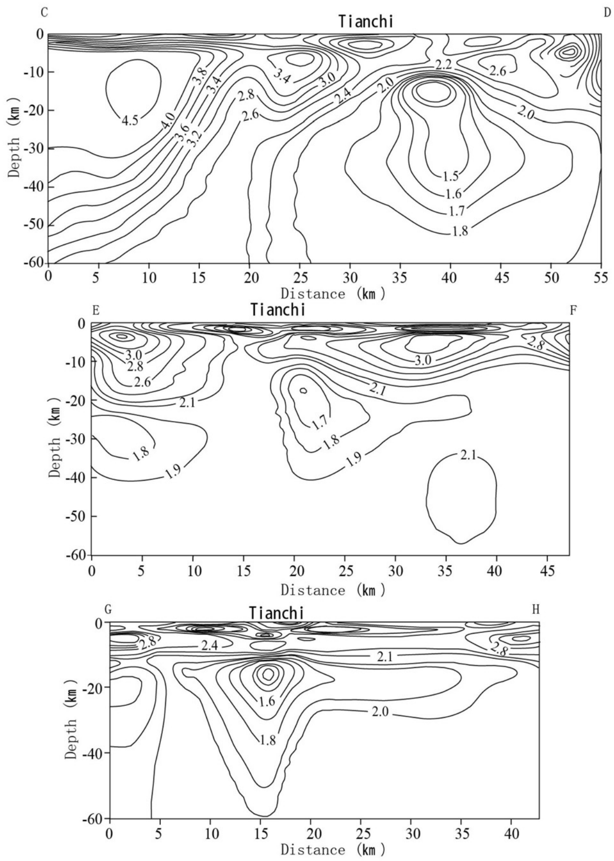

Figure 7. Magnetic survey along S-N, SW-NE, W-E profiles of Changbaishan volcano (modified from Tang *et al.* , 2001)

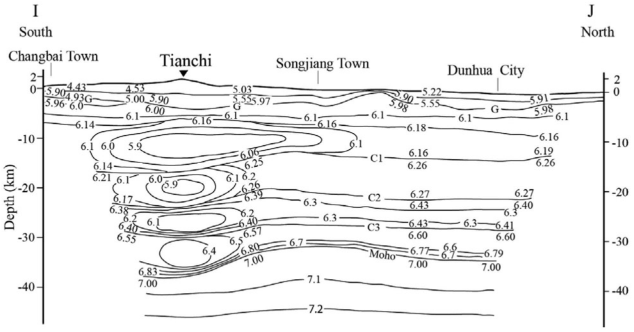

Figure 8 Vp (kms^{-1}) distribution beneath Changbaishan volcano and its surroundings (modified from Zhang *et al.*, 2002).

depths of 9-35 km beneath Tianchi caldera (**Fig. 8**, Zhang *et al*., 2002). The low velocity zone narrows downwards and is longer in the N-S direction. Its top, about 10 km beneath the volcano, is much wider than its base at depth of about 30 km. P wave velocity in this zone is typically about 2-4% lower than the surroundings. These data indicate a substantial substantial magmatic system under the volcano (Zhang *et al*., 2002). In particular they indicate generation and storage of partial melts and small magma intrusions within the middle and deep crust.

Zhang *et al*. (2002) calculated the velocity 3-D distribution at two depths of 15 km and 25 km respectively. They showed that the central part of the low P-wave velocity is 80-90 km long in NS, and 20-50 km wide in EW direction. More detailed survey work shows that at depths of 2-10 km there is a high P wave velocity dipping down to NW direction that is surrounded by low velocity material. The lowest P-wave velocity body is located north of the caldera lake. High V_p/V_s ratios (1.76-2.0 at different depths) are observed just under Tianchi caldera.

Guo *et al*. (1996) presented three seismic profiles intersecting Tianchi caldera. They identified a large-scale P wave low velocity zone in the region of Tianchi caldera, which had a dimension of 500 - 600 km long in the NE direction and 200 km wide in the NW direction at a depth of 40 to 65 km. This lower P wave velocity layer may be interpreted as a partially melted zone in the upper mantle linked to the volcanism around NE China and N Korea.

5. Volcano Monitoring

Changbaishan volcano observatory (CHVO) was set up in 1999 and has since been in full operation (Xu, 2011). The CHVO comprises 11 seismic stations, 15 mobile GPS measurement sites, 2 precision leveling survey lines with 28 sites, 3 hot spring gas spots, and basically covers the declared magma chamber fairly uniformly even though there do exist some "blind spots" on the North Korea side (**Fig. 9**).

Among 11 seismic stations, 7 of them use broad-band seismometers with period of 120 seconds for the Changbaishan central station, and 60 seconds for the other stations, whereas 4 stations use short-period seismometers with period of 2 seconds. In order to obtain more seismic data in the "unrest period", we deployed 15 mobile broadband seismometers to conduct mobile seismic campaign around the caldera region from 2002 to 2006 only in the summer time due to the limitation of weather condition in the Changbaishan mountain region.

The GPS network is set up around the caldera and covers an area of 1,200 km^2. Among 15 GPS sites, 8 sites were installed in 1999 and measurements started from 2000. Other 7 sites were installed in 2006 and measurements started from 2007. The GPS survey has been conducted with dual-frequency geodetic receivers in the August of each year. The precision ground leveling survey along two lines on both north and west slopes of the caldera has been carried out each year since 2002 in the annual interval base in order to identify possible ground vertical deformation. So far we have conducted totally 10 times leveling measurements starting from 2002 at the north slope, and 6 times starting from 2006 at the west slope.

Gas geochemistry observation at Changbaishan was initiated in 1985 by conducting temporary Rn, temperature and flux measurements once a year until 1998. Since the establishment of CHVO in 1999, routine gas chemical observations have been performed all the year round. Gas samples from Julong hot spring, which is near the CBS central station, are collected twice a week, and analyzed with SP-3420 gas chromatograph to measure the contents of major compounds such as CO_2, He, H_2, O_2 and N_2. Gas samples from Jinjiang and Hubian hot springs are collected in the September of each year, and analyzed with VG-5400 to measure the value of $^3He/^4He$ ratio.

Our continuous monitoring of Changbaishan volcano since 1999 has produced a 12-year long time series of behavior of the magma. The whole time series can be divided into three periods based on the active intensity of seismicity, ground deformation and gas geochemical variation we have observed, i.e. from 1999 to 2002, 2002 to 2006, and 2006 to 2011 respectively. During 2002 to 2006, defined as the "unrest period" in this study, the frequency of earth-

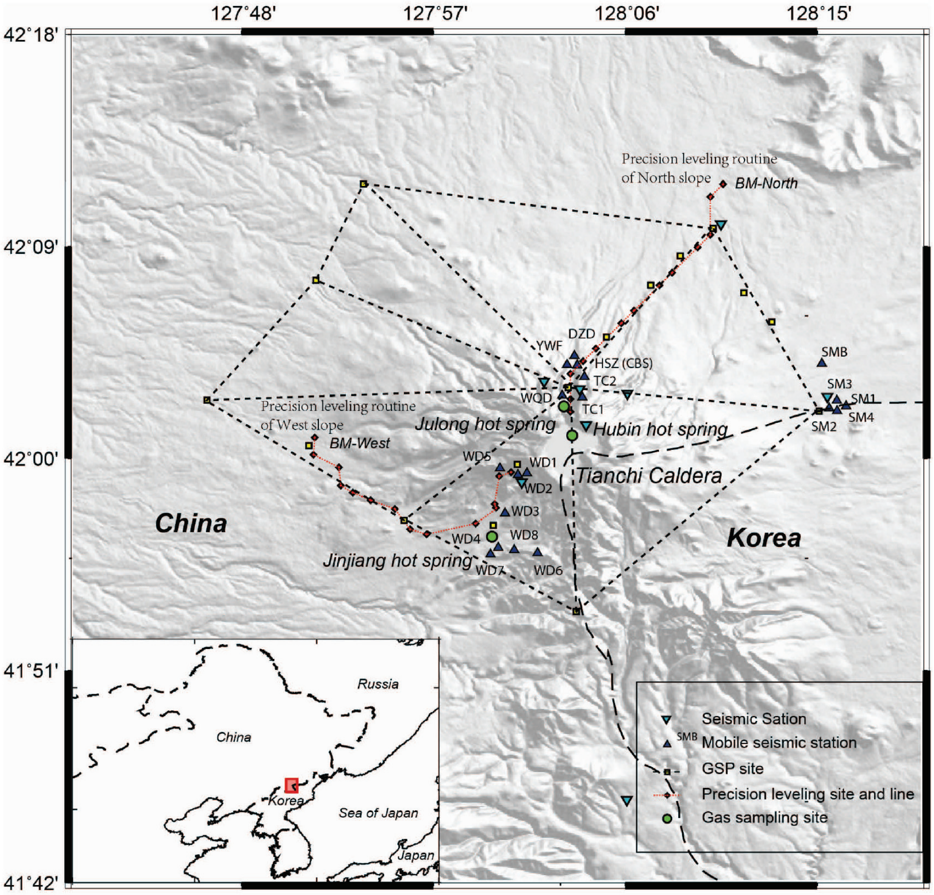

Figure 9 Monitoring network of CHVO.

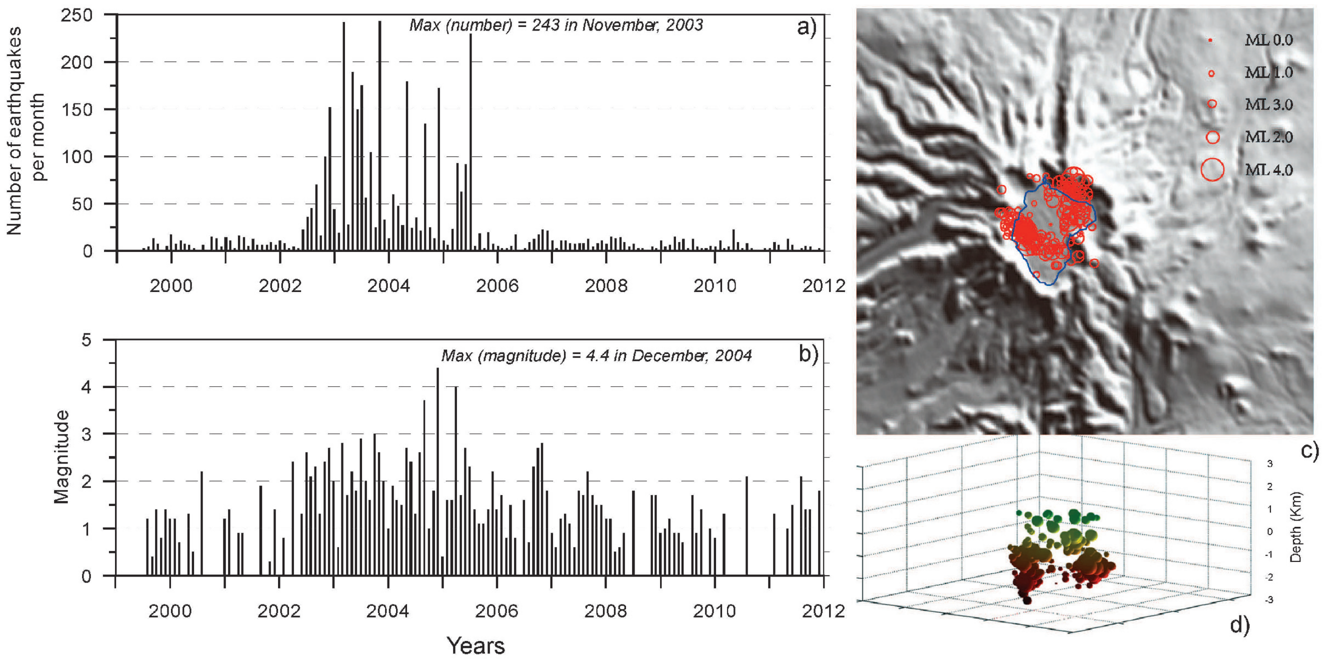

Figure 10 Seismic activity of Changbaishan volcano from 1999 to 2012

a): Monthly number of earthquakes recorded by CHVO; b): Time distribution of the maximum magnitude monthly observed by CHVO; c): Earthquake swarms detected by mobile seismic campaign in summers of 2002 and 2003; d): Relocated earthquake hypocenter distribution at depth around 5 km

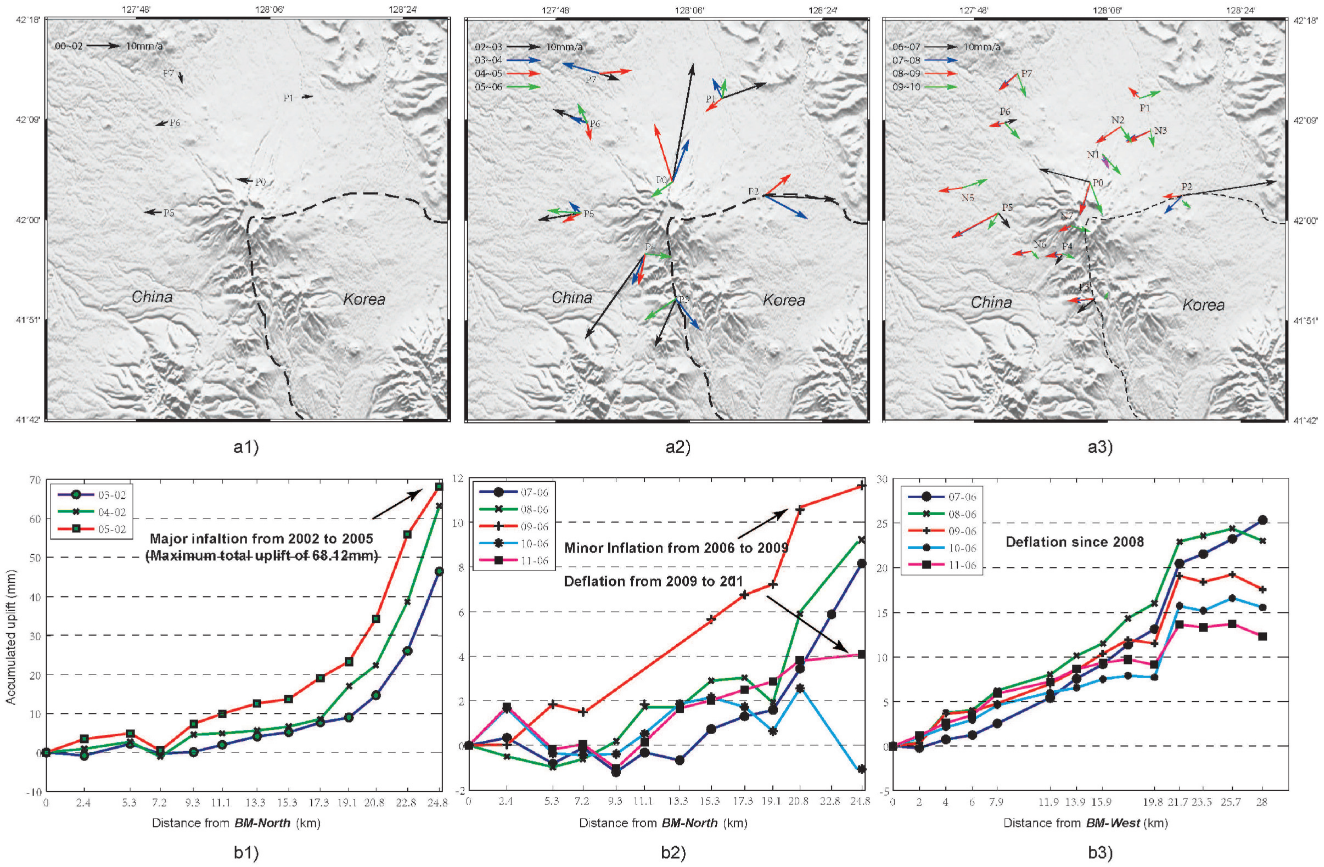

Figure 11. Surface deformation from GPS and precision leveling survey.
a): GPS horizontal displacements of : a1) 2000-2002, inactive period; a2) 2002-2006, active period with inflation,; a3) 2006-2010, inactive period with general direction shifting of displacement . b): Vertical displacements along the precision leveling routes for the periods of : b1) 2002-2005 at the north slope, b2) 2006-2011 at the north slope, b3) 2006-2011 at the west slope.

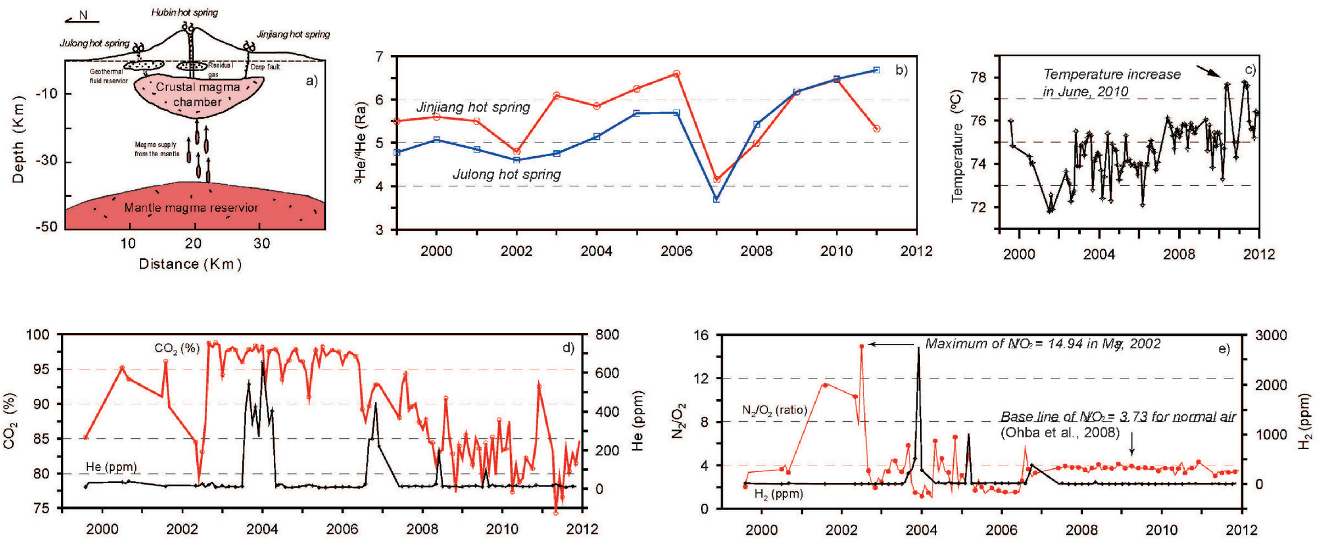

Figure 12. Gas geochemistry monitoring results from 1999 to 2012.
a): Schematic illustration of hot springs with different gas sources related to the magma system of Changbaishan volcano; b): Annual variation of $^3He/^4He$ ratio; Monthly variation of c): water temperature of Julong hot spring; d): CO_2 content (%) and H_2 concentration (ppm); and e): N_2/O_2 ratio and He concentration (ppm)

quakes appears as much as 2 orders higher than that in other two periods defined as the "inactive periods", accompanied with a great number of earthquake swarms and some harmonic events **(Fig. 10)**. The ground deformation measurements by GPS and precise leveling reveal remarkable mountain expansion and fast uplift of the caldera (**Fig. 11**). At same time period of 2002 to 2006, the contents of both major compounds CO_2, H_2, He, N_2/O_2 ratio, and isotopic helium $^3He/^4He$ ratio in the volcanic gas from hot springs keep at a distinctly high level than in other periods (**Fig. 12**). Changbaishan volcano has been in "inactive period" since 2006. However, several abnormal signals have been observed in very recent years which require our great attention. In 2009, precise leveling measurements along both north and west slopes of the volcano revealed a change of deformation mode from inflation to deflation (**Fig. 11 b2 and b3**). In the same year, GPS monitoring indicated a change of predominant direction of the surface movement from southwest to southeast (**Fig. 11 a3**). The water temperature of Julong hot spring had suddenly arisen to 77.7 °C , about 3°C increase in 2010, and has remained at such high level to present (**Fig. 12c**). These phenomena might be the indication for the beginning of a new "active period". After 2011 Japan Mw 9.0 Tohoku-oki earthquake, a coseismic offset as high as 35mm around Changbaishan area was detected by the China continental GPS network (Wang M. *et al*., 2011). Numerical simulation of changes of stress-strain field associated with the Tohoku-oki earthquake suggests that Changbaishan volcano is located in the region with a volumetric expansion ~14 nano-strain at a depth of 10 km (Wang F. *et al*., 2011). Such expansional stress induced by the Tohoku-oki earthquake may cause the opening of magma channel and result in an increase in the volcanic activity of Changbaishan volcano. Considering that there is great increasement of tectonic activity along the western Pacific subduction zone where Changbaishan volcano is tectonically correlated, as indicated by intensive earthquake occurrences and volcano eruptions in recent years, the more intensive magmatic activity Changbaishan volcano may be triggered. Under such circumstance, It is likely that the magmatic unrest process from 2002 to 2006 may serve as the long term precursor of the potential eruptive activity of Changbaishan volcano in the future, and deserves our great attention.

6. Description of field trip stops

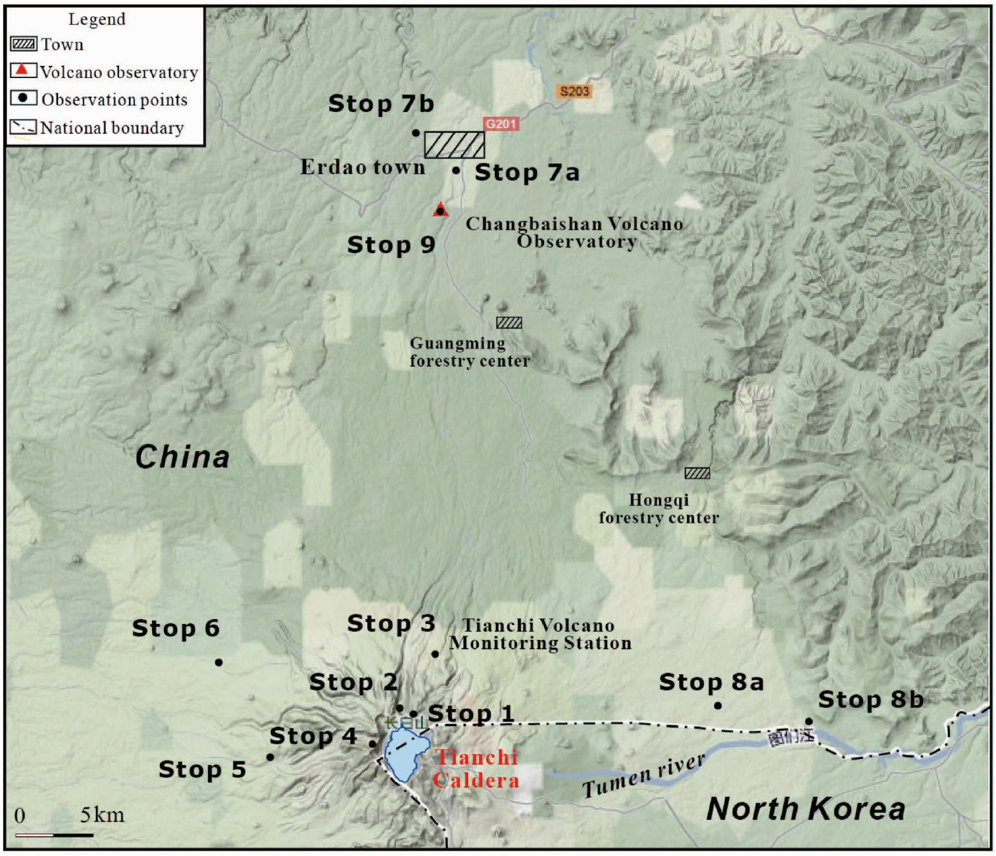

Figure 13 Locality of stops around Tianchi caldera

Stop 1 Tephra fall deposits at summit of caldera on the north flank

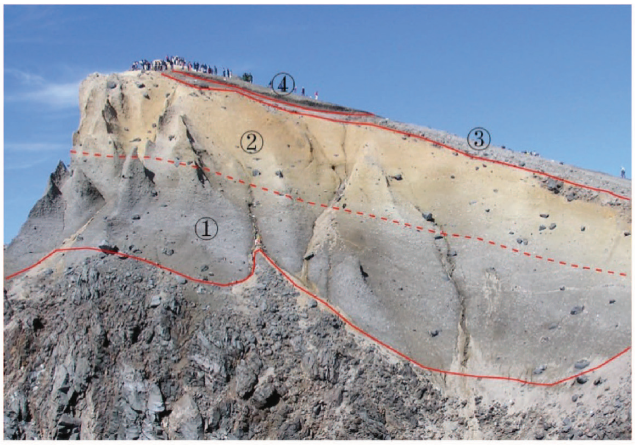

Figure 14 Pumice deposits in Tianwen peak at Tianchi crater (trachyte below the pumice deposits)

① Gray alkaline rhyolitic pumices, formed in 5000 years ago;

② Yellow alkaline rhyolitic pumices with some trachyte blocks, formed in 5000 years ago

③ White alkaline rhyolitic pumices, formed in AD 946 millennium eruption;

④ Black trachytic pumice formed by eruption after AD 946 (?).

Stop 2 Waterfall at the north flank

Waterfall is the source of Erdaobaihe river. A plank road along the face of the cliff was built in 1990's, which provide path for visitors to walk to the shore of Tianchi lake (**Fig. 15**). Near the waterfall is Julong, the famous hot spring of temperature about 78 °C, which is used for cooking eggs by local people.

Figure 15 Waterfall at the north flank – the only outlet of the Tianchi caldera lake

Stop 3 Tianchi Volcano Monitoring Station (TVMS)

Located in the Erdaobaihe river valley, 2.5 km north of the caldera rim, the TVMS was built in the mid-1990's. In a monitoring tunnel of 65-meter-long chamber, a set of broadband seismometer and two 10-meter long quartz tubes of a tiltmeter and tensometer are installed to monitor the seismicity and mountain's deformation.

Figure 16 Tianchi volcano monitoring station

Stop 4 Inner caldera (viewed from the west summit of caldera)

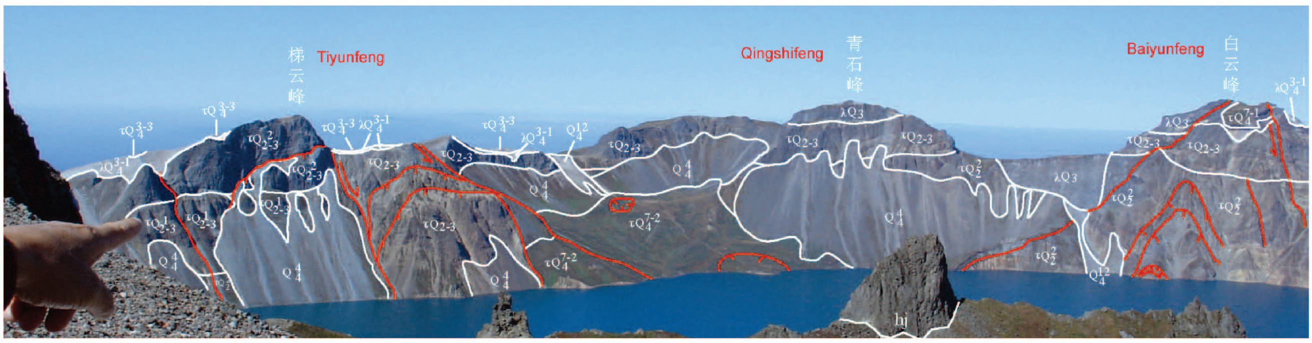

Figure 17 Inner section of the east summit of the caldera (in north Korea, viewed from the west summit in China). From the bottom to the top, the major formation includes: 1) Trachyte in the member Ⅱ of the Baitoushan formation (τQ_2^2); 2) Trachyte, alkaline rhyolite and obsidian in the member Ⅲ of the Baitoushan formation ($\tau Q_{2\text{-}3}$); 3) Alkaline rhyolite in the member Ⅳ of the Baitoushan formation (λQ_3); 4) Black trachytic pumice with debris in the Tiyunfeng formation ($\tau Q_4^{5\text{-}1}$).

Inner the caldera, there are a large number of talus deposits. By the lake, black trachytic pumice deposits of Wuhaojie formation ($\tau Q_4^{8\text{-}1}$) and modern lahar deposits ($Q_{4n}^{9\text{-}2}$) are developed.

Stop 5 Jinjiang pyrocalstic valley

About 14 km west of the caldera, Jinjiang pyrocalstic valley is about 100-meter-deep and full of pyroclastic-flow deposits by the Millennium eruption (**Fig.18**). The strata are combined with massive beds, pumice-rich layers, litchis-richer layers and welded zones. Columnar joints and block structures are also developed.

Figure 18 Jinjiang pyrocalstic valley at west flank of volcano

Stop 6 Xiaoshahe – Trees buried in the pyroclasstic deposits from the Millennium eruption

Figure 19 A 264-year old larch tree (Larix) log at Xiaoshahe buried within the thick grayish pyroclastic flow deposits from the Millennium eruption.

During the Millennium eruption, the pyroclastic flows deposits from the collapse of about 25 km high eruption column cover an area extending roughly 50 km from the caldera. The forests in the vicinity of the volcano were largely destroyed during the eruption and numerous carbonized tree logs (large and small) were buried within the tephra fallouts and pyroclastic flow deposits. In Xiaoshahe, about 22 km west of the caldera, some larch trees (Larix) log with bark, about several meters long and dozens centre meters in diameter were recovered from thick pyroclastic flow deposits (**Fig. 19**).

Stop 7 Lahar of the Millennium eruption in Erdao town region

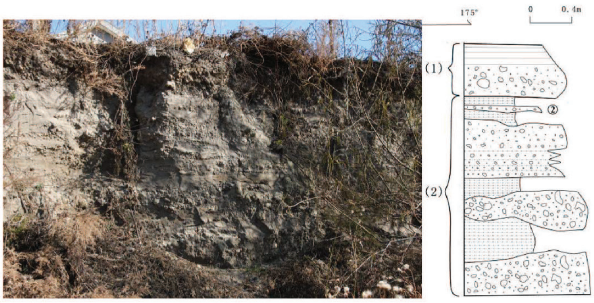

Figure 20 Section of lahar deposits near Erdao town Church

Erdao town is at about 50 km north of the caldera. It is the most vulnerable town in this area on which Erado town is built was buried by the lahars induced by the Millennium eruption. Lahar deposits in this region are well developed along the old river channels (**Fig. 20, 21**). The lahar strata are characterized by inter-bedding of pumice deposit and ash deposit (**Fig. 20**). Erdao towns has developed rapidly for tourism in recent years. Education about the volcanoes and related hazards is going to be important to provide a better understanding of the volcano to the citizens.

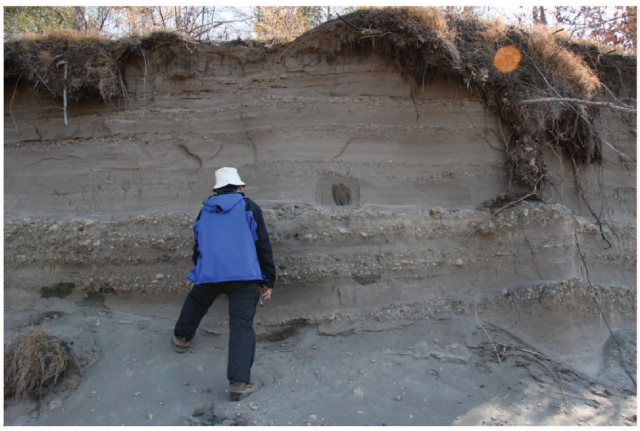

Figure 21 Section of lahar deposits from the Millennium eruption in Gaihe river, north of Erdao town

Stop 8 Yuanchi Tephra fall deposits

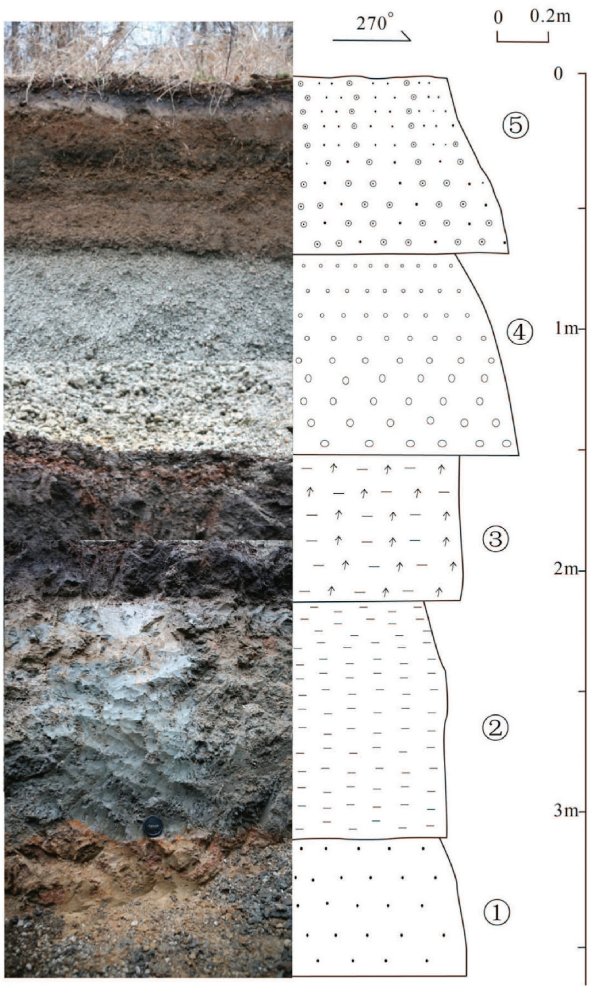

Figure 22 Cross section at Stop 8a
①Yellow mud with relict pumices; ②Gray silting deposits; ③Silting deposits with plan roots;④Fall pumices from the Millennium eruption (946 AD); ⑤Soil with relict pumices

The previous studies indicated that Changbaishan volcano has probably experienced five explosive eruptions in the Holocene, i.e. 5,000 BP eruption with gray and yellow pumice, 946 AD eruption with greyish-white pumice, 1668 AD eruption with black pumice, 1702 AD eruption with black pumice and 1903 AD eruption of with gray and pale yellow pumice (Liu *et al*., 1998; Wei *et al*. 2003; Xu *et al*. 2013). These five explosive eruptions have produced several types of hazards, such as tephra fallout. Due to prevalent wind direction, most tephra particles spread eastwardly and deposited in north Korea side, the Sea of Japan and northern Japan island.

Yunchi is located at about 40 km east of the caldera at the national border, where the tephra fall deposits from the Millennium eruption are well developed (**Fig. 22, 23**).

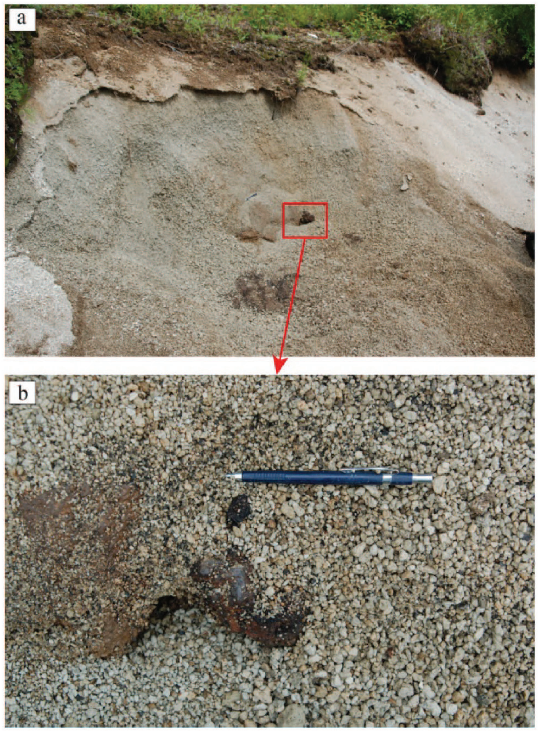

Figure 23 Outcrop at Stop 8b: fall pumices from the Millennium eruption. Note that charcoal sample (in figure b) was collected and was dated by ^{14}C technique of 972±38 AD.

Stop 9 Changbaishan Volcano Observatory (CHVO)

Figure 24 Changbaishan volcano observatory at Erdao town

Changbaishan Volcano Observatory (CHVO) is located in Erdao town, 50 kilometers north of the caldera (**see Fig. 13**). CHVO was established in 1996, and the monitoring work started in 1999. CHVO became the National Key Observatory of the Science and Technology Administration of China in 2001.

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