Stratigraphic Sequences and Magmatic Cycles of the Tianchi Volcano, Changbaishan

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Abstract

The Junjianshan Basalts has been subdivided into 3 units as the Toudao, Baishan and Laofangzixiaoshan Basalts to reconstruct the process of the shield-forming of the Tianchi Volcano, after the plateau-forming eruption. Here we define the Toudao F as the thick and long reached basaltic lava flows on the north and northwest part of the Tianchi Shield. As a representative profile we present one at Yaoshui along the Toudao River from which K-Ar ages of 2.29, 2.35, 5.02 and 5.82 Ma are dated. The basalts of the Baishan F compose the main terrain of the Tianchi Shield. These lava flows vary in thickness and ages, such as 1.28 and 1.39 Ma. The Xiaobaishan Trachyandecites—Trachytes, distributed mainly on the southern Tianchi Trachyte Cone and the northern base of the Cone, are representative of trachytic episodes of the eruption before 0.81, 0.92 and 1.19 Ma.

Basalts from the Laofangzixiaoshan F, distributed on the northeast, northwest and southwest sides of the Tianchi Lava Shield, make up a part of the surface of the Tianchi Shield, on which several scoria cones and flat craters are situated. The K-Ar ages for the Laofangzixiaoshan F are generally very young compared with the Toudao and Baishan Formations; such as the northeastern lava flow ages of 0.23, 0.31, 0.34, 0.35 and 0.47 Ma and the southwestern lavas dated as 0.4 and 0.42 Ma. These lava flows are equivalent to the parasitic Laohudong basalts in 0.34 and 0.32 Ma. Materials erupted in the Baitoushan stage constructed the strata cone with a largest thickness of about 600 m and are grouped into 3 members; Lower, Middle and Upper Members of the depositional sequence.

The Holocene volcanic strata of the Tianchi volcano are listed as Bingchang, Qixiangzhan, Baiyunfeng and Baguamiao Formations. The Bingchang F, of welded pyroclastic rocks of trachyte and comendite, locates at the depressions of Bingchang, Gudisenlin and Baishanqiao. The Qixiangzhan F is a typical clastogenic lava flow originating from satellite comenditic volcanism near the top of the Tianchi Cone, while the Baiyunfeng F is of comenditic plinian fallout and ignimbrite deposits that are widely distributed on the surface of the Tianchi volcano. The Baguamiao F is represented as dark trachytic fallout and ignimbrite deposits mantling the surface and thickening in the valleys. Eruptions from the Tianchi Volcano are reported to have taken place

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in 1668, 1702 and 1903 AD.

The Tianchi Volcano is a completely evolved magma system showing evolutionary trends as the volcanism varies with time. We note that the mechanism of magma evolutionary exhibits a successive differentiation trend and magma mixing process. This mechanism is definitely different from the formal bi-modal distribution of the magma composition.

In the early cycle of trachytic magma production, a trachyte sample is obtained from the Daewoo Hotel borehole. In the middle cycle, basaltic magmas evolved into the trachytes and trachyandesites of the Xiaobaishan Formation. The late trachyte cycle comprised the main edifice of the Tianchi stratovolcano and had a distinct explosive regime change from trachyte to comendite.

Introduction

Compared with the surrounding Cenozoic Plateau forming eruptions, the Tianchi（天池）magmatic episodes were somewhat of a late episode of activity in the different magmatic cycles in the Changbaishan（长白山）area. From the base up to the Tianchi volcanic strata consisted of Miocene, Pleistocene and Holocene components, which formed the erupted units, in a sequence from older to younger, as Toudao（头道）, Baishan（白山）, Xiaobaishan（小白山）, Laofangzixiaoshan（老房子小山）, Baitoushan（白头山）, Bingchang（冰场）, Qixiangzhan（气象站）, Baiyunfeng（白云峰）and Baguamiao（八卦庙）Formations, respectively (Jin and Zhang 1994: 15-39). A multiple magmatic evolutionary process of crystal differentiation and magma mixing or mingling appears to have happened, although it is also argued that there was a "bi-model" distribution of the magma composition that evolved from a basalt shield to a trachyte cone and comendite sheet (Jin and Zhang 1994: 75-203; Liu et al. 1998: 19-48). Here we present the most recent nomenclature for the Tianchi volcanic successions and correlated them with the various deposits around the volcano for a better understanding of the history and possible future activities of the Tianchi Volcano. It should be emphasized that there was indeed a trachytic episode during the earlier shield-forming stages at the Tianchi Volcano. As a brief outline of the comparison between the Tianchi strata and its surroundings, we first present a stratigraphic succession of the Tianchi Volcano, as in Table 1, and discuss in detail the chronology and compositional features of the volcanic succession.

Neogene Volcanic Rocks

Naitoushan Basalts（β N_1n）

The Naitoushan（奶头山）Formation is found at Naitoushan, Huangsongpu（黄松蒲）and Changhongling（长虹岭）on the northeast part of the Tianchi shield volcano, and along the Jinjiang（锦江）River on the southwest part of the Tianchi Shield. It is the earliest Cenozoic basalt near the Tianchi Volcano. A diagnostic feature of the Naitoushan Basalts found in the field, for instance at Huangsongpu, is that it contains a reasonable amount of xenoliths of peridotite. The host rocks of the xenoliths are basanites and alkaline olivine-bearing basalts.

Basaltic rocks (inclusive of basalts and basanite) have a thickness of about 90 m at the representative Naitoushan profile; where peridotite xenoliths mostly in centimeters or millimeters scale can be seen. Basanites generally feature as dark grey in color, with a porphyry texture and an amygdaloidal structure for the rock, as well as a tholeiitic texture for the matrix. The phenocrystals of the rocks are composed mainly of olivine and feldspar. The olivine, with a content of 5 %, (+2 V) =87°, fo=86 %, sometimes shows iddingsite on its edge or at a fracture of the chrysolite. Plagioclase phenocrystals, 1 % ± in content, An=73 ±, have generally a thin annulation of 0.5-1.5 mm length. Clinopyroxene phenocrystals, 1-1.5 mm long and Ng∧C=39°,

Tab.1 (continued)

				III	Trachyte intercalated basalt				*M*	Trachyte intercalated basalt	Daping	Basalt
				II	Trachyte				*L*	Trachyte	Beibaotai -shan	Trachyte Comendite
					Shuangfeng basalt			Laofangzi -xiaoshan		Basalt		
						Middle cycle of magma evolution					Beixueling	Rhyolite
	L			*I*	Andetrachyte Trachyte		Xiaobaishan			Trachyandesite, Trachyte	Lüfeng	Trachy- andesite Trachyte
			Baishan		Basalt		Baishan			Basalt	Putian	Basalt
							Yaoshui (Low Elevation)			Basalt		
						Early cycle of magma evolution	Daewoo			Trachyte		
Pliocene			Junjianshan		Basalt		Toudao (High Elevation)			Basalt		
Miocene			Naitoushan		Basalt	Plateau- forming eruption	Naitoushan			Basanite Basalt	Longdeli, Qinglinli, Datianping	Basalt

Time		Jin and Zhang, *1994* (in Chinese)				Authors here					Baitoushan Book Series, *1993* (in Korean)	
		Cycle	Strata		Rocks	Cycles	Strata Formations			Rocks	Strata Layer	Rocks
Holocene		Single cycle of magma evolution	Baguamiao		Trachytic pyroclastic rocks	Late cycle of magma evolution	Baguamiao and others			Trachytic pyroclastic rocks	Tianchi	Pumiceous pyroclastic rocks
			Baiyunfeng		Comenditic pyroclastic rocks		Baiyunfeng			Comenditic pyroclastic rocks		
							Qixiangzhan			Comenditic clastogenic lavas		
			Bingchang		Trachytic pyroclastic rocks		Bingchang			Trachytic pyroclastic rocks		
Pleistocene	*U*		Qixiang -zhan		Comendite		Yuehualin			Comendite	Jiangjun -feng	Comendite
	M		Baitou -shan	*IV*	Trachyte, Comendite		Laofangzi -xiaoshan Laohudong	Baitou -shan	*U*	Trachyte, Comendite	Xiangdao -feng	Comendite
											Wutoufeng	Basalt

Tab. 1 Nomenclature of the eruptive sequence and co-relationship with the surroundings of the Tianchi Volcano, Changbaishan

are seldom seen and contain the early olivine and melt inclusions. The basanite matrixis made up of plagioclase and interstitial material of pyroxene (15 %), magnetite (10 %), glass (15-20 %), and a little ilmenite, iddingsite altered olivine and apatite.

The Naitoushan Basalts, overlying a sandstone stratum of Tumenzi (土们子) Formation, were dated as 22.64, 18.87, 17.4 and 15.07 Ma when sampled at the northeast part of the Tianchi Volcano (Jin and Zhang 1994: 15-39; Liu 1999: 13-111). We measured three samples from a borehole near Huangsongpu (Fig. 1) and got K-Ar ages of 15.8, 18.87 and 20.04 Ma, respectively, and a K-Ar age of 18.92 Ma from the southwest surface rock of the volcano.

In North Korea some augite-peridotites xenoliths were found at Longdeli (龙德里) and Qinglinli (青林里) in Putianjun (普天郡), and Datianping (大田坪) in Yunxingjun (云兴郡, Ri 1993: 330-349). The host rocks, dark aphyric basalts, maybe equivalent to the Naitoushan Basalts in

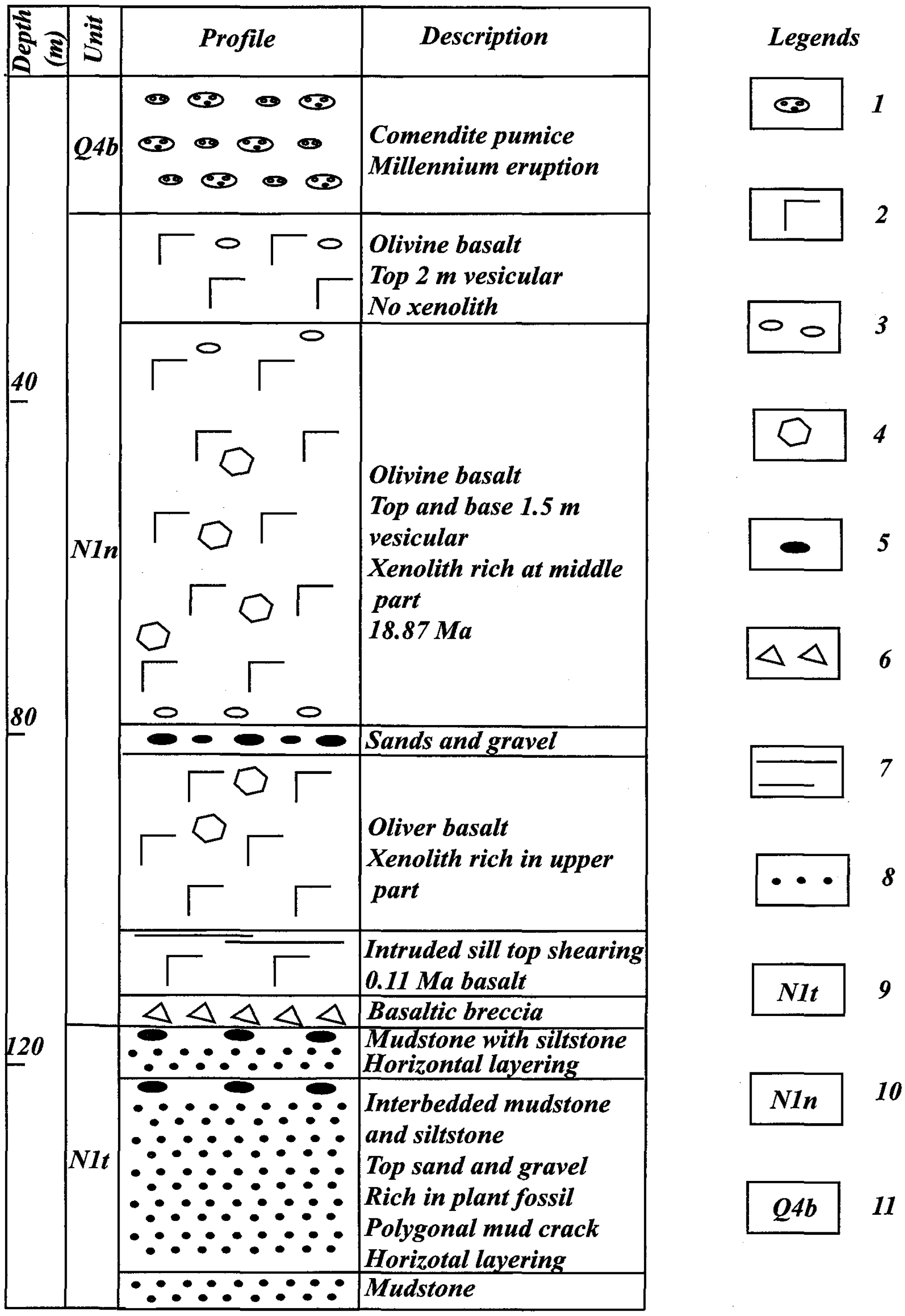

Fig. 1 A borehole profile showing a vertical sequence of the Naitoushan Basalts (basanites) near Huangsongpu
1: Ignimbrite
2: Basalt
3: Bubble
4: Peridotite Xenoliths
5: Gravel or sand
6: Volcanic breccias
7: Layering
8: Mudstone or siltstone
9: Tumemzi Formation
10: Naitoushan Formation
11: Baiyunfeng Formation

China.

Toudao Basalts (βN_2-Q_1t)

This is a strata unit, which we first introduced here to represent the earliest strata unit from the Tianchi Lava Shield. There is an inclusive unit called the Junjianshan（军舰山）Formation making up the shield composition of the Tianchi Volcano (Liu 1999: 13-111). Here we subdivide the Junjianshan F into its different units to reconstruct the history of the shield-forming eruption of the Tianchi Volcano. We define the Toudao F as the thick and long reached basaltic lava flows (originating from the Tianchi Volcano) on the north and northwest part of the Tianchi Shield. A representative profile can be seen at the Yaoshui（药水）profile along the Toudaobaihe（头道白河）where different lava flow units fill in pre-existing valleys and have been partly eroded by running water (Fig. 2 and Photo 1). The High Elevated Basalts（高位玄武岩）in the profile are dated as being 5.02 and 5.82 Ma, respectively. From a borehole at the new TVO (Tianchi Volcano Observatory, 天池火山观测站) in Erdao Town（二道镇）we measured the equivalence for the Toudao K-Ar age as 4.26 Ma. The analyzed borehole basalt was obtained from the lowest lava flow unit, equivalent to the high elevated basalts from the Yaoshui profile. This low borehole basaltic rock overlies the surface of pre-Cambrian gneiss and is underneath a palaeosoil layer beneath the surface Toudao Basalts (Fig. 3).

This earliest unit of the Tianchi Shield can be found at the drains and galleys originating from the shield or the cone. For example, a lava flow profile exists at the Bailong Power Station（白龙水电站） from which two flow units (total thickness over 30 m) can be seen. The petro-

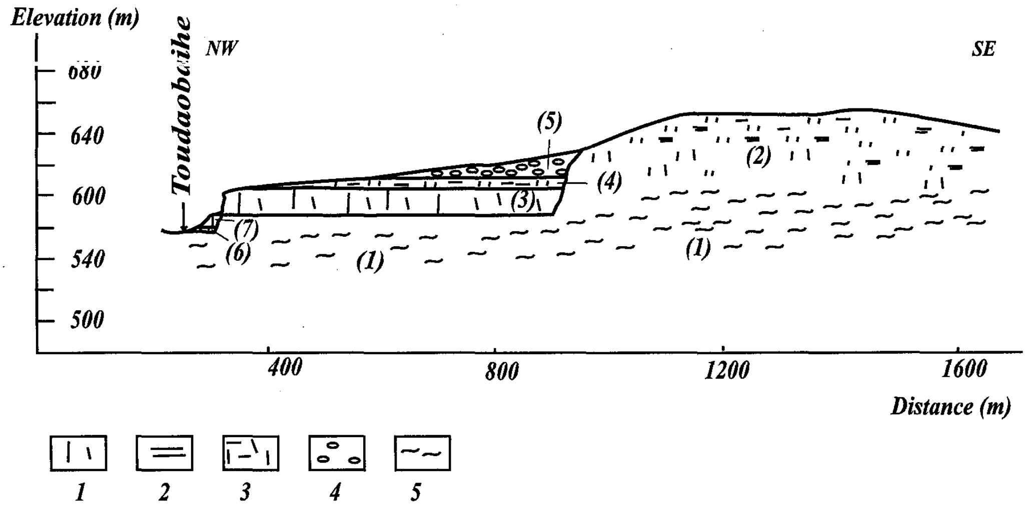

Fig. 2 The Yaoshui profile for the basalt sequence of the Toudao Formation
1:Columnar joint 2:Horizontal platy joint 3:Block joint 4:Loose sand and gravel after eruption 5:Lineation of the gneiss

The numbers in the parentheses represent the strata unit sequence. (1):Proterozoic gneiss; (2):Massive basalts with columnar and blocky joints, plateau-forming eruption (of ca. 9 Ma?); (3):Columnar joint basalt (5.82 Ma) with peperite, pillows and quenched palagonite fragment near base; (4):Massive basalt; (5):Cliff debris and talus accumulation; (6):Sandy gravel layer beneath the Tianchi Shield, with basaltic gravels of 8.92 and 9.62 Ma; (7):Multiple basaltic composite flow units with columnar joint with ages of 2.29 and 2.35 Ma, products of the shield-forming eruption.

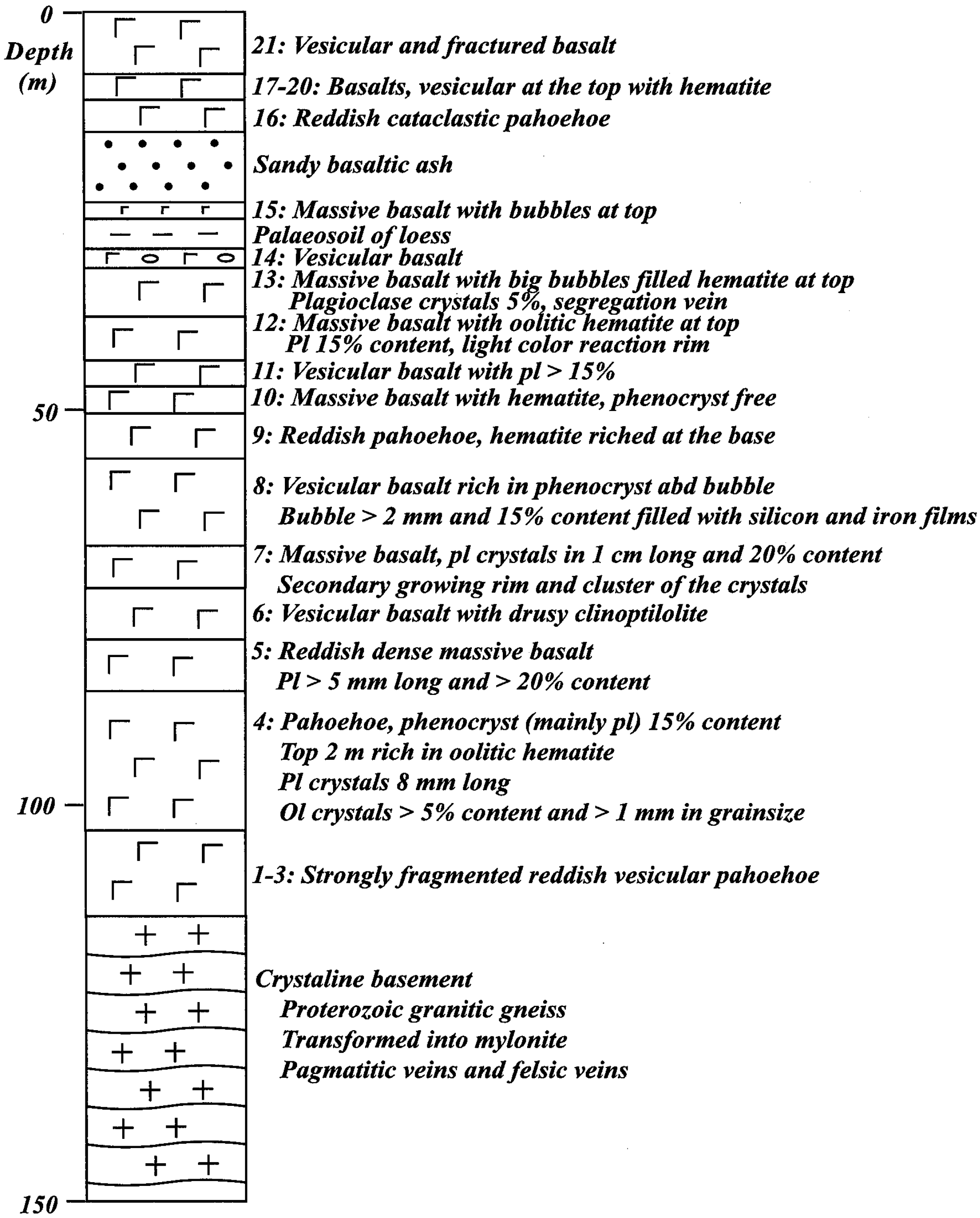

Fig. 3 A dig hole profile at TVO showing the depositional sequence and the thickness distribution of the Toudao basalts.

The numbers refer to the flow units of the basaltic lava. Flow units 1-13 are the products of the plateau-forming eruptions with a K-Ar dating of 4.26 Ma. There are two phenocrystal enriched cyclothem at units 1-8 and units 11 and 12. , The shield-forming erupted deposits, from unit 15 on contain less phenocrystals, after the palaeosoil deposit. Hematite (oolitic hematite) exists in almost the total succession, illustrating the oxidized environment of the deposits. Zeolite minerals from the buried metamorphism exist only 50 m below the surface.

logic features of the basalts, often enriched in bubbles, are of a dark grey color and have a porphyritic texture. The matrix of the basalts are composes of plagioclase and interstitial pyroxene, olivine, titan-spinel and apatite. The compositional features of the rock-forming minerals also retain differences for the different stages of the basalts (Fig. 4). Later, this is discussed further.

It is from the Yaoshui profile that we get the earliest ages of the surface shield basalts, as 2.29, 2.35 Ma and the earlier plateau-forming eruptions of 5.82 and 5.05 Ma, respectively. The plateau-forming basalt aged in the Erdao TVO borehole of 4.26 Ma is overlain by lava flows dated as being 1.91 and 1.64 Ma, north of the caldera. From an earlier survey of the lava flow sequence it was shown that there are two ages, 2.34 and 2.12 Ma, measured from samples of another borehole at Erdao Town and from the scoria cone of West Maanshan (马鞍山, Liu 1999: 13-111; Jin and Zhang 1994: 15-39).

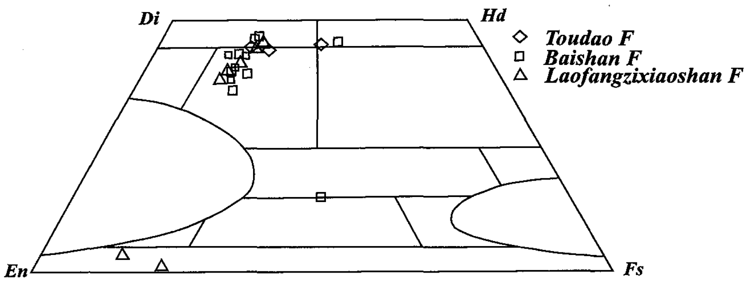

Fig. 4 Pyroxene compositional differences between the different stages of the Shield Basalts
As well as the compositional concentration of augite and diopsite, the phenocrystals composition in the Laofangzixianshan F varies a lot, is varied in the Baishan F, but less in the Toudao F. The pyroxene composition in the matrix retains the diopsite and augite species.

Quarternary Volcanic Rocks

Baishan Basalts (βQ_1b)

The basalts grouped into the Baishan F, distributed around the Tianchi cone and on the upper courses of Tumenjiang（图们江）and Yalujiang（鸭绿江）, compose the main terrain of the Tianchi Shield. The basalts on the upper Tumenjiang are also called Tumenjiang Basalt while those on the upper Yalujiang are called Lingguangta（灵光塔）Basalt. These lava flows vary in thickness, generally in dozens to hundreds of meters, and show sharp differences in their aspect ratios, among which the northern basalts are seen as having a big aspect ratio, as with the Toudao Basalts (Fig. 5). On the south flank of the Tianchi volcano a common depositional sequence can be seen as: grey basaltic brecciate lava-dark grey massive trachybasalt-vesicular basalt.

According to earlier reports, the Baishan Basalt at the Baishanlinchang（白山林场）, the place that rocks were first named as Baishan F, has a K-Ar age of 1.59 Ma. The Lingguangta Basalt is dated as being 1.66 Ma while the Tumenjiang Basalt has been dated as 1.6, 1.54 and 1.31 Ma (Liu et al. 1989: 31-41; Jin and Zhang 1994: 15-39; Liu 1999: 13-111) respectively. From a mapping project of the ages we get a generally younger set of ages than earlier publications; for instance, 1.28 and 1.39 Ma have recently been determined for the eruptions.

Xiaobaishan Trachyandecites-Trachytes (ιQ_1x)

This Trachyandecites-Trachytes Formation is distributed mainly on the southern Tianchi Trachyte Cone (or is separated from the Tianchi Cone as an earlier trachyte cone) with a thickness of about 300 m. There are also some distributions of this formation near the northern base of the Tianchi Cone. In a sequence of from the base to the top, the rocks can be listed as: dark grey trachyandesite -andetrachyte-dark grey or grey alkali-trachyte. A stone tower or stone forest shaped landscape is common (Photo 2).

The general features of andetrachytes are a dark grey color, porphyry texture and massive structures for the rock, while the matrix texture is trachytic. Phenocrystals are made up of sanidine, anorthoclase, plagioclase and hornblende. The sanidine phenocrystal is 1 % of content and has 1-1.5 mm length, and usually has a re-growing zonal texture after corrosion that contains remnant pyroxene inclusions. The 1-1.5 mm long plagioclase phenocrystal with a content of about 1 % often has a zonal texture around its multiple twins. Mini hornblende inclusions are common in the plagioclase host of the andesine species. Hornblende phenocrystals of 1-1.5 mm length have a content of 1 % and are sometimes altered to chlorite. The matrix of the andetrachytes consists of plagioclase, alkali feldspar, hornblende, biotite (chlorite alteration) and quartz. Accessory minerals are composed of magnetite, apatite and rutile.

The features of trachytes are the porphyric texture and massive grey colored structure. Their phenocrystals include alkali feldspar and pyroxene, but seldom olivine. The feldspar in platy has a 10 % content and is often in the shape of grating twin, and so can be classified into the isomicrocline of high temperature. Hedenbergite is the common species 0.3-1 mm long and is 1 % content of the pyroxene crystals. Olivine, with a grainsize of 0.3-0.5 mm and < 1 % content, is changed to ferri-iddingsite. The matrix is composed of oriented alkali feldspar, pyroxene, olivine, magnetite and some biotite and apatite.

The reported K-Ar age for the Xiaobaishan F. including the south flank (north of the Baishanlinchang) is 1 and 1.01 Ma, and the north flank (east of the Bingchang) 1.12 Ma. We recently obtained new data from the east flank of the Tianchi volcano, aging it as 0.81, 0.92 and 1.19 Ma.

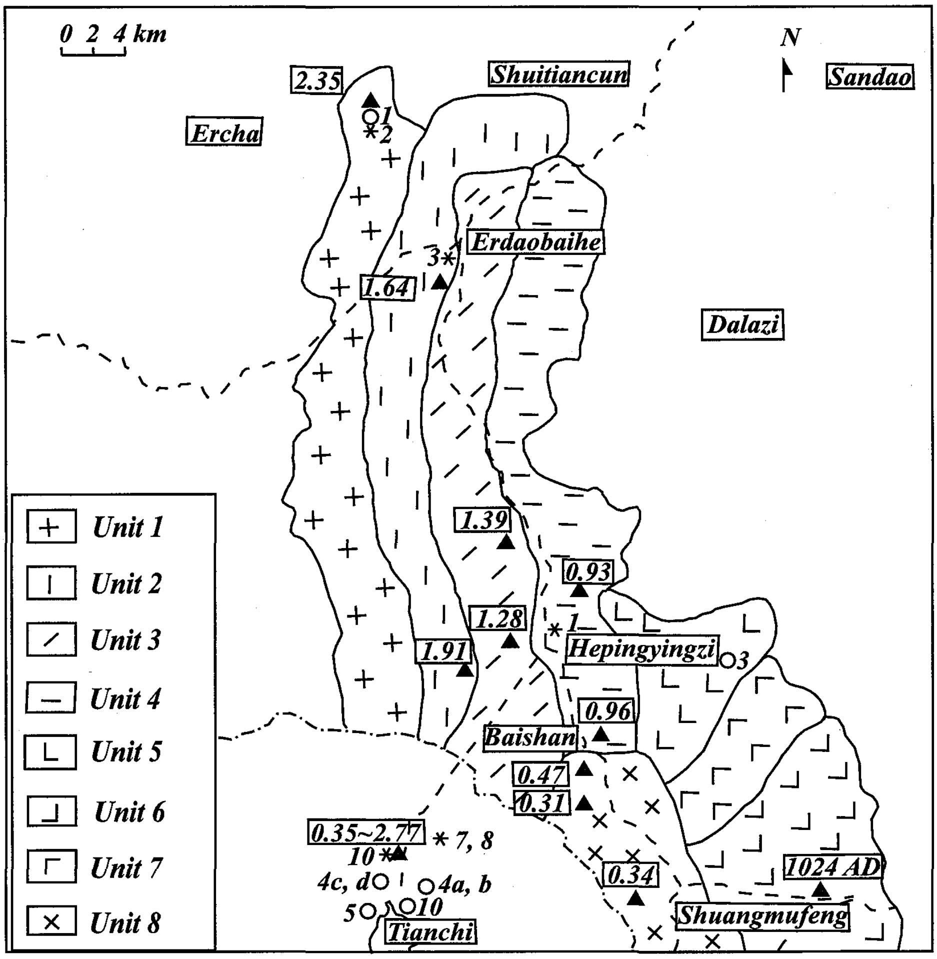

Fig. 5 Schematic distribution of the northeast lava flows of the Tianchi Volcano.

The flows vary in aspect ratios and flow distances. The dotted lines encircle the trachyte cone while the dashed lines trace the main road. Representative sampling sides and ages are marked with triangles and the numbers in Ma without specification. The locations of the representative figures and the photos used in the paper are marked with a star and a circle with labels.

Laofangzixiaoshan Basalts（$\beta Q_{1-2}l$）

These are basalts from the Laofangzixiaoshan F and distribute on the northeast, northwest and southwest sides of the Tianchi Lava Shield. The young lava flows, that generally flowed just a short distance, appear in a well preserved crust structure of lava flows (photo 3) but with no quarry or gulley to show its profile distribution. The basalts of the Laofangzixiaoshan F, originate from the Tianchi Volcano and make up some part of the surface of the Tianchi Shield on which quite a lot of scoria cones and flat craters are situated.

The basalts are dark grey in appearance and have a porphyric texture. The matrix consists of oriented plagioclase and other crystals, such as magnetite and apatite. The phenocrystals have 3 types of mineral compositions; plagioclase, pyroxene and olivine. The plagioclases species, grainsize 1-2.5 mm and 5 % by volume friction of the rock, are labradorite, sometimes with a multiple zonal texture and composition (Fig. 6). The pyroxene phenocrystals with 4 % of content often have cracks in their 1-2 mm crystals, while granular olivine has species between chrysolite and forsterite. The matrix is composed of oriented plagioclase and interstitial melaminerals such as magnetite and apatite.

The K-Ar ages for the Laofangzixiaoshan F are generally very young compared with the Toudao and Baishan Formations that make up the main part of the Tianchi Shield. The northeastern lava flows have K-Ar ages of 0.23, 0.31, 0.34, 0.35 and 0.47 Ma while the southwestern lavas are dated as 0.4 and 0.42 Ma, respectively. It is said that there are even younger K-Ar ages of 0.19 and 0.18 Ma on the eastern part of the Tianchi Shield (Liu et al. 1998: 19-27), though there also exist some old lava flows dated around 1 Ma.

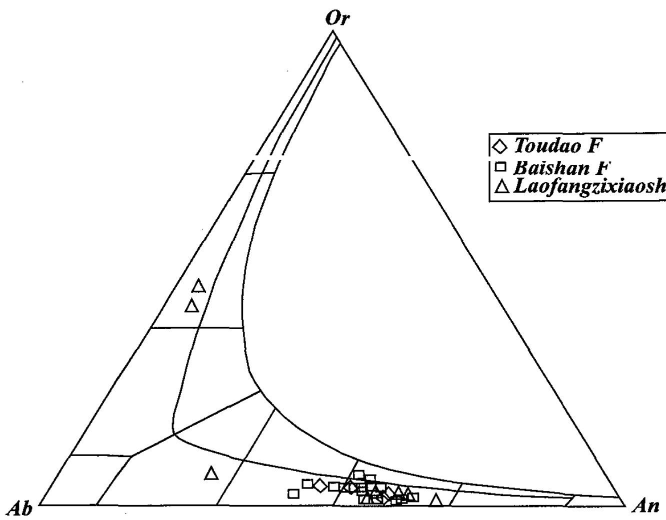

Fig. 6 Or-Ab-An plots of feldspar in shield-forming eruptions.

Feldspar phenocrystals in the Laofangzixianshan F vary a lot compared with the compositions in the Toudao and Baishan Formations.

Baitoushan Trachytes and Comendites（$\tau Q_{2-3}b$）

Ttrachytic and comenditic lavas of the Baitoushan Formation are situated around the Tianchi Caldera Lake, making a cone-shape landscape in the NW macro-axis nested on the Tianchi Basalt Shield. Erupted materials in this Baitoushan stage construct a strata cone with a largest thickness of about 600 m that was once called the Tianchi Composite Cone. The depositional sequence varies a lot at the different localities of the Tianchi Composite Cone (Photo 4) and is represented by the profile from the north flank of the Tianchi Composite Cone (Fig. 7). Generally it has a young sequence at the east part of the cone. Based on the palaeosoil strata and K-Ar dating of the rocks, the Baitoushan F has been grouped into 3 sections; Lower, Middle and Upper Members of the depositional sequence.

Lower Member: has a thickness of 207 m measured from the north flank profile. From the base to the top, the stratigraphic sequence is brown and grey trachyte-dark grey trachytic welded tuff

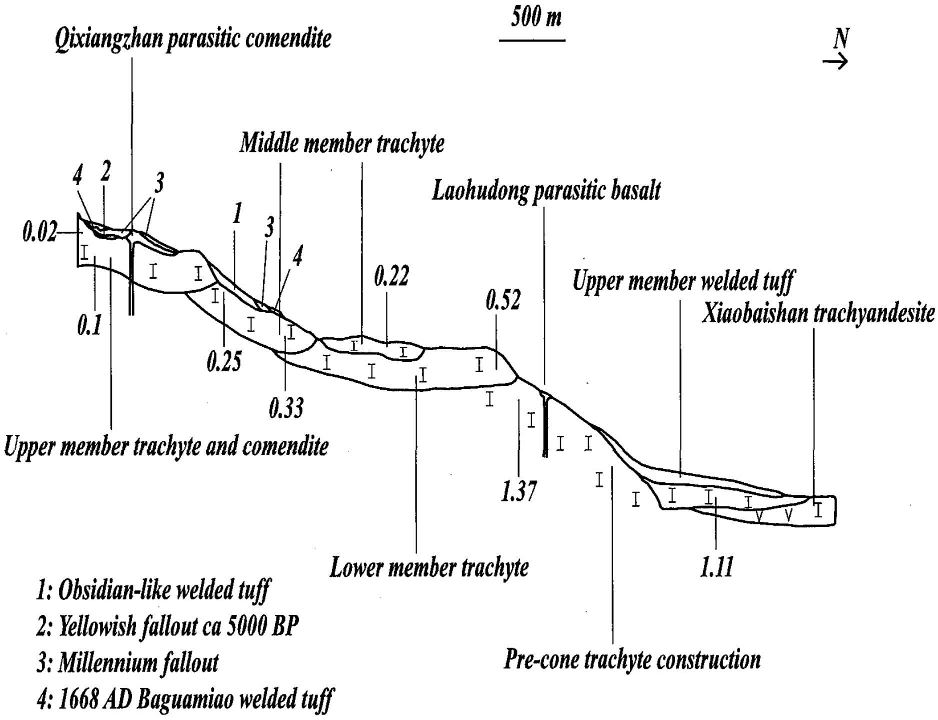

Fig. 7 The north flank sequence of the Tianchi Composite Cone construction (vertical scale double enlarged)
The lower member of the Tianchi cone nested on a pre-existing trachyte edifice dated as 1.37 Ma. The three typical stages of composite cone construction made the depositional sequence between 0.52 and 0.02 Ma (representative numbers listed). Some recent deposits (enlarged in scale) are marked by different numbers.

with breccias-brown and grey trachyte-dark grey trachytic welded tuff-grey and green alkali trachyte-dark grey trachyte-purple red trachyte-palaeosoil. The K-Ar ages for this strata unit vary from 0.53 to 0.61 Ma (Liu and Wang 1984: 229-232; Jin and Zhang 1994: 15-39).

Middle Member: has a thickness of 221 m and the sequence is from the base to the top: dark grey trachyte-dark grey alkali trachyte- purple red vesicular trachyte- palm palaeosoil. This member is much thicker in the northern inner wall of the caldera (profile at Tianwenfeng (天文峰)-Tianchi Lake) and reaches up to 490 m. There are at least 3 transitions between the pyroclastic rocks and the lavas. The strata sequence, from low to high order is: yellow, brown and various color trachytic breccias-dark grey and grayish green alkali trachyte-grayish green and grayish yellow tuff breccias-grayish green alkali trachyte-black green alkali trachyte- purple red palaeosoil. K-Ar dates for this member are between 0.44 and 0.25 Ma. The explosive intensity of this member was obviously an increase from that produced the plinian fallout fragmentation in the Sea of Japan, almost of the same area as the Millennium Eruption of the Tianchi Volcano. Parasitic basaltic volcanism developed at the time as this member, and is discussed further in the Laohudong (老虎洞) section.

Upper member: sequence thickness is 214 m and the sequence is: interbedded welded tuffs in colors of purple red and dark grey-yellow and brown trachyte and alkaline trachyte-dark grey obsidian-like welded tuff-dark grey trachyte with obsidian-like trachyte and comendite. The generally accepted time interval for this upper member of the cone sequence is between 0.22 and 0.1 Ma (Jin and Zhang 1994: 15-39; Liu 1999: 13-77). We obtained some young ages; 0.04 and 0.02 Ma, in which are consistent with the U-series dating of 23 ka from Dunlop (1996: 1-215). It is worth pointing out that detailed mapping work is needed to better understand the complicate composite-cone-construction.

Laohudong Basalts（$\beta Q_2 l$)

On the surface of the trachyte cone there exist many small parasitic basaltic scoria cones with less lava flows. The nested basaltic satellite volcanoes are represented by the Laohudong profile, and the equivalent shield-forming eruption makes up part of the Laofangzixiaoshan Basalts. The Laohudong scoria cone is about 100 m in height. The deposits are purple red basaltic scoria-dark grey olivine basalt-interbedded layers of purple red basaltic scoria and basaltic pumice.

The appearance of olivine trachybasalt is a dark grey color, a porphyric texture and massive structure with a granular matrix features. Plagioclase, olivine and pyroxene make up the phenocrystals. The platy plagioclase, of 5 % content, 0.5-1 mm long, An number of 63 and (+2V) =78°, sub-paralyzes with each other and sometimes matrix fills the cracks. The granular olivine phenocrystals, with content 1 %± and length 0.1-0.3 mm, commonly have a resorption texture preserved. Scarce augite, $Ng \wedge C$=43° and (+2V) =42°, is the pyroxene species. The matrix is composed of semi-parallel labradorite with interstitial minerals of pyroxene, olivine, magnetite and apatite. The normal mineral composition is represented by or=13.05 %, ab=29.95 %, an=18.42 %, ol=7.73 % and ne=13.05 %.

The K-Ar age measured at the lower Laohudong basalt is 0.34 Ma, with another age of 0.32 Ma measured near the Songjianghe（松江河）Hill. The Wutoufeng（无头峰）Basalts on the N Korean side of the Tianchi Volcano are equivalent to this Laohudong F.

The Holocene Trachytic and Comenditic Pyroclastic Rocks（τQ_4 or λQ_4）

Based on the existing chronological evidence in China, the Holocene volcanic strata of the Tianchi volcano are Bingchang F, Qixiangzhan F, Baiyunfeng F and Baguamiao F.

The Bingchang F, with welded pyroclastic rocks in magmatic compositions of trachyte and comendite, locates in the depressions of Bingchang, Gudisenlin（谷底森林）and Baishanqiao（白山桥）. A ^{14}C dating for the deposits of 3 to 5 thousands BP has been reported but is not a precise measurement (Jin and Zhang 1994: 15-39). The Qixiangzhan F is a typical clastogenic lava flow originating from satellite comenditic volcanism near the top of the Tianchi Cone. The lava flows down the slope shaped like a tongue or a snake with its greatest thickness being 60 m. The Baiyunfeng F is the stratigraphic unit for the comenditic plinian fallout and ignimbrite deposits are widely distributed on the surface of the Tianchi volcano. The maximum thickness of the fallout deposit on the caldera rim is over 100 m; also VPI (valley pond ignimbrite) thickens to about 100 m and has a wiggle-matching ^{14}C dating of 1024 AD 30 km east of the volcano. Most Japanese scientists note that the eruption took place in the 10 th Century (Taniguchi 2004: 5-54). The Baguamiao F is represented as a dark trachytic fallout, with ignimbrite deposits mantling the surface and thickening in the valleys (maximum thickness of 40 m±). The historical report shows eruptions from the Tianchi Volcano took place in 1668, 1702 and 1903 AD; discussed in detail in the next section.

Historically reported eruptions and the recent surface depositional sequence

There are many different historical records for eruptions from the Tianchi Volcano. Among the records there are three recorded eruptions that occurred in 1668, 1702 and 1903 AD from which some definite evidence is shown in the Tianchi Volcano (Cui et al. 1995: 36-39). Additional information, especially in Manchurian literature and legends, can be gleaned from clues of the Tianchi eruptions (Wei et al. 2001: 191-200). As a confirmation of the records for the Tianchi eruption, we found some erupted materials younger than the Millennium deposits around the caldera rim, in the depressions of the inner caldera wall, and outside the cone in the radial valleys, as listed in table 2.

Based on a literature study and a field survey of the deposits, we recognized three types of the erupted deposits to be related with the records of eruptions from the Tianchi Volcano. There was a record for volcanic eruption in 1668 AD. The eruption affected a wide area around Funing（富宁）and Jingcheng（镜城）in N Korea and was recorded in a government document (Lichaoshilu, 李朝实录, see Cui et al. 1995: 36-39). The relevant deposits might be represented by the dark grey trachytic ignimbrite inside the caldera. This dark ignimbrite is thickest on the northern caldera floor and is called the Baguamiao Formation. This deposit includes dark grey welded fallout on part of the caldera rim, a dark grey welded surge on the flank and dark grey ignimbrite and welded agglomerate deposits inside the radial valleys of the cone.

The talus deposits inside the Millennium caldera are often covered by this dark trachytic ignimbrite, as examples of the horse-toe shaped depressions of the Baiyunfeng, Wuhaojie（五号界）and Jiangjunfeng（将军峰）collapses (Photo 5). This implies that an avalanche took place after the Millennium Eruption but before the 1668 eruption. The 1668 dark ignimbrite was also covered by some fan-shaped and belt-shaped debris flows, implying that these debris flows happened later than

Stages	Episodes	Representative Deposits	Magnitude of Eruption			Surface Events Between Eruptions		
			Week	Middle	Strong	Debris Flow	Avalanche	Rock Fall
5	5	Near the banks of the Erdaobaihe and Tianwenfeng				★		
	4	Baiyunfeng				★		
	3 (1903 AD)	Phreatomagmatic deposits near the by and south edge of the lake	★					
	2	By the banks of the Chengchahe (乘槎河)				★		
	1 (1702 AD	Wuhaojie fallout		★				
4	5 (1668 AD)	Baguamiao ignimbrite near the north edge of the lake			★			
	4 (1668 AD)	Baguamiao dark fallout on the caldera rim			★			
	3	West of the Chengchahe and north of Baiyunfeng				★		
	2	Caldera wall rock fall					★	★
	1 (1413−1668 AD ?)	Light gray welded fallout northeast of the north caldera rim		★				
3	4	Lahars in valley and on the shield surface				★		
	3 (926 BP)	Brown, yellow and dark gray ignimbrites enriched carbons			★			
	2 (926 BP)	Light gray plinian pumice fallout			★			
	1	Avalanche near the base of the cone					★	
2	4	Distal block lava from Qixiangzhan		★				
	3	Intermediate comendite from Qixiangzhan		★				
	2	Proximal rheological ignimbrite from Qixiangzhan		★				
	1	Surges, block and ash flows from Qixiangzhan		★				
1	4 (3950±120 BP)	Lag breccia on the north flank of the cone			★			
	3	Purple ignimbrite on the Tianchi road			★			
	2	Colorful pumice fallout on the Tianchi road			★			
	1	Purple and gray ignimbrite near Bingchang			★	★		

Tab. 2 Holocene volcanic activity and the surface process at the Tianchi Volcano, after Wei et al. (2004: 790-794)
See Fig. 8 and the text for explanation.

1668 AD (Photo 6). Such a surface sequence can clearly be seen on the top area of the Tianchi volcano (Fig. 8).

The description at Funing and Jingcheng for the 1702 AD eruption of the Tianchi Volcano is hard to relate to a deposit around the volcano. Very limited outcrops on the caldera rim of fines of a comenditic vitric ash layer of light grey color may have been produced from the noted eruption. It is at Wuhaojie that one can see the two small satellite vents nested on the 1668 dark

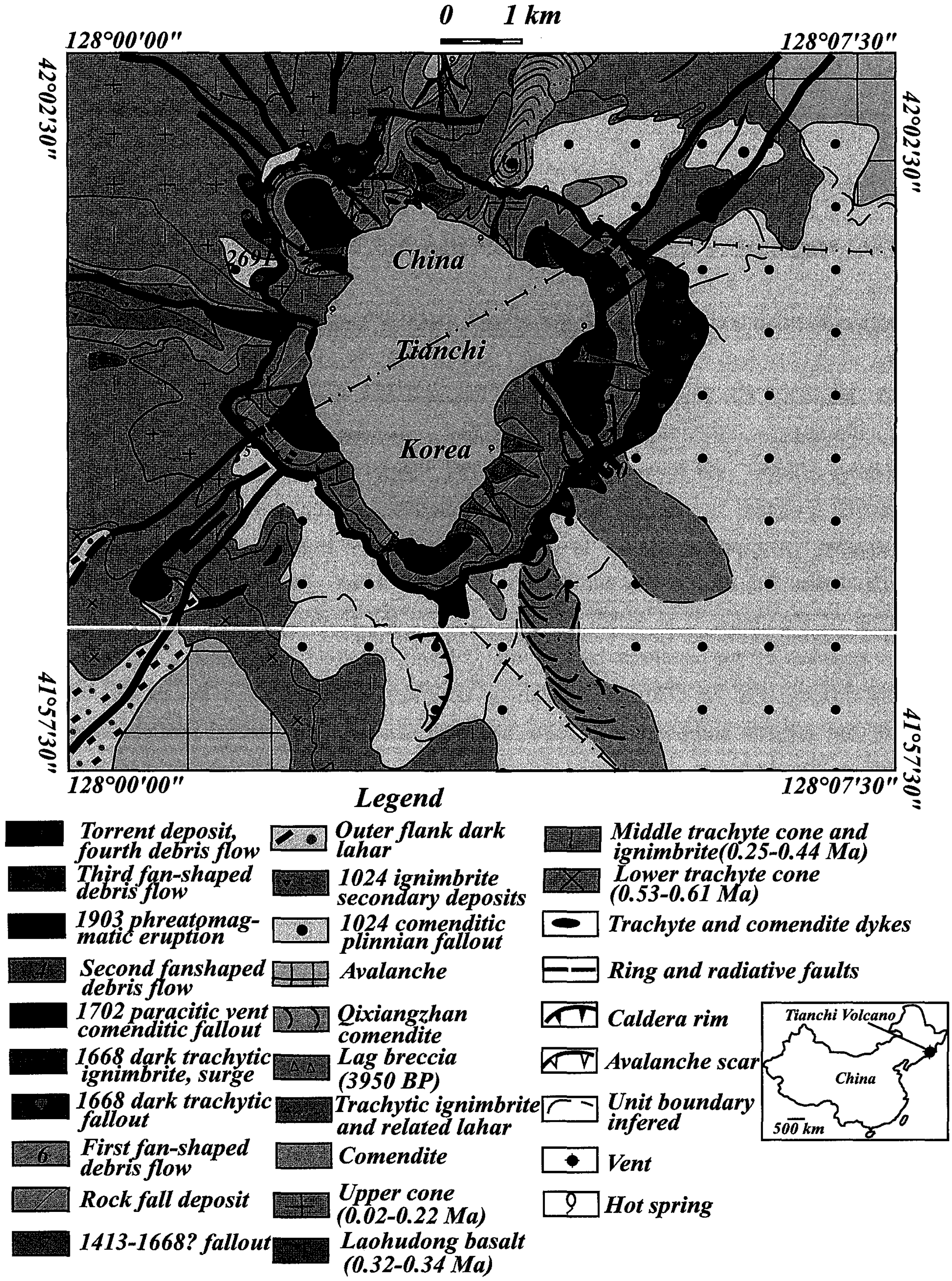

Fig. 8 Edifice texture on the top area of the Tianchi Volcano (modified from Wei et al. (2004: 790-794)

trachytic ignimbrite filling the floor of an avalanche scar. There may be another vent by the lake edge. These satellite vents and the fines of a comenditic vitric layer were formed later than the 1668 AD dark ignimbrite and we interpret them as 1702 AD products (see Fig 8). Additional places to look for a1702 AD fines vitric layer may be at the white bubble walls deposit at Sihaojie (四号界, Photo 7) and Liuhaojie (六号界, Photo 8).

A record of the 1903 AD eruption from the Tianchi volcano was written by Liu Jianfeng (刘建峰) in his survey collection entitled " Changbaishan Jianggangzhilue (长白山江岗志略, see Cui et al. 1995: 36-39) ". First, we interpret his record as a minor scale phreatomagmatic eruption from Tianchi Lake in 1903 AD. We found a 5 m thick phreatomagmatic deposit by the east edge of the Tianchi Lake (Photo 9). The 1903 AD layered pumiceous deposits interbedded with lithics rich layers cover the 1668 dark trachytic ignimbrite and show lots of evidence of interactions between magma and water (Liu et al. 1998: 49-82), which is consistent with the historical records.

Discussion: Magmatic cycles and their relationship with the strata sequence

In the Changbaishan area the Cenozoic volcanic field is located at an intersecting point of a NE Tumenjiang faults system (图们江断裂系统) and a NW Baishan-Jince faults system (白山金策断裂系统). Some of the biggest volcanoes in the area are there, such as Tianchi, Zhenfengshan (甄峰山), Wangtiane (望天鹅), Tudingzi (土顶子) and on the N Korea side, Baotaishan (胞胎山), LUfeng (绿峰) and Huangfeng (黄峰) (Ri, 1993: 330-349).

The Tianchi Volcano is one of the most completely evolved volcanoes in the Changbaishan area. Its magma composition shows systematic evolutionary trends as its volcanism varies over time, which makes for the co-relationship that exists between the cycles of the magma evolution and the units of the strata. It is worth pointing out that the magma evolutionary mechanism, based on sample analyses of the northern part of the volcano, exhibits a successive differentiation trend and magma mixing (Fig. 9). This mechanism is definitely different from the formal bi-modal distribution of the magma composition (Liu et al. 1998: 28-48). The formal model of magma composition has a gap between the basalt and trachyte or comendite during the evolution from the basalt shield to the trachyte cone and the ignimbrite sheet. However, there are multiple cycles of differentiation and a mixing or mingling process during the development of the Tianchi Volcano. As can be seen from the borehole samples at the Daewoo Hotel (大宇饭店), the magma composition during the basaltic shield-forming stage had developed trachyte facies about 2 Ma before the present one (Fig. 10). This is the oldest trachyte strata we've found in the Tianchi Volcano. Combined with the Xiaobaishan trachytic strata on the northern cone, this constitutes an important view of the multiple evolutionary mechanism of the Tianchi magma system.

We have grouped the magma evolutionary cycles at the Tianchi Volcano into three parts; that is, early, middle and late cycles. In the early cycle (Pliocene-early Pleistocene) magma evolved from trachybasalt to trachyte. Representative basaltic samples can be obtained from the high level basalt at the Yaoshui profile of the Toudao River, from the lower part of the basalts strata in the TVO borehole, and from the lower strata in the Daewoo Hotel borehole. Trachyte samples are obtained only from the Daewoo Hotel borehole, at present. The trachyte is aged at 2.14 Ma and coexists with the basalts and trachyandesites, all of an age of about 2 Ma. In the middle cycle (early

Fig. 9

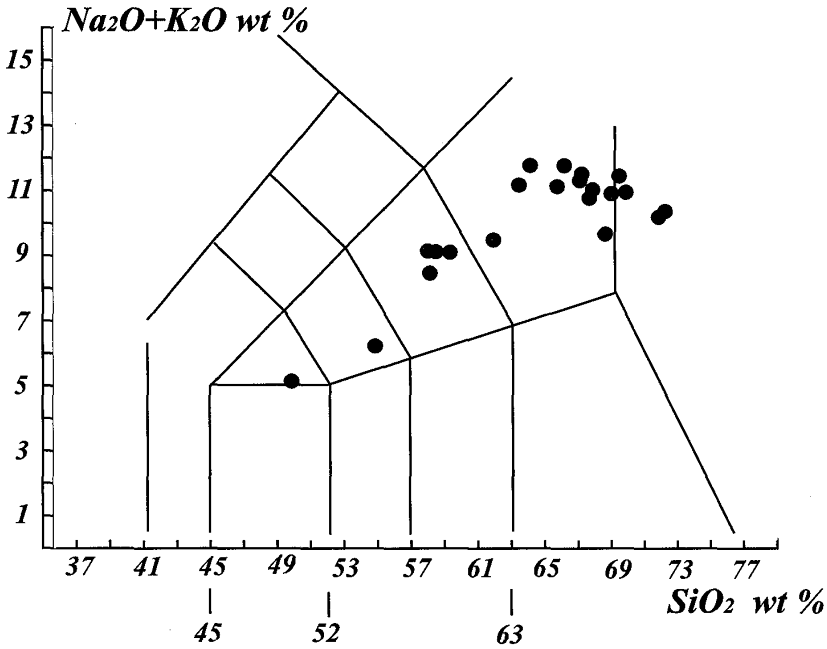

Fig. 9 Representative TAS plots of magma composition sampled from the northern part of the volcano

These differ from the early bi-model distribution of the magma composition from the Tianchi Volcano; the recent mapping research presented a continuing distribution of the magma composition. Two sets of two-end-members (with SiO_2 contents of between 49 and 65% and between 65 and 73%, respectively); the mixing processes can possibly be diagnosed according to the distributions.

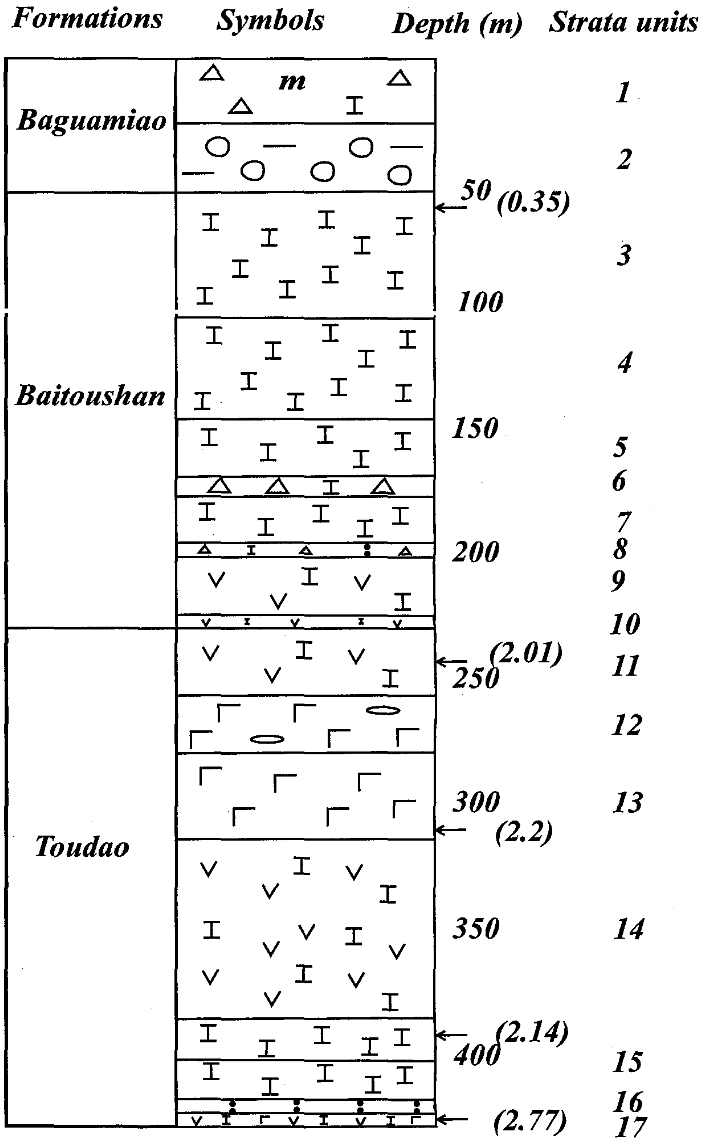

Fig.10 A borehole strata sequence from the Daewoo Hotel, in the north gulley of the Tianchi cone. The numbers in parentheses are the K-Ar ages of the rocks. The strata units between numbers 11 and 17 represent Toudao F, in which there are many trachytic deposits.

1:Welded trachytic breccias
2:Gravel deposit from debris flow
3:Trachyte
4:Trachyte
5:Trachyte
6:Trachytic breccia
7:Trachyte
8:Trachytic tuff with breccias
9:Massive trachyandesite
10:Grey and brown trachyandesite
11:Trachyandesite
12:Vesicular basalt
13:Basalt
14:Trachyandesite
15:Trachyte
16:Purple trachytic tuff
17:basaltic trachyandesite

Pleistocene) the basaltic magmas evolved to the trachytes and trachyandesites that made up the Xiaobaishan Formation. In N Korea the magma evolved further to produce alkaline rhyolites; based on descriptions from N Korean scientists (Ri 1993: 330-349). There are many different places to observe Xiaobaishan trachytes or trachyandesites. Besides the southern part of the Tianchi cone, one can find trachytic outcrops near Bingchang, Gudisenlin and Yuehualin (岳桦林) from the northern trachyte cone, and from the trachytes strata in the Shuangmufeng (双目峰) borehole in the eastern part of the trachyte cone. The late cycle (Pleistocene -Holocene) comprises the main edifice of the Tianchi stratovolcano. The basaltic magmas of the Laofangzixiaoshan Formation evolved to trachyte, even to comendite, of the Baitoushan Formation and others. The Baitoushan Period was the main episode for the construction of the Tianchi cone. Basaltic deposits, either the products of parasitic basaltic eruptions within the cone area intercalated with trachytes or Laofangzixiaoshan basalts out of the cone, were in a continuous state of eruption with trachytic magma. This constructed the land surface of the Tianchi Volcano as can be seen at present. However, in the Holocene the magmatic evolutionary trend had a distinct regime change from trachyte to comendite as well as from basalt to trachyte.

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Plate 1

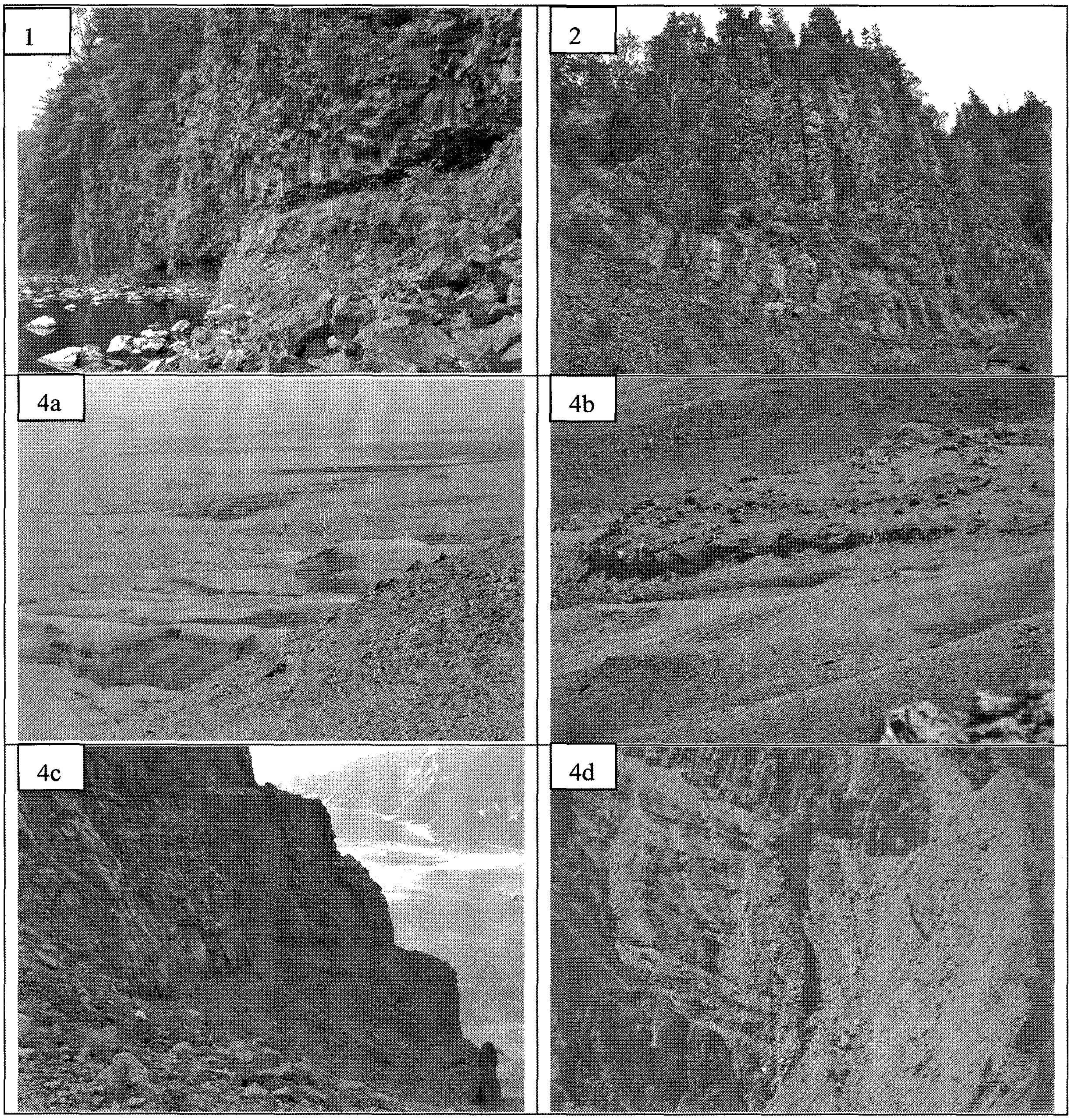

Plate 1 Outcrop photos numbered 1, 2 and 4

Photo. 1 Outcrop profile of the Toudao Basalt (Low elevated basalt)

The base of the Tianchi Basalt Shield is represented as overlain basalts) being the yellowish gravel layer (1.5 m thick). The multiple basalt flow units compound the cliff while gneiss is found beneath the water. See Fig. 2 and text for a detailed explanation.

Photo. 2 Landscape of the platy joint in a stone tower of the Xiaobaishan trachyandesite

The columnar joints and horizontal shearing joints cut the rock into the platy tower of stone.

Photo. 4 Depositional sequence of the Baitoushan F

a: The east flank of a composite cone showing the sharp highest part of the cone (0.19 Ma), the lower gentle part of the cone (0.38 Ma) and the underneath basaltic lava shield (covered with forest). b: A comenditic clastogenic lava flow from satellite volcanism (0.04 Ma) fills the valley in the eastern cone. c: Trachytic lava flows and pyroclastic rocks interbedded in the middle member of the Baitoushan F. d: Dyke intrusion along the ring faults intrudes into the volcanic sequences.

Plate 2

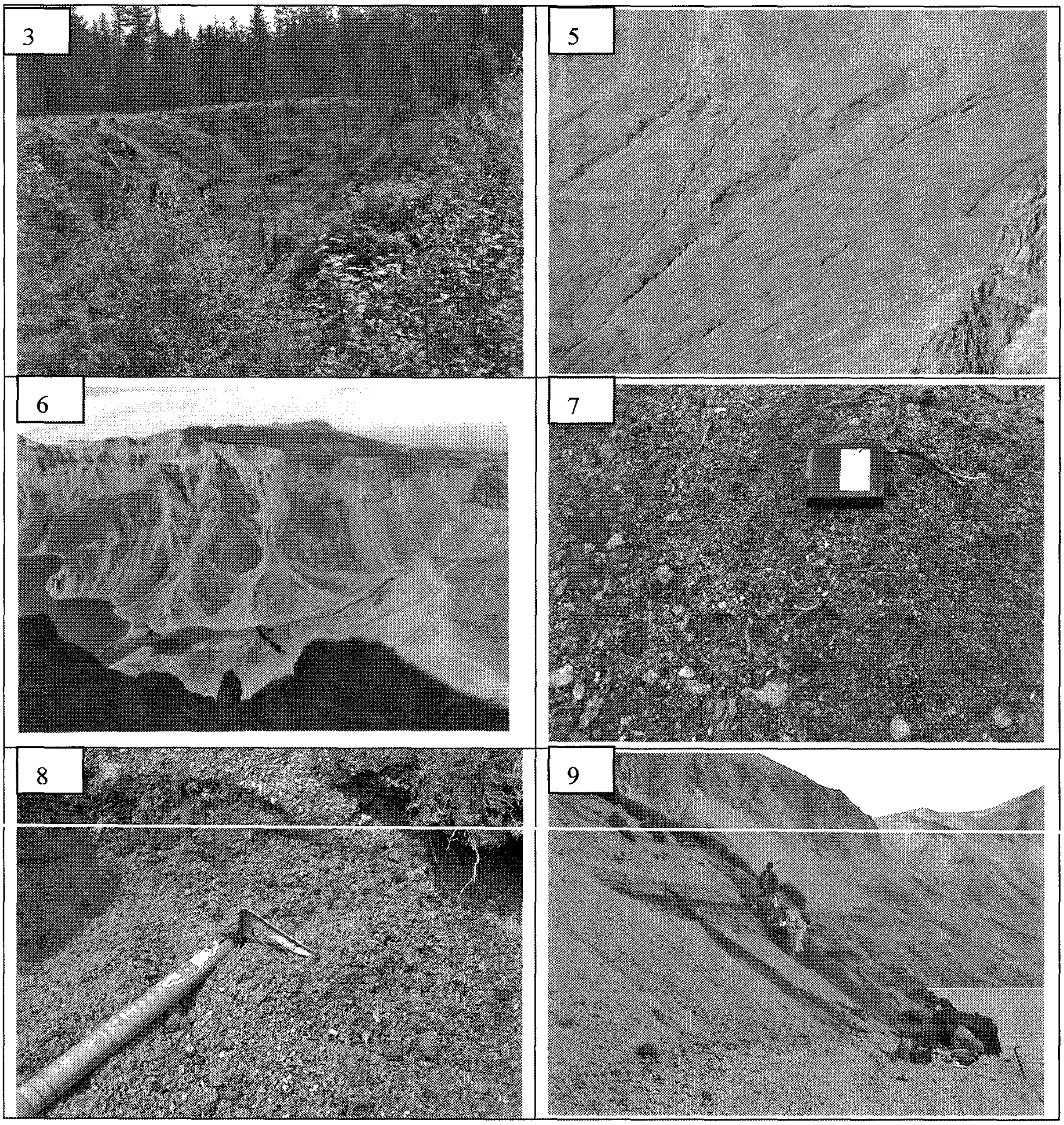

Plate 2 Outcrop photos numbered 3, 5, 6, 7, 8 and 9
Photo. 3 Surface flow features of the basaltic lava flow of the Laofangzixiaoshan F
Different flow units of basaltic flows show rough edge surface features

Photo. 5 Baiyunfeng avalanche scar filled with a 1668 dark trachytic deposit, which fills in the scar floor overlying the rock fall deposits.

Photo. 6 Different debris flows cover the 1668 deposit
The belt or fan-shaped debris flows formed after the 1668 eruption are shown.

Photo. 7 Fine white comendite pumice overlying a lag breccia near Sihaojie.

Photo. 8 White comendite pumice fallout layer near Liuhaojie.

Photo. 9 1903 AD tuff ring deposits by the Tianchi Lake; evidence of an explosive interaction between magma and the Tianchi Lake is shown.

Supplement

Chinese Spelling	Chinese	Former names or English meaning
Tianchi	天池	Sky Lake; Heaven Lake; Heavenly Lake
Changbaishan	长白山	Ever White Mountain; Long White Mountain
Naitoushan	奶头山	Teat-shape Hill
Toudao	头道	First drainage of the river
Baishan	白山	White Mountain
Xiaobaishan	小白山	Litter White Mountain
Laofangzixiaoshan	老房子小山	A Hill with an old house
Baitoushan	白头山	A Mountain with white top; Hakotusan
Bingchang	冰场	Skating Ground
Qixiangzhan	气象站	Weather Station
Baiyunfeng	白云峰	White Cloud Peak; Sogan
Baguamiao	八卦庙	Temple of the Eight Diagrams
Huangsongpu	黄松蒲	A village with yellowish pine tree
Changhongling	长虹岭	Rainbow mountain range
Jinjiang	锦江	Jinjiang River
Tumenzi	土门子	A gate of soil
Longdeli	龙德里	Longde village
Qinglinli	青林里	Qinglin village
Putianjun	普天郡	Putian Province
Datianping	大田坪	Datian Level Ground
Yunxingjun	云兴郡	Yunxing Province
Junjianshan	军舰山	Battle ship mountain
Yaoshui	药水	Medical Water
Toudaobaihe	头道白河	First drainage of the White Rivers
Gaoweixuanwuyan	高位玄武岩	High Elevated Basalt
TVO	天池火山观测站	Tianchi Volcano Observatory
Erdaozhen	二道镇	Erdao Town
Bailongshuidianzhan	白龙水电站	White Dragon Power Station
Maanshan	马鞍山	Saddle-shaped Mountain
Tumenjiang	图们江	Tumen River, Tu-man-gang
Yalujiang	鸭绿江	Yalu River; Aprok-gang; Amnok-gang, Yalu-gang
Lingguangta	灵光塔	Tower with spirit light
Baishanlinchang	白山林场	Forest Station at the White Mountain
Tianwenfeng	天文峰	Astronomy Peak; Hakugan
Laohudong	老虎洞	Tiger Cave
Songjianghe	松江河	Songjiang River
Wutoufeng	无头峰	Flat dome hard to see head
Gudisenlin	谷底森林	Forest Underneath the Ground

Baishanqiao	白山桥	Bridge of the White Mountain
Lichaoshilu	李朝实录	Historic Records of the Li Dynasty
Wuhaojie	五号界	Boundary Mark 5
Jiangjunfeng	将军峰	Peak named for General; Heishigan
Funing	富宁	Funing
Jingcheng	镜城	Jingcheng
Sihaojie	四号界	Boundary Mark 4
Liuhaojie	六号界	Boundary Mark 6
Liu Jianfeng	刘建峰	Jianfeng Liu
Changbaishan Jianggangzhilue	长白山 江岗志略	Concise records on the mountains and rivers in Changbaishan
Tumenjiang Duanliexitong	图们江断裂系统	Tumenjiang faults system
Baishanjince Duanliexitong	白山金策 断裂系统	Baishan—Jince faults system
Zhenfengshan	甄峰山	Peak of distinguish
Wangtiane	望天鹅	A mountain in shape of a swan looking at the Sky
Tudingzi	土顶子	A hill with top soil
Baotaishan	胞胎山	Mountain in shape of a fetus
Lüfeng	绿峰	Green Peak
Huangfeng	黄峰	Yellow Peak
Dayufandian	大宇饭店	Daewoo Hotel
Yuehualin	岳桦林	Yuehua Forest
Shuangmufeng	双目峰	Hills like the eyes
Xiangdaofeng	向导峰	Peak of the guider
Daping	大坪	Grand Level Ground
Beibaotaishan	北胞胎山	Northern Mountain in shape of a fetus
Beixueling	北雪岭	Northern Range of snow
Erdaobaihe	二道白河	Second drainage of the White Rivers
Chengchahe	乘槎河	A River connected to the Tianchi Lake and the head of the Songhuajiang
Songhuajiang	松花江	Songhua River, Sungri River

Supplement

Co-relationship between Chinese, Chinese spelling and English name or meaning of the different places common used for description of the Tianchi Volcano