Potential Hazards of Eruptions around the Tianchi Caldera Lake, China

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Abstract Since the eruption of the Tianchi volcano about 1000 years ago, there have been at least 3 to 5 eruptions of small to moderate size. In addition, hazardous avalanches, rock falls and debris flows have occurred during periods between eruptions. A future eruption of the Tianchi volcano is likely to involve explosive interaction between magma and the caldera lake. The volume of erupted magma is almost in a range of 0.1–0.5 km^3. Tephra fallout may damage agriculture in a large area near the volcano. If only 1% of the lake water were ejected during an eruption and then precipitated over an area of 200 km^2, the average rainfall would be 100 mm. Moreover, lahars are likely to occur as both tephra and water ejected from the caldera lake fall onto flanks of the volcano. Rocks avalanching into the caldera lake also would bring about grave hazards because seiches would be triggered and lake water with the volume equal to that of the landslide would spill out of the existing breach in the caldera and cause flooding downstream.

Key words: Tianchi volcano, eruption of small to moderate size, seiche, harzerd, NE China

1 Introduction

The Tianchi volcano, located on the border between China and North Korea, is particularly hazardous because of its history of violent explosive eruptions (Wei et al., 1997; Horn and Schmincke, 2000). One of the most destructive eruptions (VEI 7) from the Tianchi volcano about one thousand years ago is one of the largest eruptions on the Earth in the last millennium, called "the millennium eruption". The region surrounding the volcano is inhabited by large population, and is suitable for the development of forestry, agriculture and tourism. Detailed mapping of the top of the composite cone clearly disclosed such eruptive hazards of the Tianchi volcano (Fig. 1) (Wei, 2003). In addition, the existence of a large caldera lake poses a significant hazard even in the absence of eruptive activity.

Some previous investigators have addressed hazards caused by the Tianchi volcano, although not in much detail (Machida et al., 1990; Gill et al., 1992; Liu et al., 1998; Liu 1999; Wei et al., 2003). The most serious future hazards of the Tianchi volcano—comparable to the VEI-7 eruption of the millennium eruption in volume—would be caused by ignimbrites and lahars (Table 1). Ignimbrite and co-ignimbrite ashes would kill all living things up to about 60 km away from the volcano. Furthermore, the Tianchi volcano formed the headwaters of three rivers (Songhua River, Yalu River and Tumen River), and geologic evidence indicates that lahars travel hundreds of kilometers along these rivers (Wei et al., 1998). This paper focuses on hazards associated with the caldera lake.

2 Possible Consequences of Eruptions of the Caldera Lake

The VEI-7 millennium eruption resulted in a caldera with a diameter of about 5 km and an area of 20 km^2. The present caldera lake, known as Tianchi (meaning "lake of the heaven"), has a maximum depth of 373 m, an area of 8.8 km^2 and a volume of about 2 km^3. The caldera walls rise to a height of 560 m above the lake level. The lake drains into the Erdao River through a low point (elevation 2192 m) on the northern rim of the caldera.

The coming eruption of the Tianchi volcano as large as the VEI-7 event of the millennium eruption would probably displace the entire caldera lake and devastate a large area. Here we consider only small eruptions that would involve strong interactions between magma and lake water (although a flank eruption is also possible) rather than completely displace the lake. Wei et al. (2003) described a scenario of a moderate eruption (0.1–0.5 km^3 of magma) of the caldera lake. Such an eruption would take place in the next 100 years with a probability of about 10%. It would probably involve intense phreatomagmatic explosive activity, falling of ash over a large area, and production of lahars (Self and Sparks, 1978; Walker, 1981). If only 1% of the lake water were ejected during an eruption and subsequently precipitated over an area of 200 km^2, the average rainfall would be 100 mm. Moreover, lahars are

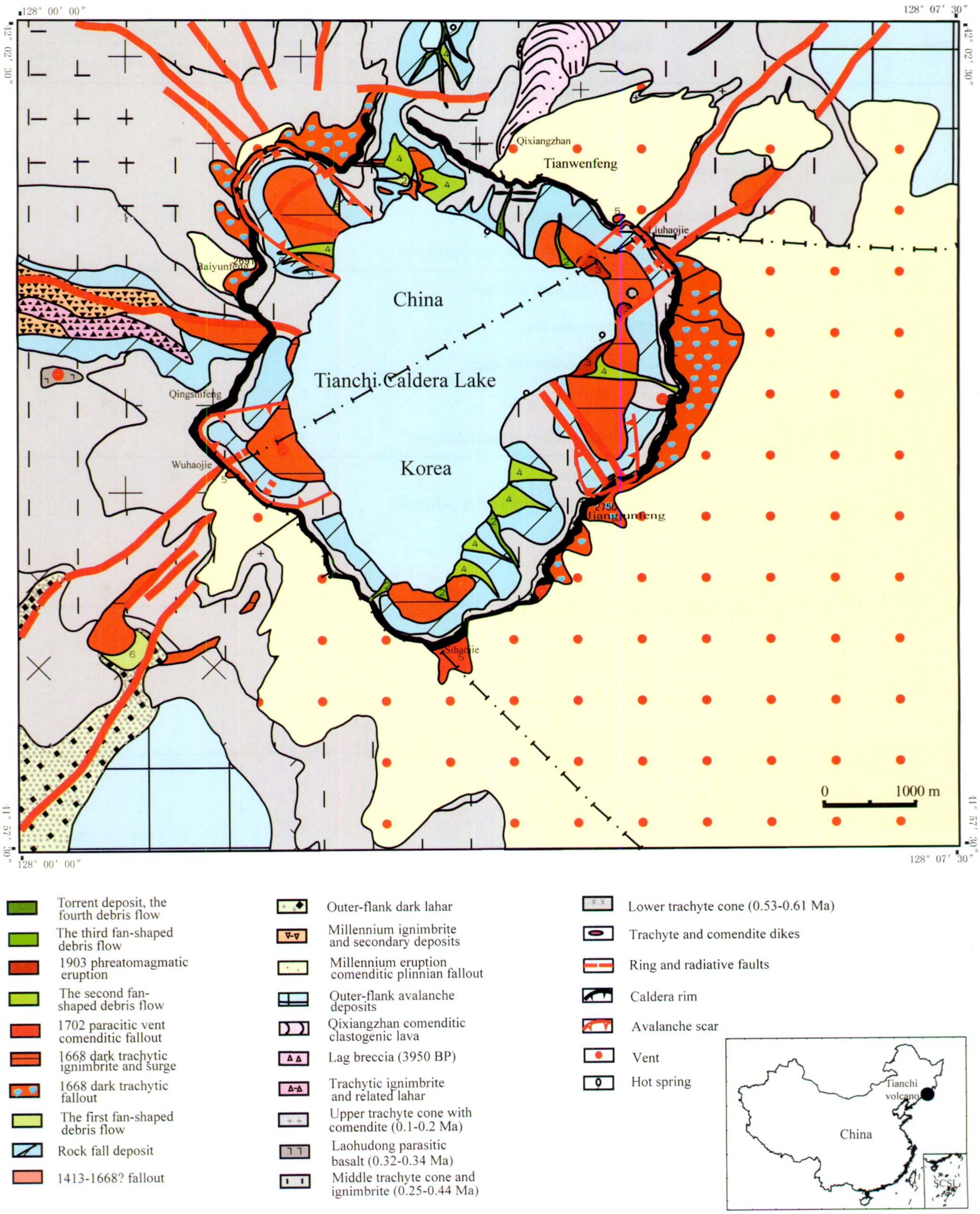

Fig. 1. Ediface texture and hazard distribution on the top of the Tianchi volcano.

Table 1 Holocene volcanic activities and surface processes in the Tianchi area

Stage	Episode	Representative terrain	Magnitude of eruption			Surface event between eruptions		
			Week	Medium	Strong	Debris flow	Avalanche	Rock fall
	5	Banks of the Erdao River and the Tianwenfeng peak (a visiting center for tour)				★		
	4	Baiyanfeng peak				★		
5	3 (1903 AD)	Phreatomagmatic deposits near the east and south parts of the lake	★					
	2	Banks of the Chengcha River (the north breach river)				★		
	1 (1702 AD)	Fallout in Wuhaojie (the boundary mark on the west caldera rim)		★				
	5 (1668 AD)	Baguamiao ignimbrite near th north bank of the lake			★			
	4 (1668 AD)	Baguamiao dark fallout on the caldera rim			★			
4	3	West of the Chengcha River and north of Baiyunfeng				★		
	2	Caldera wall rock fall					★	★
	1 (1413–1668 AD?)	Light gray welded fallout northeast of the northern caldera rim		★				
	4	Lahars in valleys and on the shield surface				★		
3	3 (926 BP)	Brown, yellow and dark gray ignimbrites enriched in carbon on the shield surface			★			
	2	Light gray pumice fallout			★			
	1	Avalanche near the base of the cone					★	
	4	Distal block lava from Qixiangzhan (Weather Station nests on a setalite vent)		★				
	3	Intermediate-source comendite from Qixiangzhan		★				
2	2	Proximal rheological ignimbrite from Qixiangzhan		★				
	1	Surges, block and ash flows from Qixiangzhan		★				
	4 (3950±120 BP)	Lag breccia on the north flank of the cone			★			
	3	Purple ignimbrite around the Tianchi Road			★			
1	2	Colorful pumice fallout around the Tianchi Road			★			
	1	Purple and gray ignimbrite near Bingchang (the middle part of the Changbai canyon)			★	★		

likely to occur as both tephra and water ejected from the caldera lake fall onto the flanks of the volcano.

3 Flood Hazards of Rocks Avalanching into Tianchi

Conical collapse is a common event in stratovolcanoes. In the Tianchi volcano, such collapse may be directed into the caldera and thus into the lake. Table 2 lists the characteristics of three sliding masses that have apparently collapsed into Tianchi during approximately 1000 years since the caldera was formed, as well as expected characteristics of the mass that may collapse into Tianchi in the future. The remnant Jiangjunfeng ridge is very sensitive to future collapse because of unstable and sharp cliffs. Avalanche into the caldera lake would induce seiche, and the water displaced by the avalanche may escape through breaches in the north wall of the caldera and cause a flood into the Erdao River, which is a tributary of the Songhua River.

The instantaneous discharge through the breach can be given approximately by the simple hydraulic relation:

$$Q(t) = cg^{1/2}h^{5/2}(t),$$

where c depends on breach geometry but is always close to 1, g is the acceleration of gravity, and h is the water level relative to the initial water level (before the avalanche). In

Table 2 Geometry of caldera avalanches

Locality	Avalanches in the past			Possible avalanche in the future
	Baiyunfeng	Wuhaojie	Jiangjunfeng	Remnant Jiangjunfeng ridge
Distance to lake surface (m)	1250	800	1300	1300
Slope above the lake	0.28	0.18	0.07	0.09
Width of entrance (m)	225	150	360	360
Cliff height (m)	60	100	200	Collapse in future
Cliff width (m)	100	200	130	Collapse in future
Cliff length (m)	500	750	500	Collapse in future
Volume (km^3)	0.2	0.06	0.15	0.14
Height above the lake (m)	440	310	560	560

detail, the flood hydrograph of the breach is probably quite complex with many peaks and troughs due to sloshing movements associated with the seiche. In other words, water would probably escape from the caldera as a series of pulses. Detailed simulation of the flood hydrograph of the breach involves modeling of the seiche within the caldera and the runup of waves against caldera walls. This would be a complicated exercise requiring detailed knowledge of the bathymetry. Regardless of the details, however, the total volume of the displaced water would be sent out through the breach. Each flood pulse tends to spread out when propagating downstream and the pulses tend to merge when they are far away from the caldera.

The sliding mass on the northern side of the Baiyunfeng peak is a case history of an avalanche event with a volume of 0.3 km^3 (the Baiyunfeng peak is the highest point on China's side of the volcano). The displaced water would raise lake level by an average of about 33 m. Substituting this value for h in the equation given above, the discharge at the breach is about 2×10^4 m^3/s.

Avalanche-generated floods along the Erdao River would be especially hazardous in the Changbai canyon (two kilometers north of the lake). Structures valued at about 20 million US dollars on the banks of the river are at risk, including the main building of the Tianchi Volcano Observatory.

4 Conclusions

The Tianchi volcano is of a highest risk in China. The magma volume of the next eruption might be in a range of 0.1–0.5 km^3. Pyroclastic surge deposits are distributed about 5 km from the center when uprising magma reaches the caldera water. An ash fallout layer could destroy or affect agriculture on an area of thousands of square kilometers, while the ash layer on the volcano slope would be transformed into lahar.

Besides direct hazards related to explosive eruption, there exists a tremendous hazard deduced from the caldera lake—waving flood from the Tianchi volcano. It may result in an unendurable flood on the banks of the Erdao River, as well as lahar along the main drainages, as long as hundreds of kilometers, around the Tianchi volcano. A seiche trigged by huge avalanche within the caldera lake would raise the lake surface by 30 m, causing a serous flood and lahar disaster along the Erdao River.

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