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The earthquake-triggered rock avalanche of Cui Hua, Qin Ling Mountains, P. R. of China—the benefits of a lake-damming prehistoric natural disaster

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Abstract

This paper deals with an investigation of Cui Hua rock avalanche, in the Qin Ling Mountains, in the Dong Cha valley, an eastern branch of Taiyi River, some 30 km south of Xi'an, Province of Shaanxi, P. R. of China. The landslide originated on lithotectonic structures along seismic active fault systems. Its occurrence could be correlated with an earthquake in 780 BC that must have triggered the landslide. Due to a stabilizing human input the landslide area in front of the dammed Tianchi Lake became an area of settlement for native people of this area, which used this rapidly geomorphologic changing system for their needs over the past 2780 years. Nowadays the lake is considered to be a reservoir for drinking water, agriculture and a hydropower plant. Even more the deposit of the Cui Hua rock avalanche has become a touristic place for sightseeing and vacation. © 2002 Published by Elsevier Science Ltd.

1. Geotectonics of the Qin Ling Mountains and the position of the rock avalanche

The Qin Ling Mountains are interpreted to be an orogenic belt of the collision type (Huang, 1978; Mattauer et al., 1985; Yang et al. 1986; Hsu et al., 1987) and are built of four tectonic units, which are exposed from north to south as the Precambrian basement, which is covered by the Sinian and Paleozoic North China facies; the Metamorphic complex with ophiolitic blocks; Flysch nappes; and the folded Paleozoic and Triassic strata of the Yangtze facies. The structures of Qin Ling, formed by a collision of the South Chinese Yangtze Block while thrusting under North China, were created during the early Mesozoic Orogeny. The Precambrian basement acted as an overthrust complex similar to the Austroalpine Nappes. The metamorphic unit is comparable to the Penninic Nappes, whereas the Flysch nappes are equivalent to Prealpine Flysch. The belt of the foreland has a tectonic role equivalent to the Helvetic Nappes of the Alps. After the Triassic intercontinental collision, Mesozoic granites were formed by partial melting of the underthrust crust. The Cui Hua rock avalanche is situated within these Mesozoic granites (Figs. 1 and 2).

2. Seismic activity in Shaanxi Province and rock avalanches around Xi'an

Due to intercontinental tectonic activity triggered by the south–north-movement of the Indian Subcontinent under the Himalayas, the central part of China is one of the most affected areas by earthquakes (Fig. 2). Nineteen earthquakes with a magnitude >5 have been registered around Xi'an, seriously affecting the central part of the Shaanxi Province, even as far as the city of Baoji, which is situated in the area of a seismic active neotectonic structure. The Qin Ling Mountains in the south as well as the Bei Shan Mountains in the north are two east–west-striking structural units, which symmetrically form the tectonic frame of the basin of the river Weihe with the city of Xi'an. Neotectonic structures within the basin have been generated and activated by young and recent earthquakes (Table 1). The first historically registered earthquake occurred in 1189 BC

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in the Qi Shan Mountains. Another famous one, which affected not only the Qi Shan but also the Cui Hua Mountains, followed in 780 BC. In these mountains, this earthquake triggered three rock avalanches, creating one of only three avalanche-dammed lakes in China. In 1072 AD another earthquake followed triggering the rock avalanche of We Hua Se in the Hua Shan Mountains (about 100 km northeast of Xi'an, close to Weinan) with a dimension of 6 km. The most devastating earthquake with a magnitude of 8, that of Hua County, followed in 1556 AD. It claimed 830,000 victims and triggered several landslides and geomorphologic changes in its epicentre.

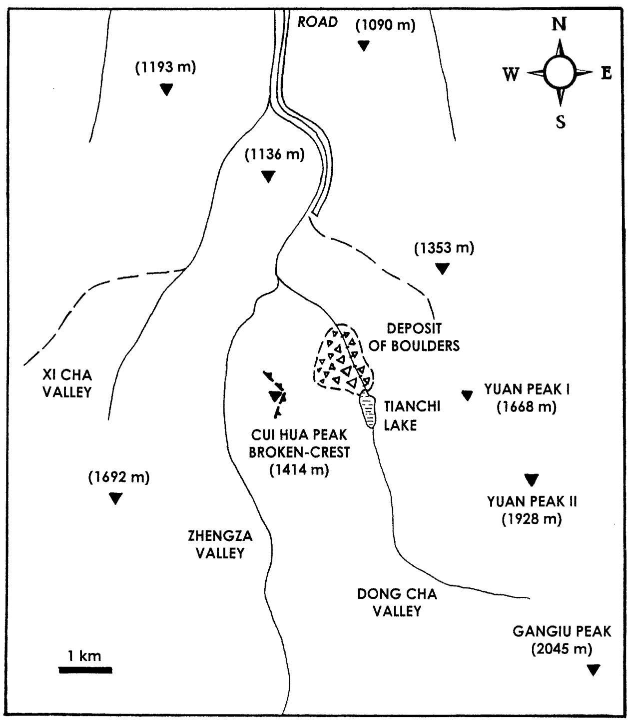

Fig. 1. Sketch map of the Cui Hua rock avalanche and the surrounding areas.

3. Two rock avalanches in the Cui Hua Mountains and their dammed lake(s)

In the Cui Hua Mountains, two deposition areas of rock avalanches are obvious, which are divided by a fault west of Tianchi Lake. The upper, the Liu Dshe Tse rock avalanche, is situated about 5 km south of Tianchi Lake. Although this dam has almost double the height (more than 500 m) of the lower one, there has never existed a lake in the hinterland, because of tectonic structures on the bottom area. The lower one, which is composed of the material of two or three avalanches, has dammed Tianchi Lake. On reaching the barrier of the natural dam, the blocky stream of boulders starts at an elevation of about 800 m (Fig. 3) and ends at 1100 m altitude. From the top, blocks fill the space towards the west like a giant fan up to the broken-crest-area, which originates at Cui Hua Peak (Fig. 4). The material of the rock avalanche covers an area of more than 1 km^2. The direction of movement was towards the northeast. The dammed Tianchi Lake has an average volume of 3 000 000 m^3, and covers an area of 0.5 km^2, whereas its depth normally varies between 8 and 12 m, reaching 20 m during the rainy season from July to August. Despite the fact that the bottom of this lake is cut by tectonical

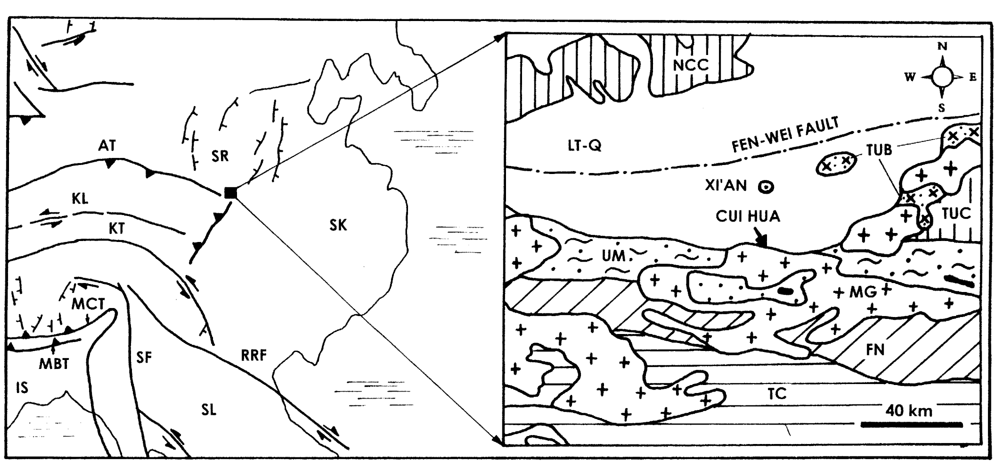

Fig. 2. Geotectonic position and modern setting (after Tapponnier et al., 1986) of the study area (2A) and Geology of the Qin Ling Mountains and the Cui Hua rock avalanche (2B). 2A: IS—Indian Subcontinent, SK—South China craton, SL—Sundaland, MCT—Main Central Thrust and MBT—Main Boundary Thrust (Himalayas), SF—Sagaing-Fault, RRF—Red-River-Fault, KT—Kang Ting, KL—Kun Lun, AT—Altyn Tagh, SR—Shaanxi Riftsystem. 2B: LT-Q—Late Triassic and Quaternary, NCC—Cover of North China, TUC—Cover of Taihua Unit, TUB—Basement of Taihua Unit, UM—Melange and Ultramafics, suture zone of the collision, FN—Flysch Nappe, TC—Thrust Cover, MG—Mesozoic Granites (after Hsu et al., 1987).

Table 1
Selected list of earthquakes in the Shaanxi Province of China from 1831 BC to 1969 (after scientific press of China, 1983)

Date (Y/M/D)	Latitude (deg)	Longitude (deg)	Ms	I	Site
780 BC	34.5	107.8	(6–7)	(6)	Qishan
35 07 11 BC	34.4	109.0	(5)	(7)	Lantian
600 12 13	34.3	108.9	(5,5)	(8)	Xi'an
788 03 08	32.5	109.4	(6,5)	(7–8)	Ankong
793 05 27	34.5	109.7	(6)	(6)	Weinan
835 04 11	34.3	108.9	(4,75)	(6)	Xi'an
836 02 25	34.3	108.9	(4,75)	(6)	Xi'an
879 03 –	34.2	109.3	(4,75)	(6)	Lantian
880 02 –	34.5	107.8	(4,75)	(6)	Qishan
1307 – –	34.5	107.8	(5)	(6–7)	Qishan
1448 09 30	38.3	109.8	(5)	(8)	Yu Lian
1487 08 10	34.4	108.9	(6,25)	(9)	Lientong
1501 01 19	34.8	110.1	(7)	(6)	Chao Yi
1502 01 17	34.8	110.1	(5)	(7)	Chao Yi
1506 03 19	35.3	110.1	(5,25)	(11)	Heyang
1556 01 23	34.5	109.7	(8)	(7)	Hua County
1558 11 21	34.5	109.7	(5,5)	(6)	Hua County
1568 01 –	34.2	109.3	(5)	(7)	Lantian
1568 04 –	34.4	109.2	(5,5)	(6)	Ling Tong
1568 04 12	33.1	107.0	(5)	(9)	Hanzhong
1568 05 15	34.4	109.0	(6,75)	(6)	Xi'an
1569 – –	32.7	109.0	(5)	(6)	Ankong
1569 – –	34.6	110.3	(5)	(6)	Tongguan
1591 – –	36.6	110.0	(5)	(6)	Yanchang
1599 – –	35.6	109.2	(5)	(6)	Huangling
1621 – –	39.1	110.9	(5)	(6)	Fugu
1624 10 –	33.2	107.5	(5,5)	(7)	Yang County
1635 10 –	33.2	107.5	(5,5)	(7)	Yang County
1636 – –	33.1	107.0	(5,5)	(7)	Hanzhong
1636 – –	36.8	108.8	(4,75)	(6)	Zhidan
1681 – –	35.8	109.4	(5,5)	(7)	Luachuan
1704 09 28	34.9	106.8	(6)	(7–8)	Lung County
1789 11 07	34.6	110.3	(5)	(6)	Tongguan
1823 08 –	32.5	107.9	(5)	(6)	Zhengba
Data are missing					
1921 10 07	36.0	110.1	(5)	(6)	Yichuan
1957 01 30	33.9	109.8	(4)	—	Shang County
1959 08 11	35.6	110.9	5,4	(6–7)	Hanchen
1959 09 28	33.0	109.3	5	—	Xun Yang
1964 06 15	33.3	110.8	(4)	—	Shang County
1965 09 14	35.1	106.9	4	—	Lang County
1967 08 20	32.7	106.8	4,8	(6)	Nanzhen

structures, it is tight enough to keep the water in its basin.

4. Mechanics of the rock avalanche and composition of the deposits

The barrier damming Tianchi Lake is composed of three rock avalanches which originated not only at the Cui Hua Peak but also from the other, northeastern flank of the valley. As these avalanches are of the same age it is postulated that the disaster occurred in three temporary phases rather than resulting from rejuvenation of older events. From a mechanical point of view, the Cui Hua rock avalanche is not a real landslide but rather an in situ collapse of a mountain crest that led to a giant blocky stream of rocks with boulders with diameters up to 70 m, which rolled and bounced only for a relatively short distance of about 1 km from southwest to northeast towards and down the valley of Dong Cha. The total volume of all three deposits, which formed a barrier damming Tianchi Lake, is about 350 million m^3, enough material to keep the dam stable, even if the impounded lake should be filled during an extraordinary flood event. The upper surface of Cui Hua rock avalanche exhibits huge blocks and boulders. The largest boulders, west of the village on top of the deposit, reach dimensions of 60–70 m in diameter

(Fig. 5). The further the blocks were transported down the valley, the smaller are the boulders. This phenomenon is called in chinese “Tang Ta Le She”.

5. Preparatory causal factors of the rock avalanche(s)

For a mountain collapse such as this, preexisting tectonic structures, which degrade to substantial horizons of weakness within a normally compact and rigidly reacting crystalline material, are the main preparatory causal factors of the event. From this point of view, the Cui Hua rock avalanche is no exception, despite the fact that geomorphologic features and climatic conditions play an important role. Investigations focusing on the first topic have shown that the area belongs to a tectonized zone within granitic to granodioritic plutonic rocks with very complicated internal structure. Lithotectonic studies along the main valley and on the broken crest of the mountain revealed tectonized horizons with a thickness of up to 10 m as well as fault planes with oriented striations in changing lithologies with different intensities of weathering. The remaining Cui Hua Peak (1414 m a.s.l.) is also seriously damaged by joint release sets (Figs. 6 and 7) and is therefore still acting as a potential mountain hazard for rock avalanches.

Fig. 3. View from the pathway towards SSE, to the 300 m high (from around 800 to 1100 m of elevation) barrier of Cui Hua rock avalanche (RB).

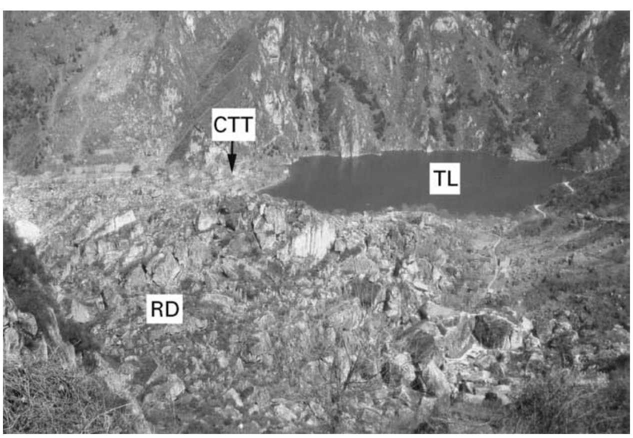

Fig. 4. View from the pathway up to the broken crest (Cui Hua Peak, 1414 m) of the rock avalanche towards the east, to the bulk of the deposit of the rock avalanche (RD), the dammed Tianchi Lake (TL) and the village Chui Tsho Tshe (CTT) behind the bulk of the deposit.

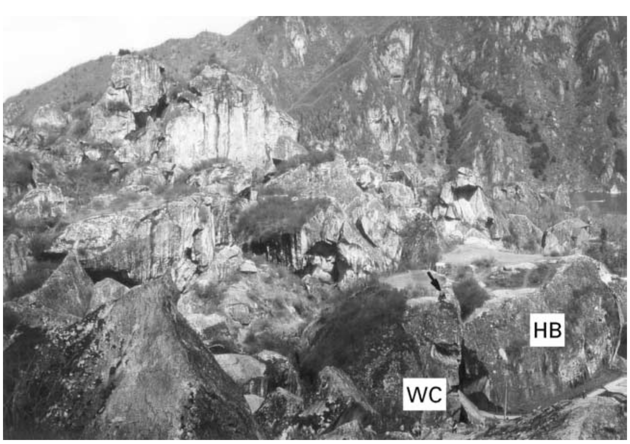

Fig. 5. The centre of the area of largest boulders of the Cui Hua rock avalanche. The total diameter of the largest boulder (HB), which is broken into two pieces (a pathway with the name “wind cave”—WC—leads through it) in the lower right corner is more than 70 m (two people are sitting on it, see arrow). It is uncertain whether it was just by chance during avalanching that these two pieces fit together like one.

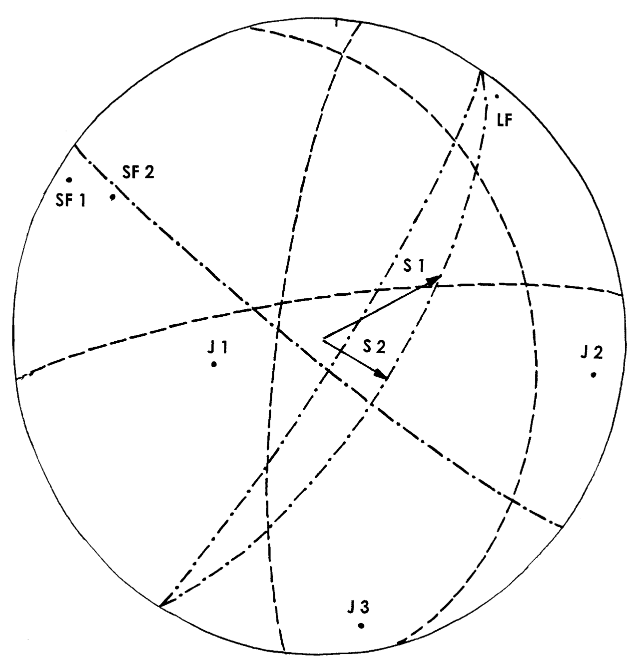

Fig. 6. Stereographic representation of data (polepoints and cirques, lower hemisphere) of tectonic and neotectonic structures at the Cui Hua Peak, the broken crest area of Cui Hua rock avalanche: LF—“lake-fault”, a branch of the Qin Ling-Eastfault; SF 1 and SF 2—“summit fault 1 and 2”; S1 and S2—striations on SF2; J1, J2, J3—three different sets of joints.

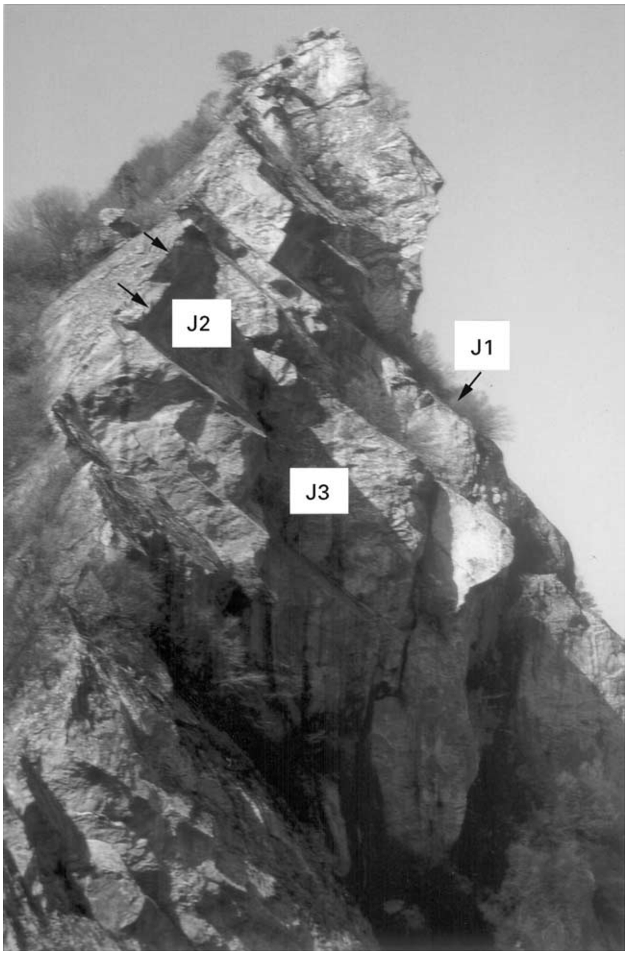

Fig. 7. The shape of the broken crest area of the rock avalanche, the Cui Hua Peak (1414 m), is formed by three major faults, "summit-fault 1 and 2" and "lake-fault". Furthermore, the summit is cut and divided through by three differently oriented sets of joints (J1, J2, J3).

5.1. Geomorphology of the northern Qin Ling Mountains and of the area of the rock avalanche

About 23 km south of Xi'an (Fig. 1) the Taiyi River, a tributary of the Weihe River, is formed by the confluence of three branches of tributary rivers coming from a western valley (Xi Cha), from the north–south-striking central valley (Zhengza) and from the south-east–northwest-striking eastern valley (Dong Cha). The latter is surrounded in the west to southwest by the ridge of Cui Hua Peak (1414 m), in the northeast by the Yuan Peaks (1668, 1928 m) and in the south by the Gangiu Peak (2045 m). All belong to the Cui Hua Mountains, with average elevations of around 1000–2000 m, a part of the Qin Ling Range. In the north of this range most of the valleys have V-shapes. As the Dong Cha valley has the same, very deep eroded habit, extreme under-cutting and oversteepening of the flanks of the valley produced the unequal weight. The collapsed eastern flank of the Cui Hua Peak must have reached a dip of more than 80° before the disastrous event (Ibetsberger and Weidinger, 1997).

5.2. Local geotectonics of the Cui Hua Mountains

The whole area of the Cui Hua rock avalanche with its complex structure has been highly tectonized for the past 100 million years. One of the main faults is the Qin Ling-Eastfault. A branch of this main structure, the "lake fault", strikes from southeast to northwest (Fig. 6), and the fault-plane itself can be seen on the orographic right side of the valley Dong Cha, downwards of the deposit of the rock avalanche. Along this fault an artificial channel, built by the local people, brings water from Tianchi Lake to an artificial waterfall. Further up the valley, this outcropping fault (N55°W/85°SW–N41°W/85°SW) borders the eastern (orographic right) side of Tianchi Lake ("lake fault") at an altitude of 1010 m, partly forming a channel within the landslide material that might have been the runoff or outbreak-channel of the lake water, before the artificial stabilization.

5.3. Lithology of the broken-crest-area at the Cui Hua Peak

Lithologically, the broken crest area is composed of plutonic rocks with migmatitic layers and aplitic dikes. These intrusive rocks were either generated during the tectonic phase of Y'ngsan or during the phase of Y'ngsi. Due to their rigid reaction, aplitic dikes play an important role as destabilizing effects on mountain flanks in general (Weidinger et al., 1996). Near the area of the summit of the Cui Hua Peak fine grained migmatites with coarse-grained granitic intrusions in between crop out. These granites are highly weathered along a structure, the "summit fault 1", at an altitude of 1400 m.

5.4. Structures within the Cui Hua Peak and the shape of the broken-crest-area

In the summit area of Cui Hua Peak, the broken crest of the rock avalanche, two local faults, "summit fault 1" (N30°E/85°SE) with a thickness of up to 10 m and "summit fault 2" (N30°E/70°SE) are striking through, dividing the summit of the mountain into two crests. That is why in between these crests an V-shaped open megajoint is exposed (Fig. 6). On the planes of the second-mentioned fault, striations oriented at N60°E/50°NE and N65°W/70°NE as well as oriented mica were noticed. These destabilizing faults are accompanied by a set of joints (J1, J2, J3) that systematically cut through the summit (Fig. 7), one directly dipping in the same direction as the dip of the flank of the peak towards the southeast but more gently dipping, a second one oriented against this direction, dipping into the peak, and a third one almost vertical to both of them. This area is still highly susceptible to more avalanching (Weidinger and Ibetsberger, 1997).

5.5. Climatic conditions and geohydrology of the area

The northern parts of the Qin Ling Mountains, where some large, long rivers dominate, are rich in ground and mountain waters. This was the reason for an extensive agricultural development at the foot of this area. The area is a part of the "warm belt" with an average precipitation of 600 mm per year. As this precipitation is not distributed regularly, hazards can be triggered by these events. The season of heavy rainfalls and dangerous and disastrous flooding is in summer, whereas the winters are extremely dry. One of these extraordinary dry seasons was in the winter of 1928. Millions of local people had to be evacuated. During the season of heavy rainfall, landsliding and different hazardous side effects are very common. Despite these facts, the influence of climatic conditions as a triggering effect of Cui Hua rock avalanche must have played a secondary role, mainly in the weathering and weakening of granitic material in the area of the broken crest.

6. Existence of the dammed lake and the stability of the natural dam

The stability of landslide dams in general depends on the size of the dislocated landslide mass, the shape of the landslide deposit and the different lithological behaviours of the envolved materials, which built up the barriers (Costa and Schuster, 1988; Schuster, 1986). With an isometric shape of the deposit and a volume more than 100 times that of the dammed waters behind, the barrier of the Cui Hua rock avalanche is safe from an outbreak of Tianchi Lake. In this case, the rate of sedimentation into the lake, due to the small catchment area of the Dong Cha River and the small amount of sediments in it, is so low that the lake can hardly be infilled with them. Similar barriers with different (higher rates) conditions of sedimentation, as the Ghona Tal landslide in northern India, have shown that such dammed lakes could rapidly and easily become parts of the geological past, within a period of less than 80 years (Weidinger, 1998). An attempt to find a way concerning the prognosis of the duration of the stability of a lake-damming landslide or rock avalanche was given in a study on similar phenomena in the Himalayas (Weidinger and Ibetsberger, 2000). It is a correlation between the grain, boulder and block sizes of the landslide material and the duration of the stability of a dam, with the result that the bigger the average diameter of the components, the longer the life of the lake. The plot of the data from Cui Hua verifies this rough diagram (Fig. 8). Instead of washing material out of the deposit of the rock avalanche, seeping waters give a stabilizing input by cementing the space between the blocks with fine-grained sediments, which are transported by the water. The benefits of this natural disaster

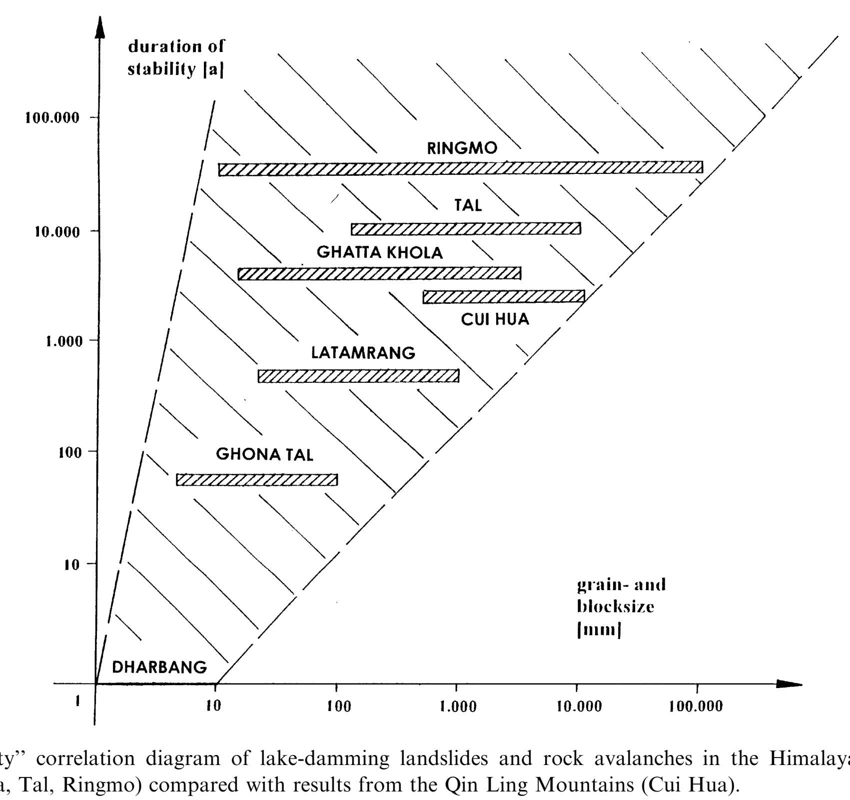

Fig. 8. "Blocksize–Stability" correlation diagram of lake-damming landslides and rock avalanches in the Himalayas (Dharbang, Ghona Tal, Latamrang, Ghatta Khola, Tal, Ringmo) compared with results from the Qin Ling Mountains (Cui Hua).

at Cui Hua Mountains discussed below result from this more or less absolute stability of the barrier of the rock avalanche and from the long life of the dammed lake behind.

7. The benefits of the prehistoric natural disaster

7.1. Tianchi Lake—a resevoir of water for agriculture, drinking-water supply and energy

At the front of the deposit of the Cui Hua rock avalanche, on the shore of Tinachi Lake at an altitude of 1210 m, local people have founded a village called Chui Tsho Tshe (Fig. 9). East of this village there exists a 100–150 m wide channel, today used as an agricultural area. From morphological analysis, this must have been a former area of outflowing or outbreaking waters of Tianchi Lake through the bulk of the rock avalanche. Normally water can easily flow through this dam because of the big boulders and the coarse-grained material. As documented along the northern side of Tianchi Lake, the shore has been made watertight by the local residents with artificial sealing of cement preventing the water from seeping through the material of the rock avalanche (Fig. 10). Nevertheless, high-grade brecciation could have occurred in the lowest parts of the bulk of the rock avalanche, giving a natural input to the tightness of the bottom by fine-grained materials. Due to this stabilizing input within the upper rim of the rock avalanche, which was done by the local people, the natural dammed waters of Tianchi Lake are kept at a higher level. The lake functions as a reservoir for feeding the crops of the village and perhaps in future as one for an already existing hydropower plant down the valley. Similar projects using a natural dam for the production of electrical energy are being considered in the Nepal Himalayas (Uhlir, 1999).

7.2. The deposit of the rock avalanche—a study area for landslide experts and a place for touristic sightseeing and vacation

Nowadays the area around the Cui Hua Peak and especially the material of the rock avalanche in front of the lake play an important role in touristic sightseeing for the nearby capital of Xi'an with its 3 million "nature-hungry" inhabitants. While the lake is good enough for boating and vacationing, the deposit of the rock avalanche can be investigated along several pathways on top of and through canyons between the big boulders. The "Ghost Canyon", one of the boulders that might have been cracked along microjoints during a later earthquake (Fig. 11), the "Wind Cave" an A-shaped joint through two (formerly one) blocks (Fig. 5) and the "Ice Cave", which retains ice in winter, when the

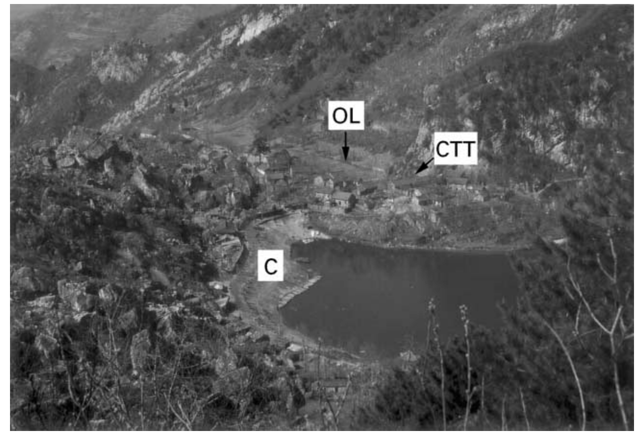

Fig. 9. The village of Chui Tsho Tshe (CTT) in front of the deposit of the rock avalanche; behind is a former outlet (OL) of Tianchi Lake, today regulated for agriculture; in the middle the artificial sealing of the lake by cementation (C), where boats are anchored.

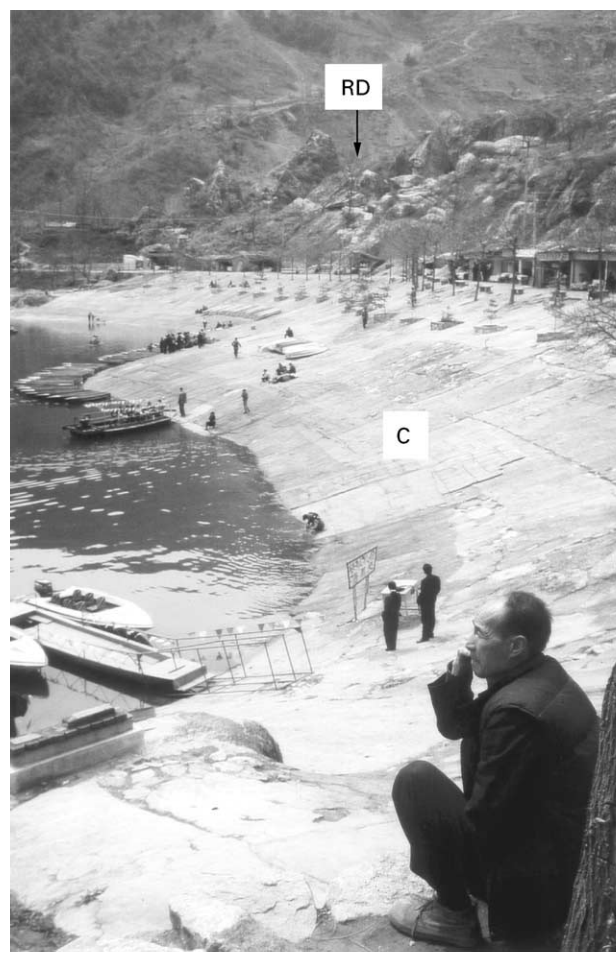

Fig. 10. The artificial sealing of Tianchi Lake by cementation (C); in the background, parts of the rock avalanche (RD).

snow reaches a thickness of 30–40 cm, at a temperature of -10° to -15°C, and several more highlights are famous spots for tourists within the area of the rock avalanche. For experts in investigating landslide

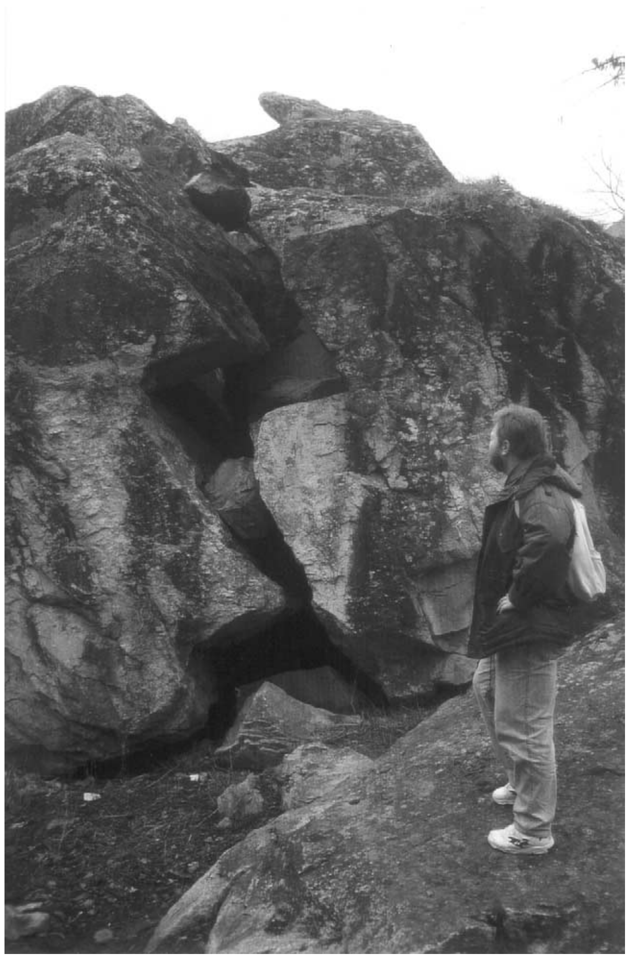

Fig. 11. This boulder of the deposit of the rock avalanche in the centre of the village Chui Tsho Tshe is bordered by a "zig-zag-crack", which is identical with the sets of joints at the broken crest area. Obviously, the block did not break in the end of the event of sliding, rolling and bouncing but later due to another earthquake.

phenomena it is an extraordinary place in the world as well. The Cui Hua rock avalanche is one of the rare examples of landslides, where one can walk and climb for several hours *within* the deposit by crossing joints, structures and caves. It is hoped that this will not be the final end of using and enjoying the result of a natural disaster, which could easily occur again at any time.

Acknowledgements

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