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Why the 2014 Ludian, Yunnan, China M_s 6.5 earthquake triggered an unusually large landslide?

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The 3 August 2014 Ludian, China M_s 6.5 earthquake has spawned a mass of severe landslides. Of them the biggest occurred at Hongshiyuan near the epicenter, which has $1200 \times 10^4 \text{ m}^3$, clogging the Niulanjiang River, and creating a large dammed lake. Post-event field investigations yield detailed data on following aspects: rock structure of landslides, lithology, and geometry of the dam, composition and grain sizes of debris avalanches. Based on these data, this work further analyzes the geology and topography of the Hongshiyuan area, and explores the mechanism for occurrence of such an unusual big landslide at this place. Our analysis suggests the following conditions are responsible for this catastrophic event: (1) during the M_s 6.5 earthquake, the special terrain and site conditions led to abnormally strong ground shake. (2) Hongshiyuan lies nearby an active fault, where intense crustal deformation resulted in rock fractures and weathering. (3) Intense incision on the river increased topographic relief with steep slopes and scarps. (4) Combined structures, including unloading fissures, high-angle joints and low-angle beds along the river as well as upper-tough and lower-soft structure on the slopes. It is the joint functions of these conditions that triggered such seldom seen landslides during a moderated-sized earthquake.

1 Introduction

At 16.30 p.m. local time on 3 August 2014, an earthquake of magnitude M_s 6.5 struck Ludian county, Yunnan Province, southwest China. The epicenter was located at 27.10° N , 103.33° E , the Longtou town in this county, with a focal depth 12 km. (<http://www.cea.gov.cn/publish/dizhenj/468/553/100821/index.html>). This event was felt in more than ten cities or counties in Yunnan, Sichuan, and Guizhou province, resulting in IX intensity at the meisoseismal area. As for 8 August 2014, it killed 617 people and 112 missing (<http://www.cea.gov.cn/publish/dizhenj/468/553/100821/index.html>).

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This shock occurred in a rugged mountainous area, which has spawned very severe landslides including rock falls, avalanche, and debris flow. Field investigations show that these landslides are of scales from tens to several ten thousands 10^4 m^3 in volume. In particular, a huge landslide happened at Hongshiyuan, on the right bank of the Niulanjiang River in the southern most heavily affected region. Coupled with the front of an old landslide on the left bank, this new avalanche body clogged the Niulanjiang River, creating a 120 m-high, $1200 \times 10^4 \text{ m}^3$ dam, which made the river level rise at least 30 m and water area increase to 3 times that of the normal case, posing severe threat on residents as well as hydropower stations both upstream and downstream the river.

Although earthquake-induced landslides are common in southwest China, it is seldom seen that a moderate quake like the 2014 Ludian M_s 6.5 could have produced such a large-scale severe land slumps. The objective of this paper is to explore the mechanism of this unusual event. Our analysis is based on the data from field observations, and focuses on the geologic conditions of the Hongshiyuan area where a huge dam on the river was created by the landslides.

2 Geologic setting

The Ludian M_s 6.5 event took place in northeastern Yunnan Province of China, between the southeastern margin of the Tibetan plateau and South China block (Fig. 1). This area is characterized by intense neotectonic movements, numerous active faults and frequent major earthquakes (Allen et al., 1989; Song et al., 2002; Zhang et al., 2004; Xu et al., 2005; Guo et al., 2013). Field investigations suggested that the Ludian quake was generated by the southwest segment of the NE-trending thrust-dominating Zhaotong-Lianfeng fault that lies at the east flank of the Sichuan-Yunnan block (Fig. 1). This fault zone consists of two faults: the Lianfeng fault and Zhaotong-Ludian fault, dominated by thrusting (Wen et al., 2013), which serves as the south boundary of the secondary active Daliangshan block (Fig. 1). In this block, there exists also the nearly

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northerly trending Daliangshan fault dominated by left slip with thrusting motion (Shen et al., 2000; Zhou et al., 2003; Zhang et al., 2005; He et al., 2008). Since Cenozoic time, the neotectonic movement in the Daliangshan block is expressed by left-slip and thrust on the Daliangshan fault as well as shortening of nearly NS-trending folds, which is about $10.9\text{ km} \pm 1.6\text{ km}$ (Chen et al., 2008). The Zhaotong-Lianfeng fault aforementioned lies just at the southeast edge of the Daliangshan block, accommodating the southeastward motion of this block (Li et al., 1975, 1993; Kan et al., 1977; Tapponnier P. et al., 1986; Armijo et al., 1989; Zhong et al., 1996; Hodeges et al., 2001; Zhang et al., 2003; Xu et al., 2003). Nearby the epicenter of the Ludian event, there exists the major branch of the Zhaotong-Lianfeng fault zone: the Zhaotong-Ludian fault and its NW-trending branch-Xiaohe fault. The Zhaotong-Ludian fault comprises three NE striking faults, from east to west which are the Sayuhe fault (F1), Zhaotong-Ludian fault (F2), Longshu fault (F3), and Xiaohe fault (F4) (Fig. 2). These phenomena show a complicated structure of this area, where NE- and NW trending faults intersect each other, and NE ones are predominant.

Except the Cretaceous System, strata from Sinian through Quaternary are exposed in the Ludian area. Of them, the pre-Mesozoic formations are most widely distributed, which are dominated by sandstone, shale, limestone and dolomitite, containing many joints and fissures. Mesozoic strata are present in the northeast and southeast of the seismic area, which are continental debris accumulation dominated by sandstone and mudstone. Few Cenozoic strata are scattered in the intermountain basins, such as the Ludian basin, which are made up of fluviolacustrine clay rock and sandy gravel (Table 1).

Geographically, the Ludian seismic area is situated in the northeastern Yunnan-Guizhou plateau. Before Miocene time, it was a relatively intact and uniform peneplain. Since the end of Miocene, due to many times of tectonic movements this area was intensively uplifted and suffered from erosion and dissolution. Consequently, the original peneplain was reformed into steep mountainous landscape with many intermountain lowlands (basins). As one of major rivers in southwest China, the Niulanjiang River

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flows from southeast to northwest through the Ludian seismic area, with incision depth up to 1200–3300 m forming V-shaped valleys. On either bank of this river, the slope is usually very steep. Almost 80 % of the slopes steeper than 40° concentrate along either bank of the Niulanjiang River. While in the north and east of the seismic area, the terrain are relatively gentle, dominated by middle-height and low hills with steepness generally less than 20° (Fig. 3).

3 Seismic dam at Hougshiyuan

The Ludian M_s 6.5 earthquake has triggered a huge landslide on the right bank of the Niulanjiang River nearby the Hougshiyuan village (27.035° N, 103.397° E). Meanwhile it also partly reactivated the old landslide on the opposite left bank, part of which thrust down into the river. Both produced a huge barrier that clogged the river, resulting in a dammed lake (Fig. 4).

3.1 Geometry and composition of the seismic dam

The seismic dam at Hougshiyuan clogs in the V-shaped valley of the Niulanjiang River. From planar projection, it is up to 1000 m long and 270 m wide, with average width 262 m along the river and 301 m across the river, respectively, and a total projection area 80 000 m². The elevation is 1216 m at the top, and 110 m at the base, with dam height 120 m (Fig. 5). The total volume of the dam is estimated to be about 1200 × 10⁴ m³ (Institute for Earthquake Engineering Survey of Yunnan Province, 2014).

Overall, the dam top is higher on the right bank and lower on the left bank, and the culminations are 1270 m on the left bank and 1349 m on the right bank, respectively. Avalanche accumulation of the new landslide is present on the edge of the right bank. Upstream the dam, the slope is relatively steeper with an average slope ratio 1 : 2.5, while downstream the dam, the slope is relatively gentle with an average slope ratio

is 1 : 5.5. The dam top is 17 m wide at elevation 1222 m, and the base is 910 m wide along the river. And the length along the dam axis of elevation 1222 m is 307 m (Fig. 5).

This seismic dam was resulted from rapid avalanche. Its source was primarily from the higher place on the right bank of the river, added by avalanches from the old landslide on the left bank. Pebbles dominate the dam, which are weakly weathered or fresh dolomitic limestone and dolomite with maximum grain size over 5 m. In the dam, the pebbles with sizes exceeding 50 cm account for 50 %, 20 ~ 50 cm for 35 % and less than 2 cm for 15 % of the total, respectively.

3.2 Old landslide on the left bank

The old landslide aforementioned lies at the southern end of the seismic dam. It is 1200 m wide at the base, 900 m from the top to the bottom in planar projection, with average thickness 80 m and volume $7920 \times 10^4 \text{ m}^3$ (Fig. 5). It is upper steep and lower gentle, with slope angles 36° and 18° above and below elevation 1400 m, respectively. Relevant data reveals 25–40 m thick cover on the river bed at this place, of which the muddy soil is thick up to 18–24 m. The river valley of this stretch convexes slightly to the right, implying a possible landslide-damming event in history. Because the front of this old landside was deposited on the original river bed, the right bank has been eroded by the river.

Affected by the 2014 Ludian M_s 6.5 quake, the rear edge scarp of the old landslide, which is 300 m high (elevations of rear and frontal edges are 1850 and 1550 m, respectively), suffered from local collapse (delineated by red dashed line in Fig. 7). Consequently, part of its front slipped into the river (delineated by yellow dashed line in Fig. 7). Meanwhile, the surface layer of this old landslide became loose, causing big massive boulders and pebbles to slide into the river, which joined the avalanches from the right bank to create the dam on the river. Nevertheless, the whole body of this old landslide remained stable during the shock, only a lot of cracks appeared on its surface. The triggered failures are composed of pebbles and massive stones intercalated with silt and clay, of which the largest boulder is up to 5 m in diameter.

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3.3 New landslide on the right bank

The avalanche on the right bank of the Niulanjiang River triggered by the Ludian event is the primary part of the seismic dam at Hongshiyuan. Its source is at elevation 1680 m. Upstream the river, this avalanche is 890 m long and the highest rear edge wall is up to 500 m. Total volume is estimated about $1000 \times 10^4 \text{ m}^3$ (Fig. 8). Field investigations indicate that the avalanche consists of medium-bedded dolomitic limestone and dolostone intercalated with sandstone and shale of Ordovician, Silurian, Devonian and Permian systems. These rocks are laced with numerous joints and fissures. In particular, unloading cracks and broken rocks characterize the upper landslide body. Detailed descriptions of this landslide are in the next section.

4 The new huge landslide at Hongshiyuan

4.1 Geological environment

As stated previously, the Ludian seismic area lies between the Sichuan-Yunnan block and Daliangshan block, southeast of the Tibetan plateau (Fig. 1). The Hongshiyuan seismic dam is nearby the Zhaotong-Ludian fault zone that consists of many NE- and NW-trending faults dominated by thrusting (Fig. 2). Influenced by the intense fault activity, fractured rock and strongly weathering surface characterize this region, particularly along faults or compressive fractured zones. Thickness of the weathering layer is controlled by lithology and topography. In general, dolomite, limestone, quartz-sandstone and siltstone have relatively stronger capability of resistance to weathering, while shale and argillaceous rocks are weak in this aspect. On the ridges and gentle slopes, weathering beds are thick, while they are thin in cols, gullies, and steep slopes. Previous data and the field investigations after the 2014 Ludian M_s 6.5 quake reveal that the weathering reaches down to depth 20–25 cm beneath the surface on either bank of the Niulanjiang River in the vicinity of Hongshiyuan. The horizontal extensions of weathering are

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20–25 m on the right bank and 25–30 m on the left bank, respectively. In particular, at the sections of limestone and dolomite, the intense dissolution-erosion weathering is as deep as 20 m, and weak dissolution-erosion weathering affects the depth 60 m. These intense weathering effects provide major material sources for large-scale landslides.

4.2 Structure of rock

On either bank of the river around the seismic dam, rocks strike in different directions, while all dipping gently. On the right bank, rock attitudes are NW 20–30°/SW 15–30°; and on the left bank, rocks dip toward downstream with attitudes NE 20–60°/NW 10–30° (Fig. 9).

Because of long-term various geologic effects, gentle folds or flexures characterize strata in this area. On either bank of the river, steeply dip unloading fissures developed well in rocks, which have relatively flat surfaces, generally opening 1–2 cm. Most of these fissures have no filling, part filled by calcareous or silt material that destroyed completeness of rock. In situ observations found three sets of joints in rock on the slope, i.e. steep joints normal to the river, joints parallel to the river, and inerbed joints (Table 2).

According to attributes of three kinds of joints, we use the projection on the equator plane of the Wolf net to describe the structure of the rock on the slope around the landslide (Fig. 10). It can be assumed that the steep joint normal to the river (i) and that parallel to the river (ii) cut the rock body into a small mass. Plus the gentle dipping joint (iii), they will generate an unstable block (shaded area in Fig. 10). Under seismic motion, this block will be prone to slip toward the open side of the slope (along river flow) (arrow in Fig. 10).

At this place, upper portion of the slope is dolomitite that is relatively tough, while sandy mudstone and shale constitute its lower portion, which are relatively soft (Figs. 9 and 11). In this case, the rock of lower portion of the slope is steadily deformed under the gravity load of the upper portion rock. Consequently, the brittle rock in the upper portion of the slope is prone to fracturing, while the soft rock in the lower portion of the

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slope will become potential slip surfaces. When an earthquake occurs, the fractured rock will slide down along the unloading fissures parallel to the river or other structural surfaces (such as interbed joints), leading to landslides. As the soft rock is present in a large area, and fissures and joints developed well in the touch rock of the upper portion of the slope, the resulting avalanches will also cover a big area (Fig. 11).

4.3 Topography

Near the Hongshiyuan village where the largest seismic landslide occurred, the Niu-lanjiang river runs through a deep and steep valley with topographic relief as big as 800–1000 m. On the left bank, slope angles are 35–50°, and slope height near the riverbed is 200–220 m. On the right bank, slope angles are 35–50°, locally up to 70° or more, and the slope is 800 m high over the riverbed (Figs. 3 and 9). Such a topography condition makes this place be prone to enormous landslides.

4.4 Seismic acceleration

Although the 2014 Ludian earthquake is a moderate event, the Longtoushan station nearby the epicenter recorded high acceleration values of ground motion. The peak ground accelerations of NS, EW and vertical components are 948.5, 704.9, and 503.8 Gal, respectively (Fig. 12). The intensity of the most heavily affected area is IX degree according to Chinese seismic intensity (Seismic intensity zoning group et al., 1990), where lies the Hongshiyuan seismic dam near which is only 10 km distant to the epicenter. It means a rather strong effect of the Ludian quake.

Meunier et al. (2008) found that seismic landslides are easy to take place at the top of a mountain ridge and its vicinity, and the slope that is away to the epicenter can amplify the seismic acceleration considerably. The large landslide at Hongshiyuan is just on the slope that is away to the epicenter of the Ludian quake, and the avalanche source is almost on the mountain top. Such special conditions of local topography may explain

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the unusual big seismic acceleration near Hongshiyuan, which likely fueled the seismic landslide here.

4.5 Unloading rock fissures

The valley of the Niulanjiang River is deeply incised with very steep slopes on either bank (Fig. 3). Under extensional stress, numerous unloading fissures developed in the rock of the slopes. Near the Hongshiyuan seismic dam, either bank of the river is of steep slopes, on which the rock contains particularly evident unloading cracks. On the surface, a mass of medium to steeply dipping unloading fissures, that are parallel to the river, are seen. For instance, at the slope behind the Pearl spring at the upstream right bank about 1.8 km to the seismic dam near Hongshiyuan, there exists a long unloading crack (Fig. 13). It dips almost vertically, parallel to the bank, with maximum opening width 15 cm by eyesight (Fig. 13). Cut by this crack, the rock surrounding it is nearly separated from the slope, forming a dangerous rock mass that is 30–40 m high, 15 m wide and 5 m thick, with a volume of 3000 m³. Beneath this rock mass, thin-beds of rock dip gently downstream. Gentle terrain appears below the steep slope, where the upper portion of the rock mass has partly broken off and hangs in the air locally (Fig. 13).

From observations to fissures on the surface of either bank of the river, the depth of the intense unloading zones is estimated to be over 50 m. Such fissures and rock structure aforementioned may jointly form unstable rock masses on the slope, which would become the favorable place for large-scale landslides.

5 Discussion on the formation mechanism of the seismic dam at Hongshiyuan

Field surveys reveal the landslide geometry and its material composition at Hongshiyuan. Based on these data, we have calculated the static factor of safety (Fs) of the slope before and during the Ludian earthquake by applying GeoStudio software (Bishop et al., 1960; Morgenstern et al., 1965; GEO-SLOPE International Ltd, 2010).

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The results show that t F_s of the slope is 1.450 before the event, implying a safe state. While it drops to 0.962 after 300 gal of seismic motion is loaded (Fig. 14a), which means this slope enters an unstable state. Although this numerical calculation is preliminary, its results demonstrate that the seismic motion can lower F_s of the slope, leading to its instability. In other words, the Ludian earthquake should be the direct cause for the landslide at Hongshiyuan. On the other hand, however, if there was no existing slide plane, the scale of the seismic landslide would have been very small under the same seismic motion, at least not so large as the real case we see now (Fig. 14b). Thus we suggest that the existing potential slide plane or its formation should be another critical reason for the unusually big landslide at Hongshiyuan.

Khazai and Sitar's (2003) analysis of the Chi-Chi earthquake data suggest that only the very large catastrophic dip slope failures could be specifically tied to a particular geologic setting. Keefer defined fourteen types of landslides primarily by material and character of movement in his study and indicated that weathered and intensely fractured rocks were kinds of materials to form rock avalanches (Keefer, 1984). More detailed and specific studies indicate that faults, joints and fissures can control the rock avalanches occurrence since these faults or joints proper are potential planes for sliding or landslides (Sun et al., 1997; Hermanns and Strecker, 1999). During the 2008 Wenchuan earthquake, lots of large landslides may have occurred on pre-existing fractures or discontinuities that were undetectable prior to the earthquake and be composed of fracture rocks (Qi et al., 2011; Chen et al., 2012). Based on analysis of geology, geomorphology, and lithology which are prone to large slope failures, it is obvious that the unusual big landslide occurred in such a setting with those conditions aforementioned. The formation mechanism of the big rock avalanche at Hongshiyuan by the Ludian quake may have three stages as follows:

- *Stage 1*: Under strong ground shaking, the joints parallel to and normal to the river and unloading cracks (red bars) are opened and connected (Fig. 15a).



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- *Stage 2*: Joints along beds (green lines) develop further, resulting in rock masses that intersect each other (Fig. 15b).
- *Stage 3*: Rock masses lose stability, sliding downward, collapsed, and moved over a short distance along the sliding surface to the inside of the valley. This stage is a process of rapid motion as well as rock-mass colliding each other and fracturing. Finally, it creates masses of varied sizes and powder-like piles, which block the river course coupled with the old landslide on the left bank, resulting in a dammed lake (Fig. 15c).

Of these stages, the first and second may proceed simultaneously, hardly being distinguished. When the earthquake occurs, because of intense tensile stress at the slope, the first stage may be slightly ahead the second one. And during the second stage, extensional split of vertical fissures happens from the beginning to the end.

6 Conclusions

The 3 August 2014 Ludian, China M_s 6.5 earthquake has spawned severe landslides. Of them the biggest occurred at Hongshiyuan near the epicenter, which is $1200 \times 10^4 \text{ m}^3$ in volume, clogging the Niulanjiang River, and creating a large dammed lake. Post-event field investigations yield detailed data on following aspects: rock structure of landslides, lithology, and geometry of the dam, composition and grain sizes of debris avalanches. Based on these data, this work further analyzes the geology and topography of the Hongshiyuan area, and explores the mechanism for occurrence of such an unusual big landslide at this place. Our analysis suggests the following conditions are responsible for this catastrophic event:

1. During this M_s 6.5 earthquake, the special terrain and site condition may lead to abnormally strong ground shaking at Hongshiyuan and directly cause the failure.

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2. The site where Hongshiyian lies is nearby an active fault, where intense crustal deformation resulted in rock fractures and weathering, providing major material sources for large-scale landslides.

3. Intense incision in the river increased topographic relief with steep slopes and scarps, which is prone to enormous landslides.

4. Combined structures, including unloading fissures, high-angle joints and low-angle beds along the river as well as upper-tough and lower-soft structure on the slopes, stimulating failures by providing potential slide plane.

It is the joint functions of these conditions that triggered such seldom seen landslides during a moderated-sized earthquake.

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Table 1. Simplified geologic strata system of the area most severely damaged by the M_s 6.5 Ludian earthquake.

Stratum	Lithology
Quaternary (Q)	Grey and brown gravel, clay, sand, and silt loam, 25–80 m thick
Neogene (N)	Grey-white and grey-green conglomerate, clay rock intercalated with lignite beds, semi-consolidated, 180–366 m thick
Jurassic (J)	Brown-red and purple-grey medium-thick bedded mudstone, siltstone with marl, 366–1000 m
Triassic (T)	Purple and yellow-green medium-thick bedded siltstone, silty mudstone, 352–726 m thick
Permian (P)	Lower: grey, dark-grey, and grey-white thick bedded or massive limestone intercalated with a few dolomitic limestone; upper: basalt; totally 1038–1675 m thick
Carboniferous (C)	Grey-white thick bedded limestone, dolostone, biological debris limestone, and oolitic limestone intercalated with dolomitic limestone; sandy shale and coal-bearing beds in the lower portion, total thickness 2500 m
Devonian (D)	Lower: green-grey medium-thick beds of quartz sandstone, siltstone with argillaceous shale; middle and upper: grey thick bedded argillaceous limestone, dolomitite, limestone with mudstone, 219–742 m thick
Silurian (S)	Grey-black and dark brown thin to medium thick shale, limestone and sandstone, 530 m thick
Ordovician (O)	Grey-green and brown-red shale intercalated with thin beds of sandstone, yellow-brown moderately thick and thin bedded argillaceous sandstone and dolomitite, 970 m thick
Cambrian (ϵ)	Grey-white and grey-green thin bedded siltstone, dark-grey massive dolomitite, limestone, argillaceous dolomitite, hundred to thousand meters thick
Sinian (Z)	Purple-grey thick bedded quartz sandstone, grey thick bedded dolomitite, and grey-purple thin bedded phyllite, more than 1000 m thick

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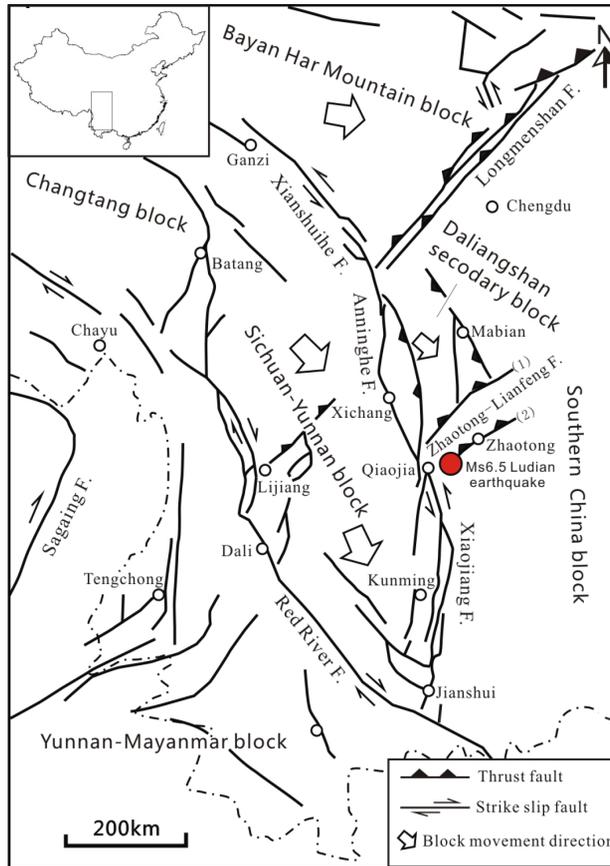
Table 2. Features of rock joints in the landslide body at Hongshiyan (after Institute for Earthquake Engineering Survey of Yunnan Province, 2014).

Joint	Code	Attitude (strike/dip direction/dip angle)	Description
Normal to river	I	NW 30°/NE 80°	Mostly open, as wide solution fissures on surface filled with secondary mud
Parallel to river	II	EW 3/S 80–83°	Affected by unloading rebound, open at shallow depth, with fluctuating – rough surface and large extension
Interbed	III	NE 20–60°/NW 10–30°	Downstream gentle dip, mostly closed, large extension, locally as mud interbed, primarily develop in thin bedded and medium bedded sandy mudstone of Ordovician



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(1): Lianfeng fault; (2): Zhaotong-Ludian fault

Figure 1. Sketch map showing tectonic and dynamics setting of the 2014 Ludian M_s 6.5 earthquake. (1): Lianfeng fault; (2): Zhaotong-Ludian fault.

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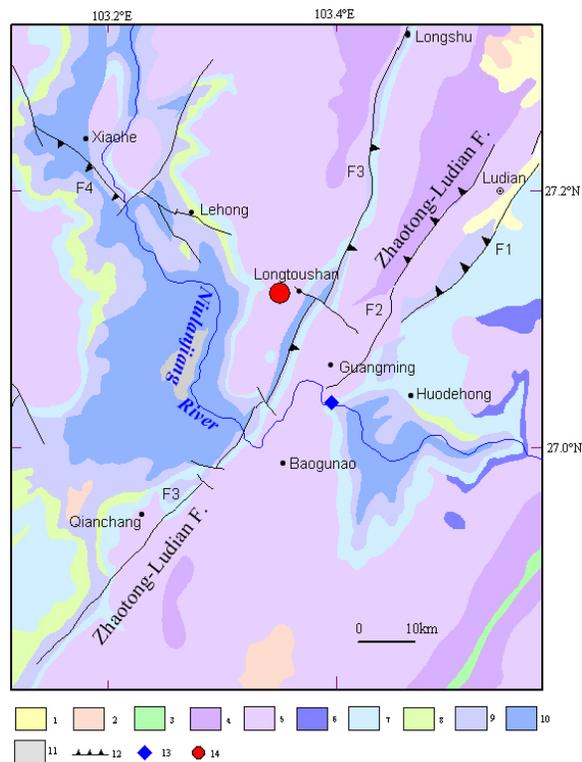


Figure 2. Geologic map of the Ludian seismic area (modified from Geological and Mineral Bureau of Yunnan Province, 1990). 1 Quaternary. 2 Neogene. 3 Jurassic. 4 Triassic. 5 Permian. 6 Carboniferous. 7 Devonian. 8 Silurian. 9 Ordovician. 10 Cambrian. 11 Sinian. 12 fault (triangles indicate dipping directions). 13 Seismic dam at Hongshiyuan. 14 Epicenter of Ludian M_s 6.5 event. F1: Sayuhe fault. F2: Zhaotong-Ludian fault. F3: Longshu fault. F4: Xiaohe fault.

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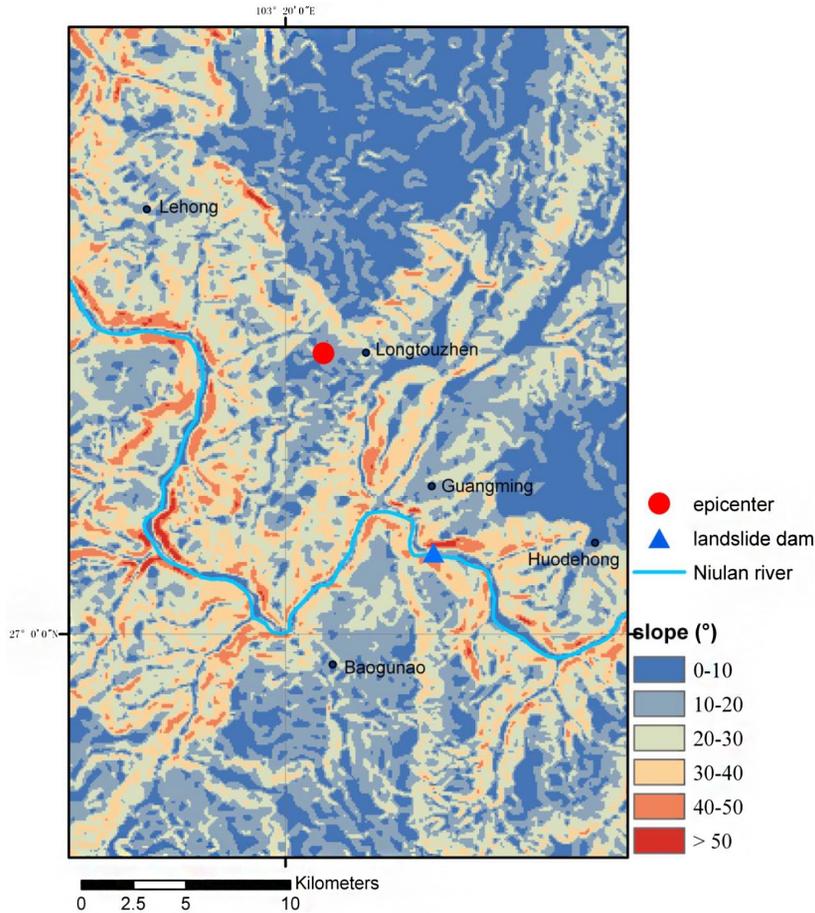


Figure 3. Map showing slope angles in the Ludian seismic area.

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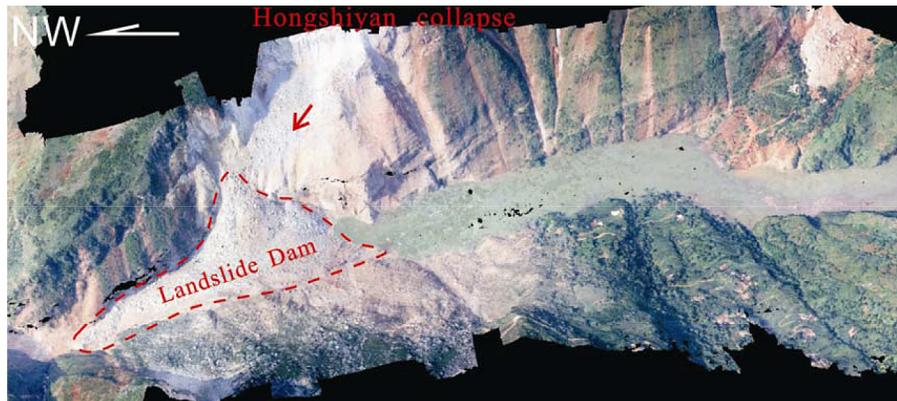


Figure 4. Unmanned Aerial Vehicle photo showing the seismic dam on the Niulanjiang River (Provided by Institute of Geophysics, China Earthquake Administration).

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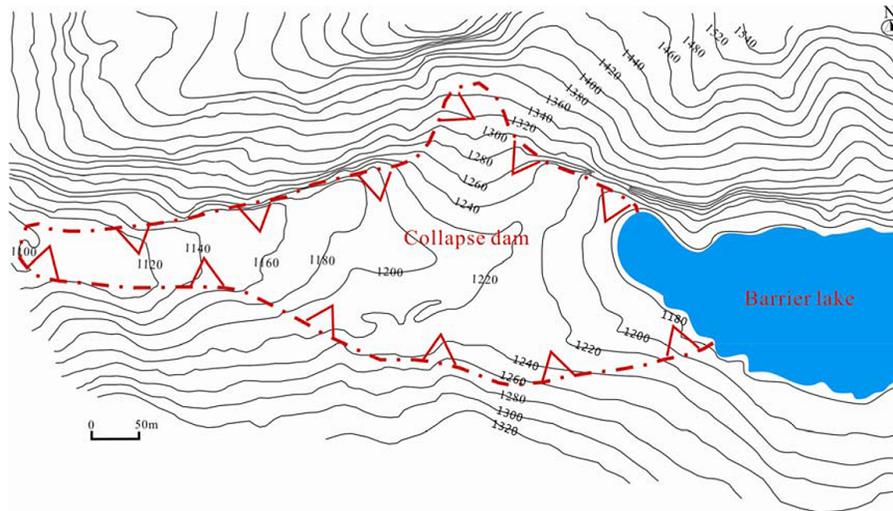


Figure 5. Planar distribution of the seismic dam on the Niulanjiang River at Hongshiyuan (Contours are elevations above sea, modified from Institute for Earthquake Engineering Survey of Yunnan Province, 2014).

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Figure 6. Overall look of the seismic dam (view toward west).

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Figure 7. Photo showing the old landslide on the left bank of the Niulanjiang River. Red dashed line denotes old landslide. Yellow dash line shows the frontal part that collapsed during the 2014 Ludian event (view toward south).

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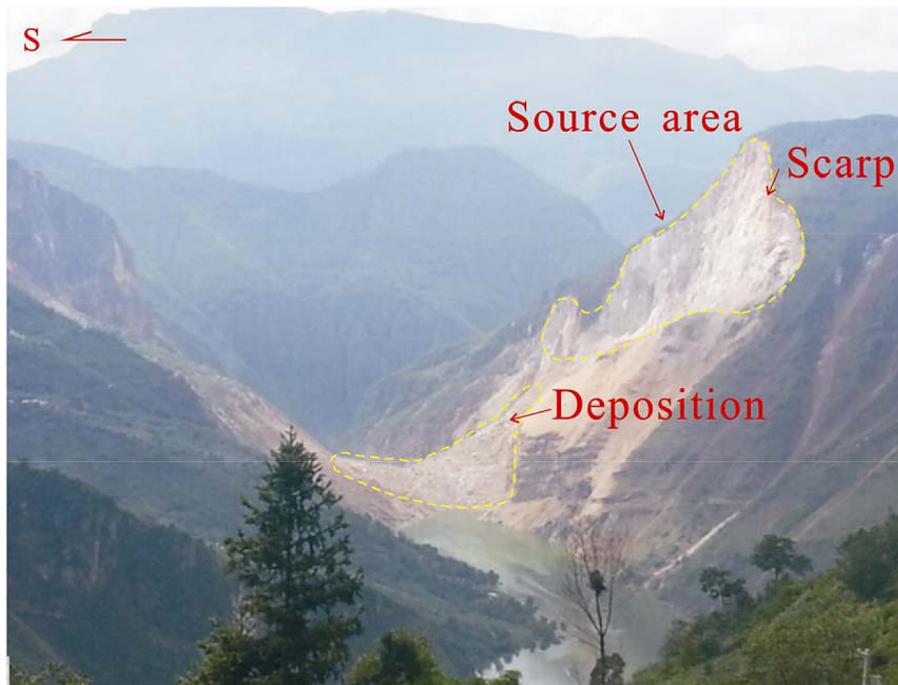


Figure 8. New landslide induced by the 2014 Ludian quake on the right bank of the Niulanjiang River (view toward west).

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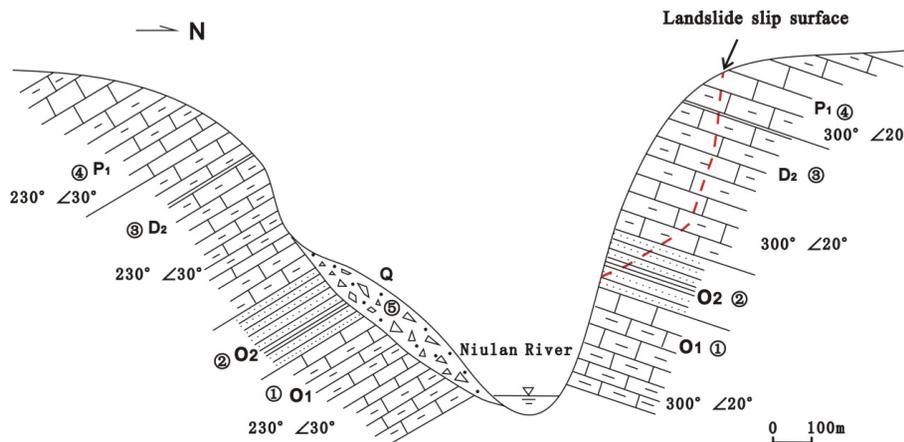


Figure 9. Cross section at the dammed lake before the 2014 Ludian quake. 1 – Dolomitite and limestone of lower Ordovician. 2 – Sandstone with shale and mudstone of middle Ordovician. 3 – Dolomitite and limestone with argillutite of middle Devonian. 4 – Massive limestone and dolomitite of lower Permian. 5 – Quaternary diluvium deposit.

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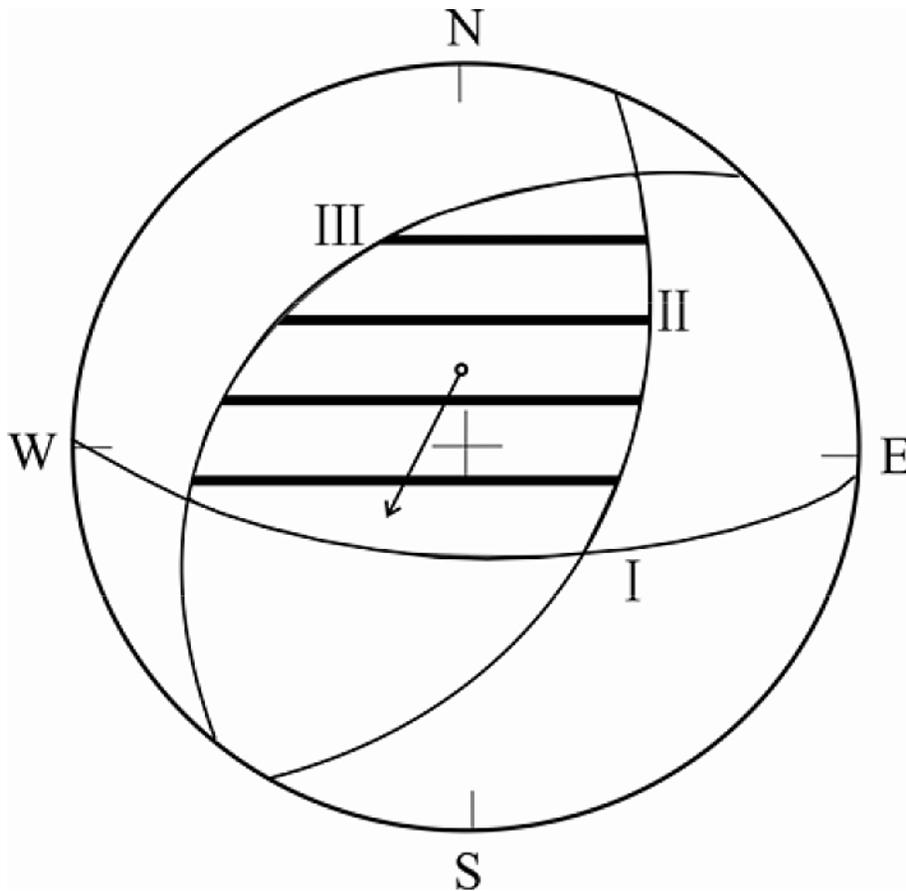


Figure 10. Wolf projection of joints in individual avalanches at Hongshiyan (projection of lower hemisphere). I: steep joint parallel to river, II: steep joint normal to river, III: interbed joint (see Table 2).

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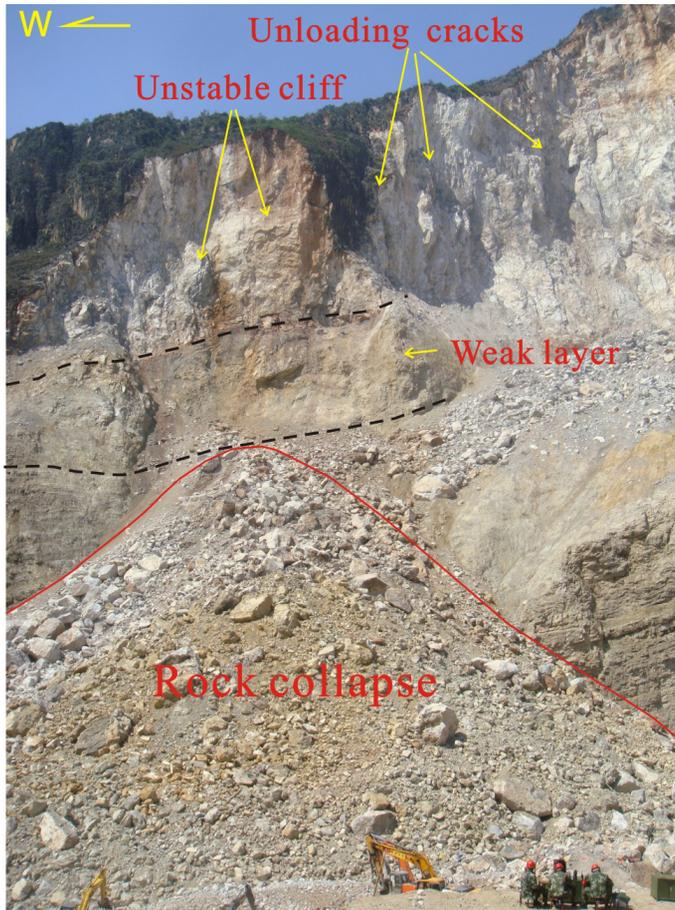


Figure 11. Rock structure that unleashed rock avalanches at Hongshiyuan during the Ludian earthquake.

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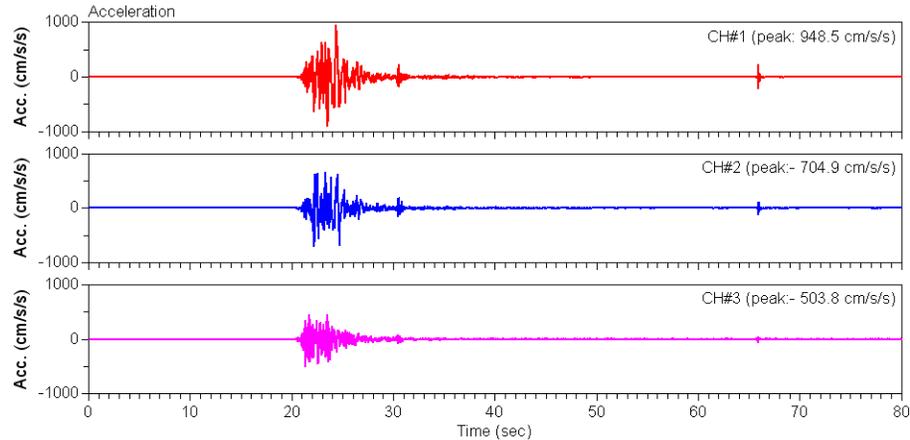


Figure 12. Peak ground accelerations recorded by the Longtoushan seismic station during the 2014 Ludian M_s 6.5 earthquake. Red: EW component. Blue: NS component. Pink: vertical component.

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Figure 13. Unloading fissures (shown by yellow arrows) on the rear edge of slope at Pearl spring.

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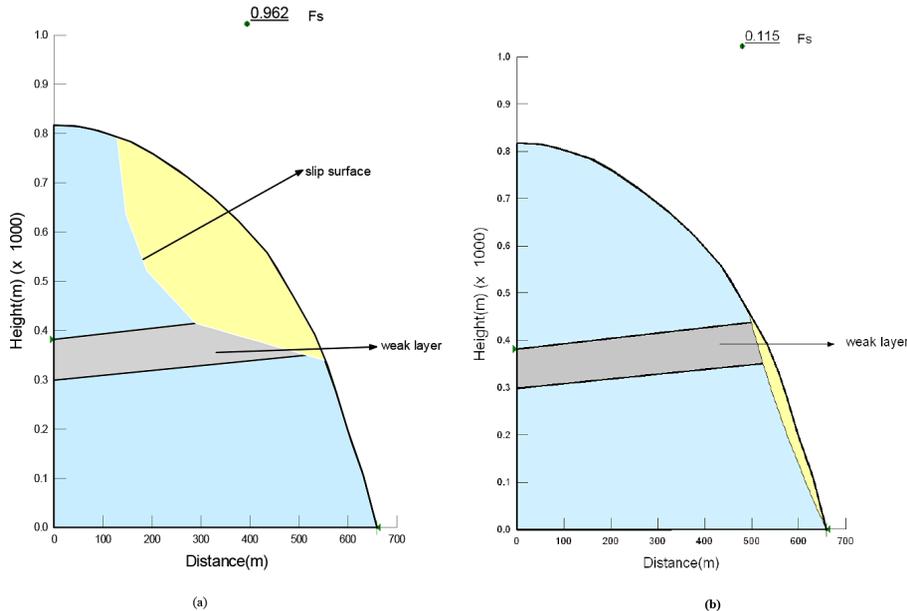


Figure 14. F_s of the Hongshiyuan slope under seismic loading (Yellow parts represent the slope failures; **(a)** with a slip surface; **(b)** without a slip surface).

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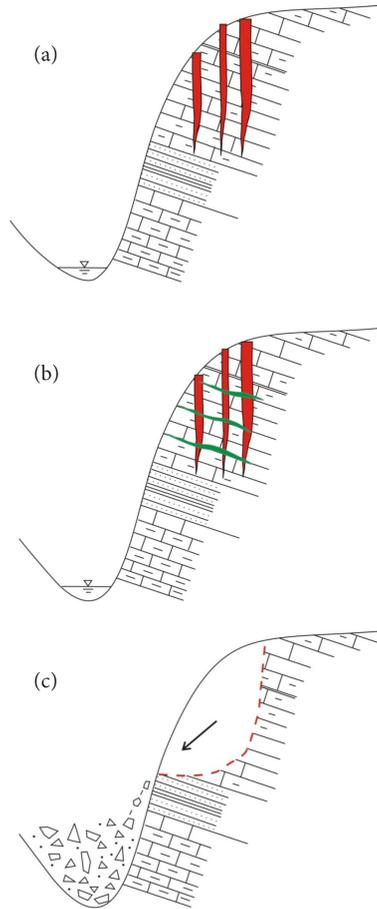


Figure 15. Schematic diagram showing assumed forming process of rock avalanche at Hongshiyuan. (Red bars are unloading cracks, green lines are joints along beds.)

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