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# Use of Indirect Evidence for the Prehistoric Earthquake-Induced Landslides Identification

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## Abstract

Presence of large and/or long runout prehistoric rockslides is often equalized with an evidence of strong past earthquakes without providing any additional reasons in favor of such assumption—just due to enormous size and surface expression of these features. The erroneous assumption on seismic origin of a particular landslide or group of landslides would cause not only an overestimation of seismic hazard, but, also, underestimation of an overall landslide hazard due to much longer recurrence period of large earthquakes in comparison with other triggering phenomena like rainstorms. Examples of reliable substantiation of seismic origin of large rockslides based on identification of spatially distributed sedimentary features in the lacustrine environment closely timed to river damming event are presented and discussed.

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## Keywords

Landslide · Earthquake · Rockfall · Sedimentation · Liquefaction

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## 1 Introduction

Presence of large and/or long runout prehistoric rockslides is often equalized with an evidence of strong past earthquakes without providing any additional reasons in favor of such assumption—just due to enormous size and surface expression of these features.

Indeed, many high magnitude earthquakes were accompanied by large bedrock landslides and rock avalanches. The 1911 Sarez earthquake ( $M \sim 7.4$ ) in the Pamirs triggered the 2.2 km<sup>3</sup> Usoi landslide (Gaziev 1984; Schuster 2002; Ischuk, 2011; Ambraseys and Bilham 2012), the 1949 Khait earthquake ( $M7.5$ ) in the Tien Shan—the 7.5-km long rock avalanche (Leonov 1960; Evans et al. 2009b), the 1959 Hebgen Lake earthquake ( $M7.1$ ) in Montana, USA—the Madison Canyon landslide (Hadley 1964), the 1970 Ancash earthquake ( $M8.0$ ) in Peru produced the Huascarán ice-rock avalanche (Plafker and Eriksen 1978), the 2002 Denali Fault earthquake ( $M7.9$ ) in Alaska—several

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spectacular rock avalanches (Jibson et al., 2006), the 2008 Wenchuan earthquake (M8) triggered the giant Daguangbao rockslide  $0.75\text{--}1.1\text{ km}^3$  in volume and numerous smaller landslides and rockslides (Wu et al. 2010; Yin et al. 2011). The list can be expanded.

At the same time numerous large bedrock landslides had occurred without seismic triggering—the 1903 Frank rockslide  $30\text{ Mm}^3$  in volume in Canada (Krahn and Morgenstern 1976), the 1964 Aini landslide  $\sim 20\text{ Mm}^3$  in volume in Tajikistan (Fedorenko 1988), the 1962 Huaskaran ice-rock avalanche—the aseismic predecessor of the larger 1970 event (Evans et al. 2009a), the 1974 Mayunmarka rockslide 1.6 billion cubic meters in volume in Peru (Hutchinson and Kojan 1975), the 1987 Val Pola rock avalanche  $\sim 40\text{ Mm}^3$  in volume in Italy (Crosta et al. 2011), the 2000 Yigong landslide  $300\text{ Mm}^3$  in volume and about 10 km long in Tibet, China (Shang et al. 2003), etc. Thus, neither size of slope failure nor its abnormally long runout can prove its seismic origin itself.

If, however, the assumption on seismic origin of a particular landslide or group of landslides is erroneous, it would cause not only an overestimation of seismic hazard, but, also, underestimation of an overall landslide hazard. Direct linking of large-scale rock slope failures' formation with strong earthquakes only, which are relatively rare events with typical recurrence intervals at a particular causative fault varying from several hundred to several thousands of years, means that large bedrock landslides should occur with same recurrence. However, other natural phenomena that can trigger such slope failure (e.g. rainstorms, hurricanes, and abnormal snowmelt) are much more frequent. For example, 3 typhoons hit Taiwan annually on average (Jan et al. 2005) while large earthquake occur at this island several times per century only (Hung 2000; Cheng 2007). In the area where the 1999 M7.6 Chi-Chi earthquake induced large Tsao-Ling landslide, 5 large-scale slope failures occurred since 1862, but only three of them—in 1862, 1941, and 1999—were triggered by earthquakes. Two others—in 1942 and in 1979 were rain-induced phenomena (Hung 2000).

No doubts that seismicity, strong earthquakes in the first place, is one of the main factors leading to slopes' instability. But such large-scale bedrock landslides origin should be not just postulated, but substantiated somehow. This is especially important for the regions where historical data on various natural phenomena are available for a short time, much less than the recurrence period of large earthquakes. Several examples of such substantiation from the Tien Shan mountains are described and discussed hereafter.

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## 2 Spatially Distributed Sedimentary Features Closely Timed to Slope Failure Event

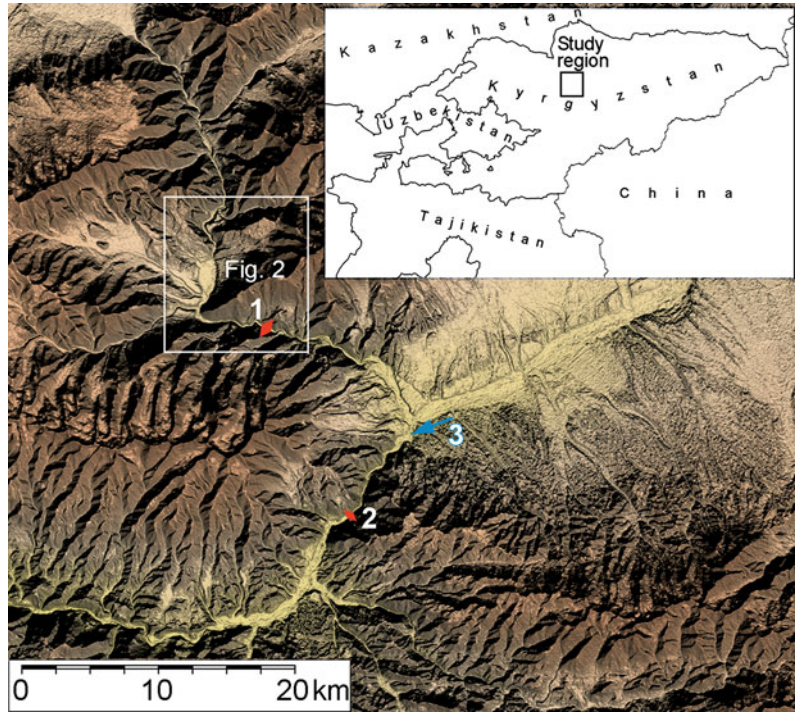
Reliable and well-grounded assumption on seismic origin of a particular large-scale bedrock landslide could be based on the analysis of minor slope failures or liquefaction-induced features located at some distance from the master event but closely related to it in time. This can be exemplified by the Late Pleistocene Kokomeren rockslide and by the Holocene Lower-Aral rocks avalanche in Central Tien Shan, Kyrgyzstan (Fig. 3.1) both of which caused river damming.

### 2.1 The Kokomeren Rockslide and Dammed Lake

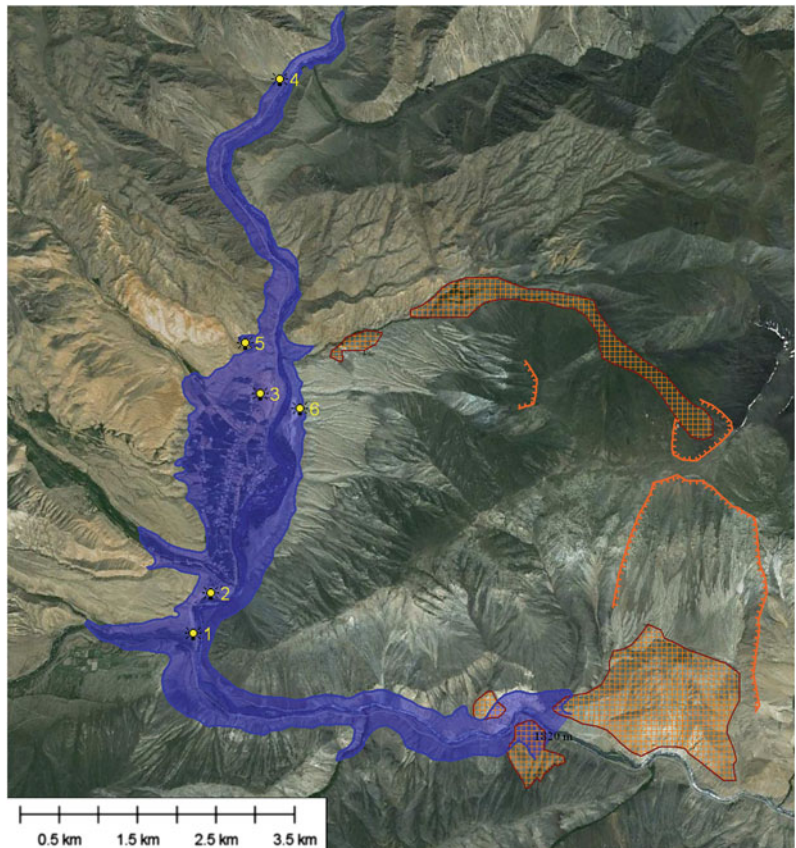
Rockslide about  $1\text{ km}^3$  in volume occurred on the 1600-m high northern slope of the Kokomeren River valley, formed a dam with maximal height up to 400 m that was deeply eroded subsequently, and a lake that impounded river valley for at least 14 km (Fig. 3.2).

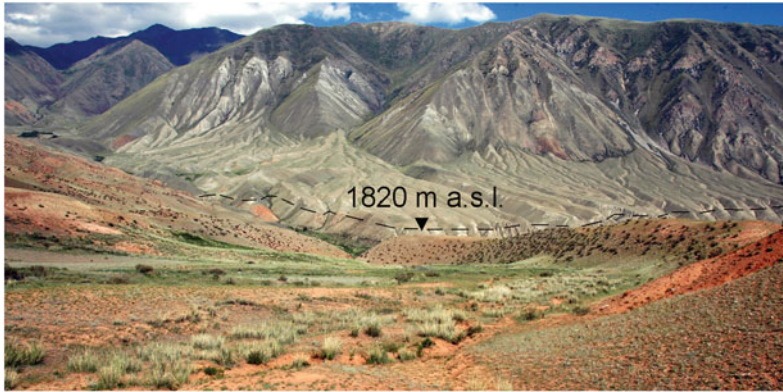
Judging from the uppermost level of lacustrine sediments that have been identified (4 and 5 on Fig. 3.2), water rose at least up to 1820 m a.s.l., indicating the dams' effective height not less than 130 m. Since the river had cut a new bypass gorge through the bedrock and there are indications that the lake had been significantly

**Fig. 3.1** Location of the case studies described. 1 the Kokomeran rockslide, 2 the Lower-Aral rockslide, 3 liquefaction site in the past Lower-Aral lake sediments



**Fig. 3.2** Past lake dammed by the Kokomeran rockslide at minimal water level of 1820 m a.s.l. Hatched areas—landslide deposits; red lines with short teeth—headscarps; yellow numbered dots—outcrops mentioned in the text





**Fig. 3.3** The Kyzyl-Oi intermountain depression, whose lower part was submerged by the lake. Neogen red beds at the foreground; Paleozoic ridge with coalescing debris

flow fan at the background. Active fault passes at the foot of the ridge. Elevation marks point 6 on Fig. 3.2

filled by lacustrine sediments, it was hypothesized that the water body had existed for about 1000 years (Hartwich et al. 2008).

Features that had originated simultaneously with master event should be imbedded in the stratigraphic sequence immediately below or within the basal layer of the lacustrine sediments. Such units were found out about 5 km upstream from the dam (from 1 to 2 on Fig. 3.2), where the lake had occupied small intermountain neotectonic Kyzyl-Oi depression. Between this site and the dam the lake had filled deep narrow gorge (see Fig. 3.2) that was impounded, most likely, shortly after damming. Considering present-day mean discharge of the Kokomeren River of about  $80 \text{ m}^3/\text{sec}$  [State Water Inventory 1987], water probably appeared at this site less than in 5 days after river damming. Such time span is much less than the precision of any numerical dating method (Walker 2005).

West bank of the lake within the depression was composed of Neogene red beds and characterized by rather smooth terrain, while its east bank lies at the foot of high ridge composed of Paleozoic dark gray metasediments (Fig. 3.3). Here the main part of the lacustrine succession is represented by “classical” laminated silt (1 on Fig. 3.4), locally interbedded by alluvial gravels and debris flow sediments with semi-rounded granite clasts brought by ephemeral streams from the west.



**Fig. 3.4** Lacustrine sediments in the Kyzyl-Oi depression. This exposure is between sites marked by 1 and 2 on Fig. 3.2. Here 1 laminated silt unit; 2 basal matrix supported breccia unit

This unit is underlain by 1–1.5 m thick unsorted, poorly bedded matrix-supported breccia with up to 5 cm clasts of east-bank metasediments “floating” in red matrix that originated from the reworked Neogene clay and silt brought from the west (2 on Figs. 3.4, 3.5). Besides dark-gray angular clasts there are some semi rounded “boulders” of Neogen siltstone or mudstone (at 65–80 cm on Fig. 3.5) whose roundness indicates that they were transported from a more distant zone. At some locations this

**Fig. 3.5** Sedimentary features of the coarse bedded basal breccia underlying laminated silt layers



breccia is mixed with well-rounded alluvial cobbles and boulders that could be brought here from the adjacent river terrace. Basal breccia is exposed in several outcrops at a distance of about three kilometers (from point 1 to point 3 on Fig. 3.2).

It is evident that basal unit reflects initial reworking of the surficial sediments by rising water. However, presence of large amount of unrounded clasts of metasediments at a rather large distance from their source slope could be due to abnormally intensive entry of debris from the high east-bank slope caused by strong motion of the main shock and, likely, aftershocks. Most probably they were brought here by debris flows that originated on the steep opposite slope of the valley (see Fig. 3.3). Pure gravitational collapse of scree would not be able to bring debris 200–300 hundreds meters far from the slope foot.

At the southern end of this outcrop (point 1 on Fig. 3.2), which is at a closest distance from the high opposite slope, the basal breccia is replaced by chaotic clast-supported dump of angular blocks up to 30–50 cm, rarely 1 m in size (Fig. 3.6). Blocks at the upstream part of this outcrop are partially mixed with well-rounded granite boulders typical of stream facies of alluvium. This unit is a typical rockfall from the opposite—east bank of the river that collapsed, likely, directly in the stream just before the site was submerged by rising water. Similarly to the matrix-supported basal breccia it had been overlaid by laminated silt layers visible at a right upper part of Fig. 3.6.

Later on the entire succession resting within the active fault zone was tilted northward and, again later on—displaced by significant (up to several meters) right-lateral strike-slip offset along NE-SW-trending rupture, proving the recurrent style of tectonic deformations along this fault zone (Strom and Stepanchikova 2008). It can not be excluded that the Kokomeren rockslide itself could be triggered by the earthquake at the same fault. However, the surficial manifestation of that event is masked by rockfall and stream alluvium.

Lake sediments on the opposite—east bank of the river are represented by coalescing debris flow fans (can be seen on Fig. 3.3 at the background) overlying alluvial gravels. The elevation at which these fans' surface remains now shows that they were deposited at the level much higher than the level of the west-bank basal unit (compare Figs. 3.3 and 3.4). It should be noted that debris flows did not erode the top of the alluvial gravelly sediments. All this indicate that distal parts of debris flows had entered into the lake that was impounded less than in one year [volume of the lake is roughly estimated from 5 to  $7 \times 10^8 \text{ m}^3$ , while Kokomeren present-day mean annual discharge is  $2,5 \times 10^9 \text{ m}^3/\text{year}$  (State Water Inventory 1987)].

There is also some not very clear evidence that these fans had buried deposits of several minor rock avalanches, similar to a larger one that had collapsed from the northern side of the same ridge where the Kokomeren rockslide had originated (see Fig. 3.2). Ambiguity of such

**Fig. 3.6** Accumulation of angular blocks of metasediments mixed at the right side with alluvial granite boulders. Site is about 70–100 m downstream from the outcrop shown on Fig. 3.4



interpretation comes from the fact that both rock avalanches and subsequent debris flows had exactly the same source zone and, thus, are composed of very similar material. I want to point out that formation of debris flows is typical of the epicentral zones of strong earthquakes, which could be exemplified by the events following the 2008 Wenchuan earthquake (Tang et al. 2011).

Additional evidence in favor of the Kokomeren landslide seismic origin are: (A) it fell on the terrace about 100 m high above that time riverbed, which excludes slope undercutting by erosion as possible alternative triggering factor; (B) active fault displacing river terraces few hundreds meters downstream from the dam site stretches directly toward the headscarp area (Strom and Stepanchikova 2008).

## 2.2 The Lower-Aral Rock Avalanche and Dammed Lake

One more case study allowing some speculations on the simultaneity of the master landslide and of minor sedimentary features could be found in the same valley, 13 km downstream from the Kokomeren landslide. Here, immediately south from the Aral village, in the road cut one can observe laminated lacustrine silt

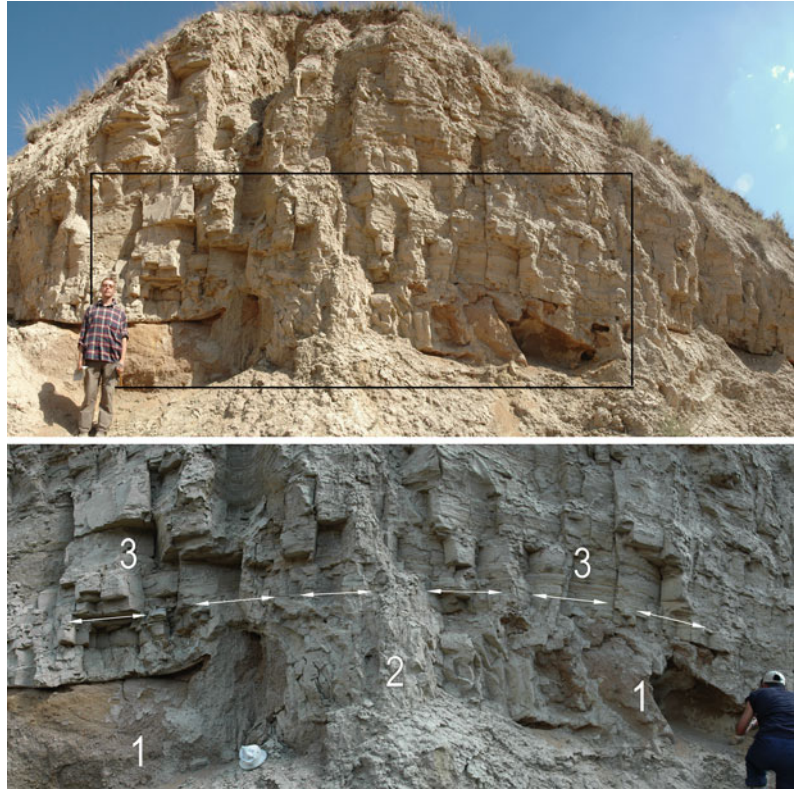
overlying thick unsorted and poorly bedded mixture of coarse arkose sand and detritus representing the reworked granite talus (Fig. 3.7).

This site is located at the distal part of the past lake dammed about 10 km downstream by the Holocene Lower-Aral rock avalanche that had blocked the Kokomeren River by a 70-m high dam (2 on Fig. 3.1).

The most interesting peculiarity of this outcrop is the presence of liquefaction-induced features—the lowermost layers of laminated silt had sank into the underlying basal coarser unit, while younger laminae are not subjected to such deformations. It means that both units—massive poorly sorted basal layer and overlying laminae were in liquefiable state and, thus, liquefaction occurred soon after these units deposition.

The observed features could be explained as follows. The main shock of an earthquake (of course not of the same that, likely, triggered the Kokomeren rockslide) caused rock avalanche that blocked the valley. The narrow gorge was impounded rather soon after the event—less than in one month approximately, judging from the  $2,5 \times 10^9$  m<sup>3</sup>/year mean discharge of the river (State Water Inventory 1987) and lake volume of about  $1.2 \times 10^8$  m<sup>3</sup>. Slope reworking by rising water caused formation of the basal unsorted unit (1 on Fig. 3.7), and, later on, gave place to deposition of overlying initial laminated silt

**Fig. 3.7** Lacustrine sediment accumulated at the tail-end of the past lake dammed by the Lower-Aral rockslide. *Above*—an overview. *Below*—marked part photographed in the shadow. 1 basal massive coarse arkose sand; 2 lower part of silt unit affected by liquefaction, whose portion in the center sank in the basal sand; 3 upper part of silt unit (boundary is marked by beheaded arrows) represented by nearly horizontal laminated layers

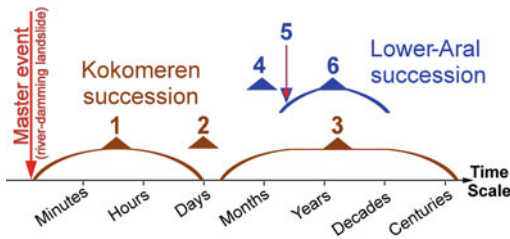


layers (2 on Fig. 3.7). Liquefaction of loose water-saturated sediments and formation of liquefaction-induced features could have been caused by strong aftershock(s) that occurred after the primary earthquake. Subsequent lake sedimentation was not disturbed by any dynamic effects and resulted in accumulation of undisturbed laminated silt layers (3 on Fig. 3.7).

Quite limited extent of the outcrop (practically the entire site can be seen on the upper part of Fig. 3.7), and absence of other similar exposures do not allow such sound conclusion on seismic origin of the features described as, for example, in the Issyk-Kul basin, where liquefaction-induced features were observed in the numerous kilometers-long exposures of Quaternary lacustrine sediments (Korjenkov 2000). Nevertheless, this case study demonstrates another type of the phenomena distant from the master event in space but closely linked with it in time, which allows assumption of seismic origin of both.

### 3 Discussion

According to Malamud et al. (2004) strong earthquakes and other energetic triggering phenomena like typhoons and snowmelt usually produce one or few large and extra-large landslides along with numerous medium and minor features. Indeed, the 1911 M7.4 Sarez earthquake triggered only one gigantic Usui landslides without anything else comparable (Ischuk 2011), the same year M ~ 8.2 Kemin earthquake—four large bedrock landslides up to several tens of million m<sup>3</sup> in volume and hundreds small and medium-size landslides and rockfalls (Bogdanovich et al. 1914), the 2005 M7.6 Kashmir earthquake—one extra-large Hattian Bala rockslide ~85 Mm<sup>3</sup> in volume and numerous smaller events (Owen et al. 2008), the 2008 M7.9 Wenchuan earthquake—one gigantic Daguangbao bedrock landslide 0.75–1.1 km<sup>3</sup> in volume (Wu et al. 2010; Yin



**Fig. 3.8** Succession of events that occurred after formation of large-scale Kokomerren landslide (*brown*) and Lower-Aral landslide (*dark-blue*). Large *red arrow*—master event likely triggered by strong earthquake. 1 rockfalls and abnormal talus formation; 2 deposition of poorly sorted breccia at the base of the dammed lake sediments; 3 laminated lacustrine silt accumulation; 4 deposition of poorly sorted coarse arkose sand at the base of the dammed lake sediments; 5 formation of the liquefaction-induced features likely triggered by strong aftershock; 6 laminated lacustrine silt accumulation

et al. 2011), several much smaller landslides—one-two orders less in size and more than 60,000 medium and small slope failures (Yin et al. 2009; Huang and Li 2009), etc.

It is evident that hundreds and thousand years after the event it would be difficult to proof that several large-scale slope failures occurred simultaneously, though it is one of the most widely used criteria, allowing seismically triggered landslides identification (Crozier 1992). This criterion is often used for landslides located close to a large active fault (e.g. Belousov et al. 1994, Bull 1996). Such approach requires extensive dating, which is not always easy to perform and whose precision could be not as high as necessary.

Case studies described above allow sufficiently sound conclusion on very close timing of master events—large-scale slope failures and of other phenomena that occur at a rather large distance from the former ones. In the Kokomerren case these are rockfalls and increased talus accumulation that could occur within few days between rockslide formation and rise of water in the reservoir. In the Lower-Aral case liquefaction of loose lake sediments could take place shortly (likely from months to years) after river-damming landslide (Fig. 3.8). Close timing, in turn, along with sound reasoning that spatially distributed minor sedimentary features could be triggered by seismic shaking,

provide strong, though indirect argument of seismic triggering of master events.

Back analysis of slope stability can be very useful to discriminate between seismic and non-seismic origin of the master landslide. In the above cases, however, one can not reconstruct the pre-sliding topography and structural pattern of the detachment zone with relevant accuracy. This prevents reliable estimate of safety factor leaving us with indirect evidence only.

In the two landslide cases discussed, the “classical” silt laminae are underlined by unsorted or poorly sorted unit up to 1–1.5 m thick. This reflects the initial stage of the impoundment when rising water reworks the local slope materials. It could be hypothesized that abnormally intensive material reworking was supported by additional drift of debris or by its loosening caused by strong seismic shaking. Confirmation or disproof of this assumption requires more studies of the sediments accumulated in the existing and past lakes dammed naturally or artificially.

## 4 Conclusions

Careful analysis of basal units of sediments from landslide-dammed lakes allows identification of spatially distributed sedimentary features closely timed to the main landslide occurrence even if we have no possibility to date them precisely. Time span between phenomena that produced both master and accompanying events could be much less than the precision of most of modern dating methods (Walker 2005).

Convincing evidence that spatially distributed minor sedimentary features closely timed to master event could be triggered by seismic shaking, provide additional, though indirect argument of seismic triggering of the river damming landslide itself.

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