Recent earthquake-triggered landslide events in Central Asia, evidence of seismic landslides in the Lesser Caucasus and the Carpathians

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ABSTRACT:

This chapter presents an overview of earthquake-triggered landslide hazards in Central Asia, with a focus on the Tien Shan and Pamir Mountain Ranges. It essentially compiles information presented by the author in his previous publications as well as other published results. This overview will show that in Central Asian mountain areas most giant mass movements are likely to have a seismic origin – though it cannot be proved for most of them (see companion report by A. Strom). Here, we will briefly introduce those paleo-cases to establish a link with the Carpathian Mountains and the Lesser Caucasus, where old massive landslides could have a seismic origin as well and thus could provide information on ancient high-magnitude earthquakes for which no written information is available.

In recent history, large earthquakes triggered only minor slope failures in the Carpathians and the Lesser Caucasus, while almost all M>7 events that occurred last century in Central Asian mountain ranges triggered numerous landslides, including at least one two-billion m^3 mass movement. However, none of these events can be compared with the 1999 Chi-Chi, the 2005 Kashmir or the 2008 Wenchuan earthquakes, which had triggered many thousands of landslides. The question is then – are such events impossible in Central Asia (maybe due to the much dryer climate than in the regions affected by the cited earthquakes) even though high-magnitude earthquakes are relatively common in the Tien Shan and Pamir? One possible response will be provided by a detailed outline of the largest earthquake disaster that had affected the Central Asian mountain regions in historic times: the Khait event in 1949. Some additional notes will outline the potential for future massive landslide activation during earthquakes in Armenia and Romania.

INTRODUCTION

During the last twenty years, after a series of disastrous earthquake events in mountain regions in Taiwan (1999), El Salvador (2001), Pakistan (2005), China (2008) and Nepal (2015), increasing attention has been addressed to landslides triggered by earthquakes.

Previously, landslides have been considered as minor effects of earthquakes compared to the impact of the ground shaking itself. Schuster and Highland (2001) partly attributed the perception of the relatively small impact of earthquake-triggered mass movements to the fact that many related losses are often referred to as direct consequences of the earthquake. The assumption of the global 'secondary' importance of earthquake-induced landslides and other ground failures was confirmed by a study undertaken by Bird and Bommer (2004) – even though they also admit that, for some earthquake risk scenarios, seismic ground failures need to be taken into consideration to correctly estimate total losses. Explicitly, it was only noticed for the two El Salvador earthquakes in 2001 that 'the most devastating impact … has been the triggering of hundreds of landslides in volcanic soils, …' (Bommer et al., 2002).

This study of Bird and Bommer (2004) had been completed well before the M=7.6 earthquake hit the Kashmir Mountains on October 8, 2005. For this event, Petley et al. (2006) estimated that about 30% of the total number of people killed (officially 87,350), i.e. 26500, had been victims of co-seismic landslides. Less than three years later, on May 12, 2008, the Wenchuan earthquake hit the Sichuan and neighbouring provinces of China and caused 'more than 15,000 geohazards in the form of landslides, rockfalls, and debris flows, which resulted in about 20,000 deaths' (Yin et al., 2009). These deaths represent again almost 30 % of the official total number of fatalities (69,197) of this event.

In this paper, the focus will be on the Central Asian mountain regions, the Tien Shan and Pamir, on the basis of landslide case histories related to the following earthquakes (see locations in Fig. 5.1): M=6.9 Belovodsk, 1885, M~7.3 Verniy, M=8.2 Kemin, 1911, M=7.6 Sarez, 1911, M=7.4 Khait, 1949, M=5.5 Gissar, 1989 and M=7.4 Suusamyr, 1992 (Mushketov, 1890; Leonov, 1960; Havenith & Bourdeau, 2010). One landslide case history is added to document the mid-term effect of small and medium-sized earthquakes on slope stability and related hazards in the Tien Shan Mountains.

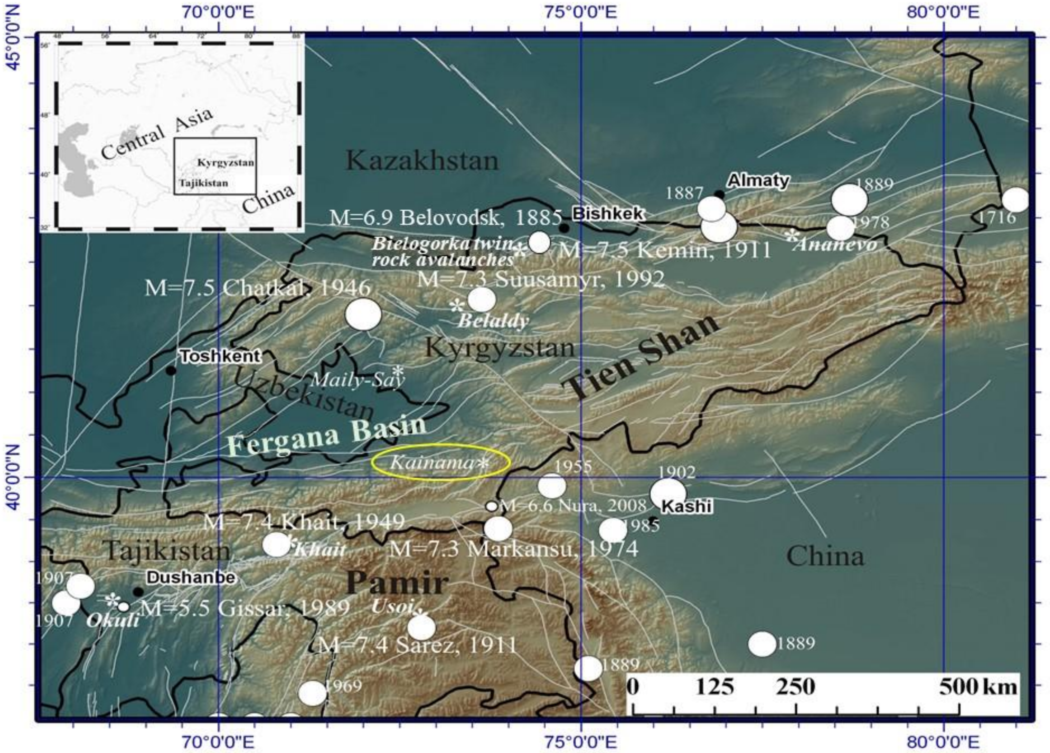


Fig. 5.1. Map of the Tien Shan and Pamir Mountains in Central Asia, with locations of major faults and earthquakes (circles show all M≥6.9 earthquakes recorded prior to 2010 with the year of occurrence; the magnitude is indicated for analysed events) and related major mass movements (stars) (modified from Havenith & Bourdeau, 2010).

Three other historical M>7 earthquakes in the Tien Shan Mountains will not be further documented here since we know very little about their related impacts: the 1889 M>8.0 Chilik earthquake north east from Issyk-Kul Lake, the 1946 M7.5±0.2 Chatkal earthquake in the Western Tien Shan, for which some data about triggered mass movements and landslide dams are provided by Leonov (1965), and the M=7.3 Markansu earthquake affecting remote areas of the Southern Tien Shan, for which Nikonov et al. (1983) indicated some data about induced ground failures.

Special attention will be paid to the long-term effects of earthquakes in mountain regions. Examples will be shown for clearly delayed triggering of slope failures after earthquakes and post-seismic increase in landslide activity, as was observed after the 2008-Wenchuan earthquake in Sichuan, China. In this regard, we will also analyse previously called ‘secondary or tertiary effects’ of earthquakes, such as natural dams and related flooding impacts. In the Tien Shan, the most recent massive natural dam was formed after the Suusamyr earthquake in 1992 – it partly failed in 1993, thus causing a long-runout debris flow downstream (Havenith & Bourdeau, 2010).

Massive rockslides that have characteristics of seismic slope failures (initiation high on slopes, very deep scarps, anti-dip failure) can also be found in the Carpathians and the Lesser Caucasus – where they are far less studied (e.g., in comparison to the Greater Caucasus and the Tien Shan - Pamir). Especially in the Carpathians, such ancient massive rockslides could play a major role in seismic hazard assessment, as little historical information is available for the time before the largest event that is known for the Vrancea seismic region (SE Carpathians, Romania), the M7.8-7.9 ‘Great Earthquake’ in 1802 (Havenith et al., 2016). Since then, at least 4 other M>7 earthquakes occurred in the same area – but none had triggered landslides that are comparable to the large old deep-seated mass movements that our team is now studying in the SE Carpathians – they could be markers of ancient (>300 years) M>=8 earthquakes. Below, we will provide some data on two of those massive landslides.

Surprisingly, also relatively little historical information is available for landslides triggered by earthquakes in the Lesser Caucasus – even though Armenia and the neighbouring regions have a rich and long well-described earthquake history. At least, two massive slope failures are more-or-less well documented, one triggered by an earthquake in 1840 from Mount Ararat (formerly located in Armenia, now in Turkey), as well as the rock avalanche of Kamaz Mountain, triggered in 1139 by the Ganja earthquake, damming several lakes, including the well-known Goy-Gol Lake, in Azerbaijan (both case histories are briefly reviewed below). Other well-known giant mass movements are generally much older – but are also worth study (e.g. in Garni), for the same reasons as those presented for Romania: they can help assess seismic hazards, especially for long return periods, notably by setting the maximum possible magnitude.

Most of the information presented here for Central Asia has been extracted from Havenith et al. (2015) and Havenith and Bourdeau (2010), for Armenia from Matossian (2017), and for Romania from Mreyen et al. (2017).

Case histories from Central Asia

Nadim et al. (2006) assessed landslide and avalanche occurrence probabilities worldwide on the basis of morphological, geological, meteorological and seismological data. They clearly showed that all landslide hotspots are located in seismically active mountain ranges. For Central Asia (Fig. 5.2), they estimate that global landslide hazard can be rated as medium to very high. They further noted that some areas in Tajikistan are marked by the highest mortality risk due to landslides.

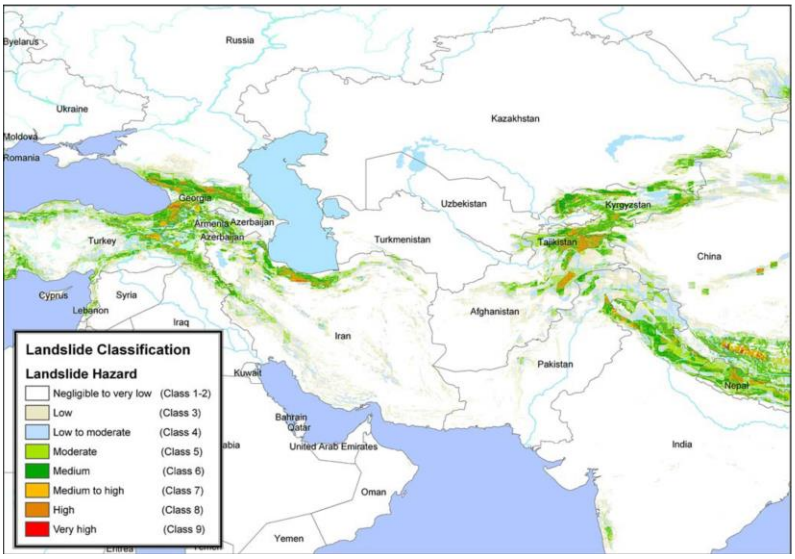


Fig. 5.2. Landslide hazard map of Central Asia and Middle East (from Nadim et al., 2006)

Below, we present a short overview of earthquake events that have (or are believed to have) triggered landslides in Central Asia, focusing on effects in the Kyrgyz Tien Shan and two major events in Tajikistan, in 1911 and 1949. However, it should be noted that the 1887 Verniy and 1889 Chilik events also caused widespread and large rock slope failures, mostly in the northeastern Kazakh part of the Tien Shan (some exceeding several tens of millions of cubic meters in volume, according to Mushketov, 1890 and 1891); we will not review those in detail as we did not directly study their effects.

1885 Belovodsk earthquake

The first documented observations of seismic surface effects in Kyrgyzstan were made after the M=6.9 Belovodsk earthquake rupturing the Issyk-Ata thrust fault (see Fig. 5.1). This seismic event affected the northern slopes of the Kyrgyz Range (Ignatiev, 1886; Mushketov, 1890), as well as the region around the capital Bishkek (that time called Pishpek). According to both contemporaneous reports and oral accounts, the earthquake caused many slope failures. Two neighboring rock avalanches located close to the village of Bielogorka occurred at an epicentral distance of less than 15 km and at about 25 km south of the activated Issyk-Ata fault. Besides the geographic relationship, no direct (temporal) links exist, however, between the earthquake and the rockslides. Anecdotal evidence is only provided by an old man who claims that his ancestors were killed by the larger rock avalanche in 1885 (K. Abdrakhmatov, personal communication). Further discussion on the seismic origin of the rock avalanches is presented in the next section.

In August 2017, we had completed a new survey with a drone of the Bielogorka site and a 3D model has been constructed (Fig. 5.3). In 1998, we had tried to provide a minimum date to those rock avalanches through dendrochronological analyses applied to Archa trees growing on the deposits of the rock avalanches. We had hoped that this minimum age would be close to 110 years, thus providing the missing temporal link between the 1885 earthquake and the occurrence of those massive failures. However, those analyses provided maximum ages of only 50 to 60 years for the Archa trees, which is much more recent than the seismic event. One explanation for this difference is that those trees did not start growing on the deposits (which are purely made of bare rocks) right after failure, but that first some local soils had to develop before trees could grow on them. Another reason advanced by Strom and Abdrakhmatov (2018) is that all trees in that region had been cut by local people to get fuel during the difficult times of the Second World War (as all trees, also outside the rockslide zone, were found to be not older than 55 years in 1998). Anyway, our data showed that the rock avalanches are not 'ancient' and must be younger than a few hundreds of years. We, therefore, concluded that the only event that could have triggered those 'twin rock avalanches' must have been the 1885 event.

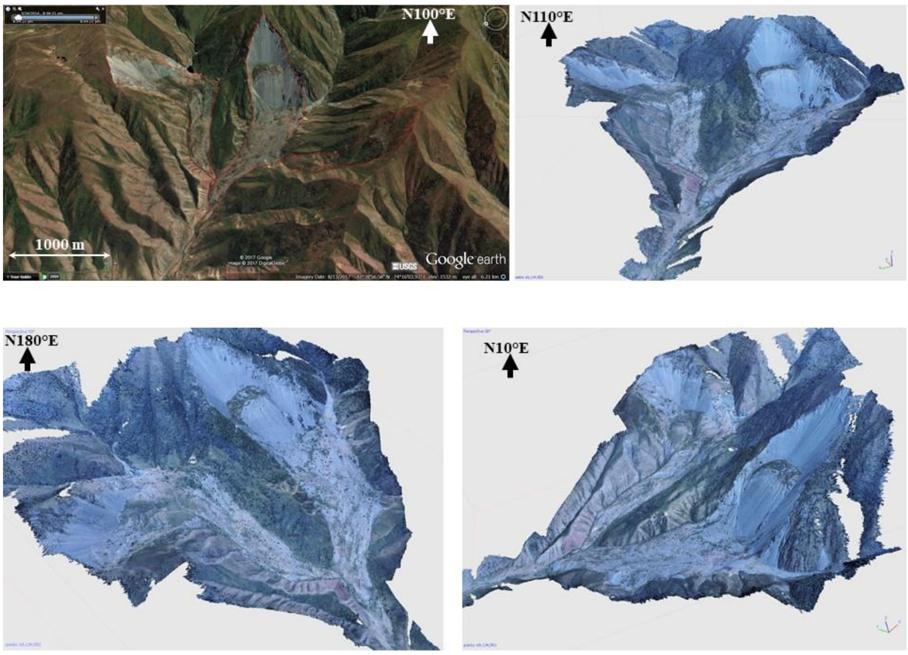


Fig. 5.3. Bielogorka twin rock avalanches (coordinates: N42°38'26", E74°16'54"). Top left: Google Earth view (2017 image, see also scale and view orientation); other views of 3D drone image model (completed in 2017)

1911 Kemin earthquake

The Kemin Ms = 8.2 earthquake of 1911 (January 3) is one of the largest events ever recorded in the Tien Shan; it was first analyzed by Bogdanovich et al. (1914). The earthquake caused extensive landsliding along the activated fault segments over a length of 200 km. The largest mass movements were three rockslides, one within the Kemin valley, another one north of Lake Issyk-Kul, and the third one in the upper reaches of the Chilik River. The first rock avalanche (about 15 x 10^6 m^3) made of limestone material occurred along the activated Chon Kemin fault at about 60 km W of the epicenter; it is known to have buried a village of yourts with 38 inhabitants. The second 'Ananevo' rockslide located in the north of Lake Issyk Kul (at some 80 km E of the presumed epicentre) is one of the most prominent features produced by the Kemin earthquake (see Fig. 5.4). Failure took place at the southern end of a mountain ridge, just above the discontinuous Chon Aksu fault also activated by the 1911

Kemin earthquake (see also lake dammed by reactivated fault scarp at about 30 km to the W of Ananevo rockslide in Fig. 5.5). According to Delvaux et al. (2001), this section of the Chon Aksu fault is a thrust gently dipping towards the northeast into the collapsed slope. Evidence of the presence of the fault is the related scarp with a height of 1 m at 3 km WNW of the site, increasing up to almost 10 m at 12 km to the WNW. On the site itself, outcrops at the foot of the southwest-oriented slope show particularly disintegrated and weathered granitic rocks within a 100-200 m thick fault zone.

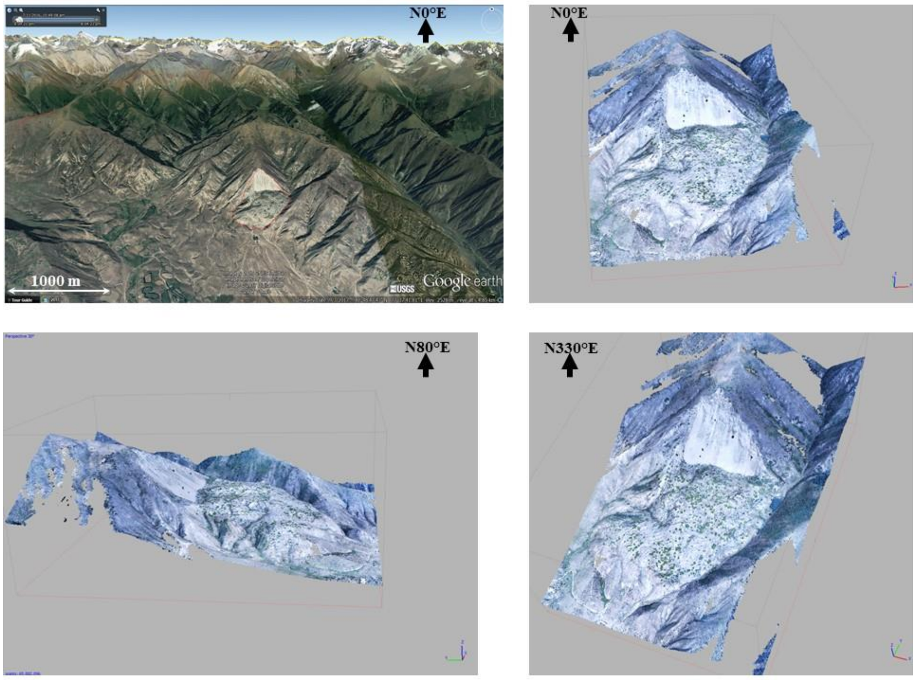


Fig. 5.4. Ananevo rockslide (coordinates: N42°48’15”, E77°37’40”). Top left: Google Earth view (2017 image, see also scale and view orientation); other views of 3D drone image model (completed in 2017)

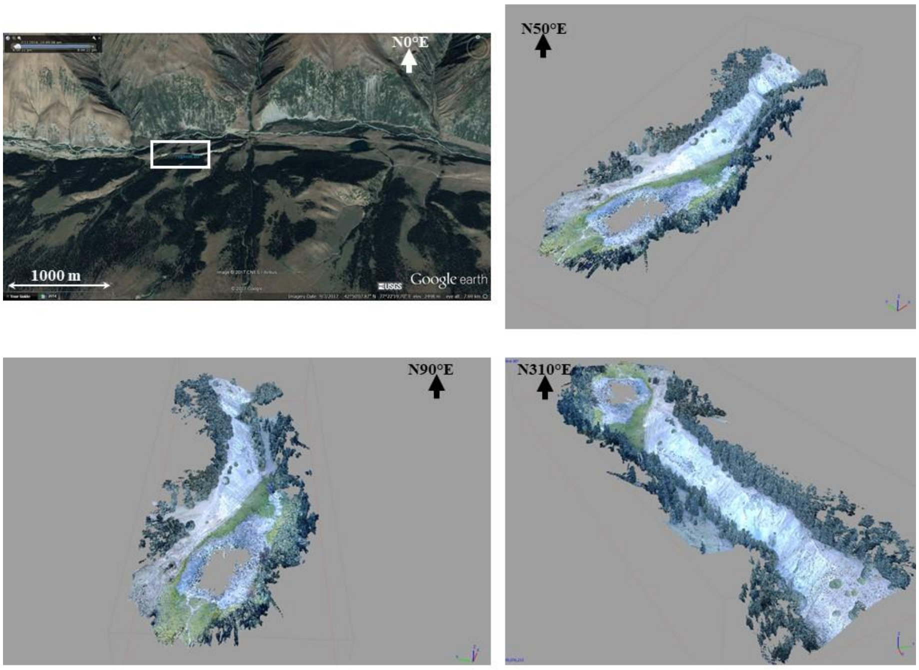


Fig. 5.5. Chon Aksu fault scarp dammed lake (coordinates: N42°50’15”, E77°21’54”). Top left: Google Earth view (2017 image, see also scale and view orientation); other views (of rectangle shown in Google Earth image) of 3D drone image model (completed in 2017)

1911 Sarez earthquake

The Sarez earthquake, Ms=7.6, struck the central Pamir Mountains, Tajikistan, on February 18, 1911. Such an earthquake is likely to have triggered hundreds or thousands of mass movements, but only one is well documented: the giant Usoi rockslide (Fig. 5.6), which fell from a 4500 m high mountain down to an elevation of 2700 m in the valley (Schuster & Alford, 2004). This rockslide has formed a dam with a volume of about 2 x 10^9 m^3 on Murgab River. According to Schuster & Alford (2004), the location of the slide is related to 'a high degree of rock fracturing from previous tectonic activity…a major thrust fault with an unfavorable orientation …and… a series of intensively sheared zones forming geometric setting for a typical wedge failure.' One more, though several orders of magnitude smaller, slope failure occurred on the opposite slope of the ridge in the Kudara River valley.

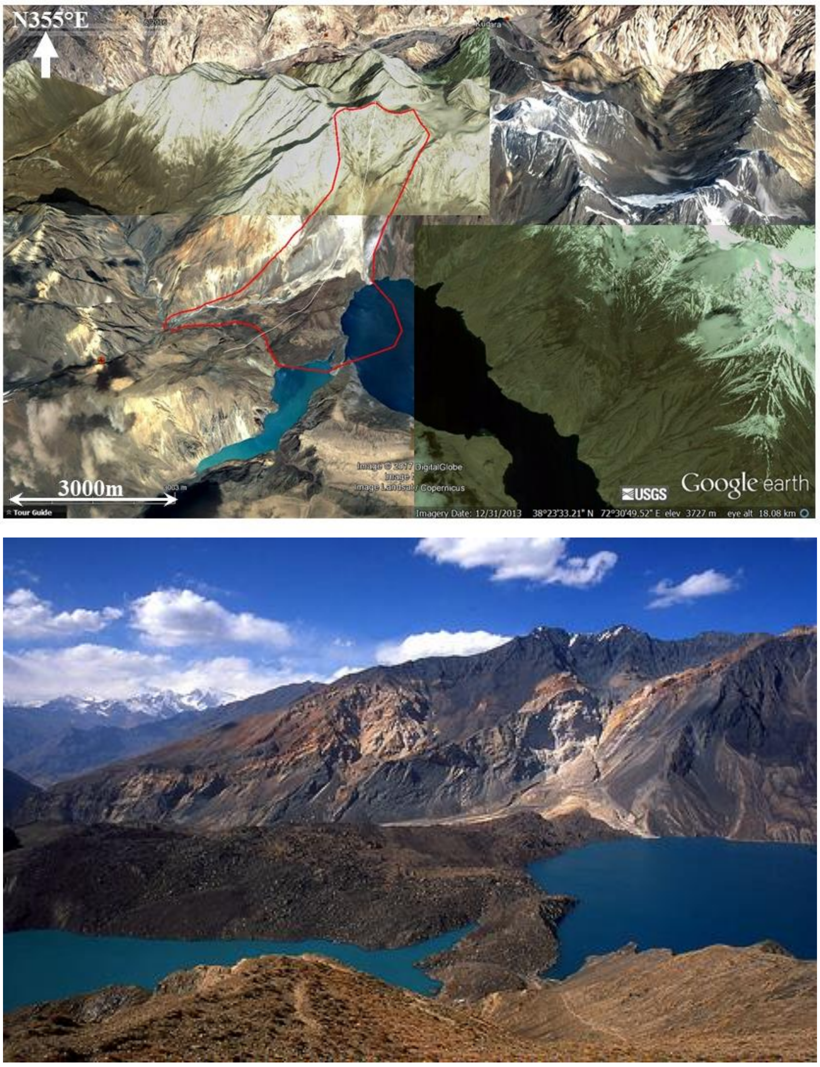


Fig. 5.6. Above: Usoi rockslide (coordinates: N38°17'10", E72°36'20") outlined in red with dammed Sarez (right) and Shadau (left) lakes (compiled Google earth imagery). Below: field view of dam and source area (behind) – (Photo from: http://wikimapia.org/1739699/Sarez-Lake#/photo/584782).

Behind this 600 m high natural dam (the highest dam in the world), Lake Sarez and the smaller Lake Shadau had been impounded (views shown in lower part of Fig. 5.6), the first one with a maximum depth of 500 m.

Various scenarios consider the risk related to the failure of the rockslide dam due to internal erosion or overtopping, as well as to a flood wave induced by the impact of mass movement into Lake Sarez. Those scenarios are discussed by Schuster and Alford (2004) – the worst-case scenario flood wave could affect more than 5 million people living in the Amu Darya River Basin.

1949 Khait earthquake

According to Leonov (1960), the M=7.4 Khait earthquake that struck Northern Tajikistan on July 10, 1949, produced one of the most destructive earthquake-triggered landslide events in human history. The western world, however, knows relatively little about it – probably because most information has been published in Russian. First, a massive rock avalanche had buried the villages of Khait and Kusurak, with up to one thousand inhabitants (Fig. 5.7); the exact number of fatalities will never be known since 'during the formidable rule of Joseph Stalin, information about accidents and natural catastrophes was suppressed unless special permission was granted' (Yablokov, 2001). This rock avalanche had been triggered from Borgulchak Mountain at an altitude of about 2950 m and travelled more than 6 km before reaching the inhabited valley at an altitude of 1550 m. The volume was initially estimated to more than 200 x 10^6 m^3 (Leonov, 1960). However, more recent investigations by Evans et al. (2009) and Strom and Abdrakhmatov (2018) indicated that the total volume was much lower, respectively, of about 75 x 10^6 and 100 x 10^6 m^3. Evans et al. (2009) also observed that a significant part of the mass movement was made of loess, which probably contributed to the mobility of the initial rockslide.

Second, Evans et al. (2009) indicate that in the Yasman Valley opposite to the Khait rock avalanche, hundreds of loess earth-slides coalesced to form one massive earth-flow, which is believed to have buried about 20 villages. In total, the Khait rock avalanche, as well as the Yasman loess earth-flows, are likely to have killed more than 5000 people during the 1949 event.

In addition to the catastrophic impacts, Russian geologists described also the general conditions of the earthquake-triggered slope failures. For instance, Leonov (1960) wrote (translated from the Russian original): '…involved are also amplification effects that can explain landsliding far from the epicentre…'. We have visited the Khait rock avalanche and Yasman earthflow sites in summer 2010. We also climbed to the scarp area of the rock avalanche that initiated at an altitude of almost 3000 m. There, we found a characteristic feature of massive rockslope failures triggered by seismic shaking: the scarp formed behind the crest (almost 100 m behind the original crest line), thus increasing the total volume of failed material. Such a feature confirms the severe shaking that was responsible for 'behind-crest' ruptures, which was likely due to topographic amplification effects.

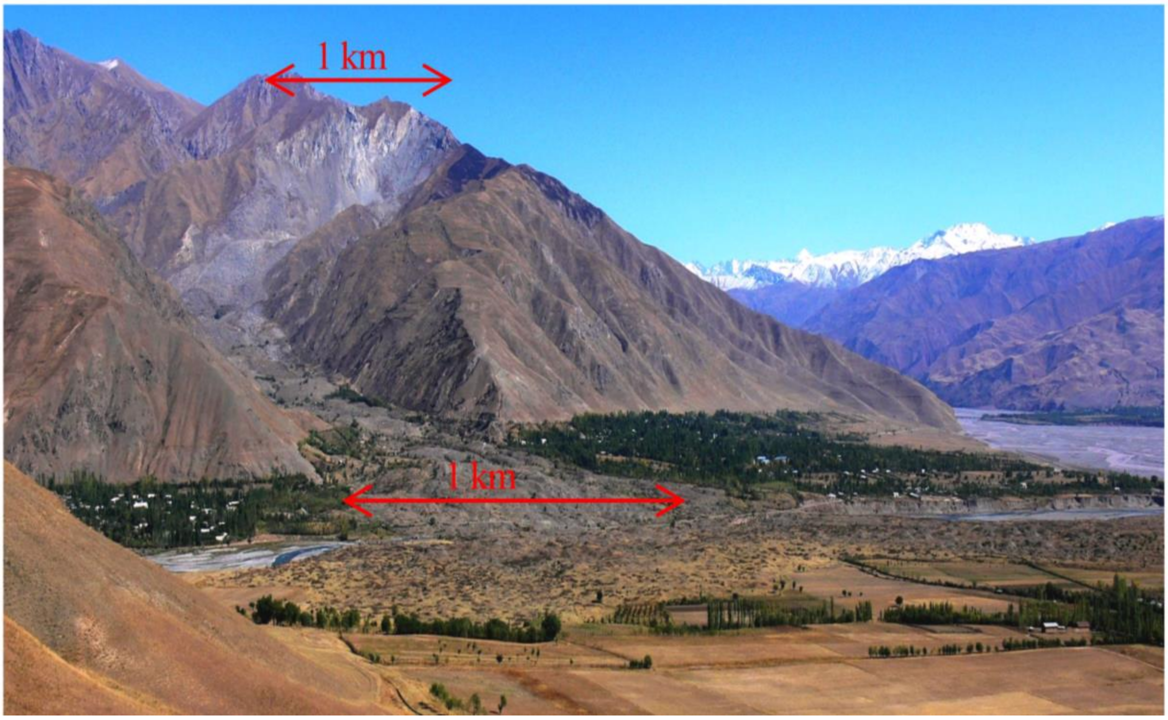


Fig. 5.7. Khait rock avalanche (coordinates: N39°11'13", E70°53'05"): view towards the East from Yasman valley (color version of photograph of 2005 provided by A. Ischuk, published in Evans et al., 2009).

1989 Gissar earthquake

South of Dushanbe, in Gissar, Tajikistan, an Ms=5.5 earthquake on January 23, 1989 triggered a series of earth-flows in loess. At least 250 people were killed and tens of houses were buried, mostly under Sharora landslide. According to Ishihara et al. (1990), Zerkal (1996) and Voznesensky and Zerkal (1997), those slides were all related to extensive liquefaction, which had developed for a horizontal acceleration of about 0.15g. All these authors associated the liquefaction to the 'collapsible nature' of the highly porous loess material (a silt-sized deposit with an average content of clay of 15 % and a low plasticity).

Fig. 5.8. Okuli-bolo loess earth-flow (coordinates: N38°29'01", E68°38'12") (Photographs by Ishihara, 2002)

The largest landslide, called 'Okuli-bolo' (Fig. 5.8), had an estimated volume of 20 x 10^6 m^3. Ishihara (2002) indicated that 'at least two slides seem to have been triggered independently from the hillsides on the north, which then merged into the main stream of the mudflow.' The sliding surface of most landslides was located at a depth of about 15 m, within the saturated part of the 30 m thick loess deposits. Ishihara et al. (1990) also noted that the scarps of many landslides were located along a water channel installed on the shoulder of the hills. They assumed that 'water in the channel had been infiltrating in the loess over years, leading to final failure during earthquake due to liquefaction of water-bearing loess layer'. This is supported by their observation of muddy water oozing from the earth-flow.

1992 Suusamyr earthquake

The most recent large seismic event hitting the Tien Shan Mountains was the Ms=7.3 Suusamyr earthquake on August 19, 1992, triggering various types of ground failures in the Northern-Central Tien Shan (Bogachkin et al., 1997).

Most of the 50 people killed in the remote areas were victims of mass movements. Korjenkov et al. (2004) described a series of ground failures: sagging of mountain slopes, rockfalls, landslides, soil avalanches and flows, mud/debris flows, and also a great variety of gravitation cracks. Extensive ground failures could be observed along the crest and southern slope of the Chet-Korumdy ridge – here, most landslides had developed from previously existing ground instabilities (see views of Chet-Korumdy landslides in Fig. 5.10).

Most of the ground and slope failures that spread over 4000 km^2 around the Suusamyr Basin and the neighbouring mountain ranges were relatively small (much less than 10^6 m^3). A map presenting all detected landslides in the Suusamyr region, as well as ground failures induced by the Suusamyr earthquake, is presented in Fig. 5.9 (modified from Korjenkov et al., 2004).

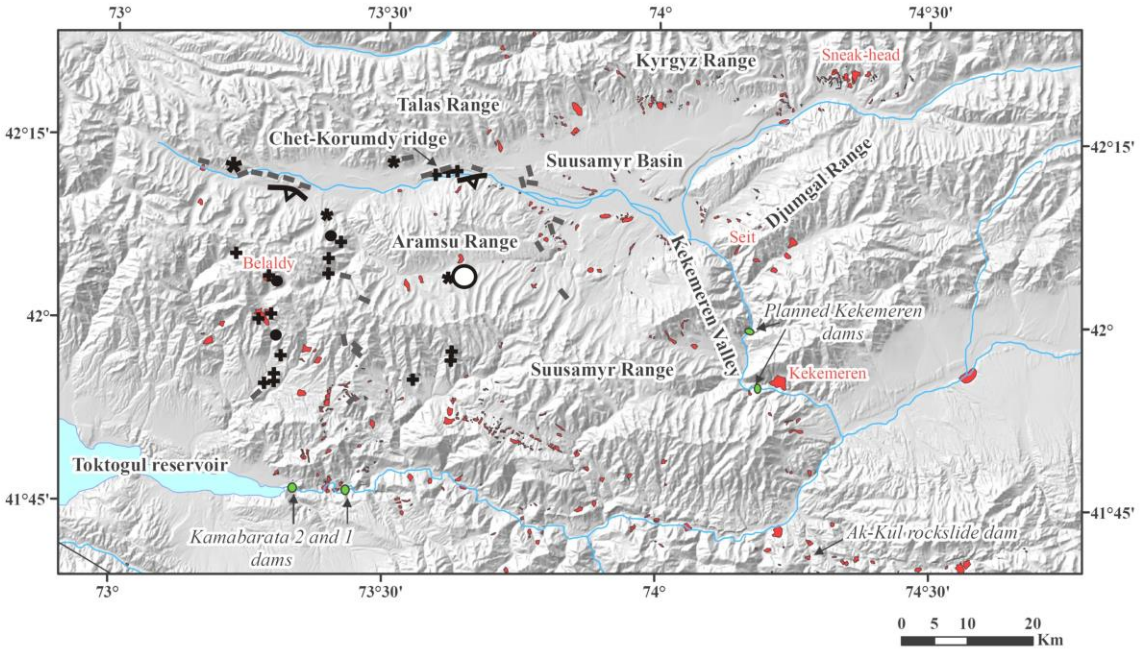


Fig. 5.9. Map of all detected landslides in the Suusamyr region (red), including several ground failures (partly hidden by the black symbols that specifically identify 1992 ground deformations) triggered by the Suusamyr earthquake (modified from Korjenkov et al., 2004 - circle: M=7.3 epicentre; black lines with triangle: 1992 fault scarps; crosses: rockslides and landslides; stars: mud eruptions; grey bars: ground and slope fractures, black dots: rock falls).

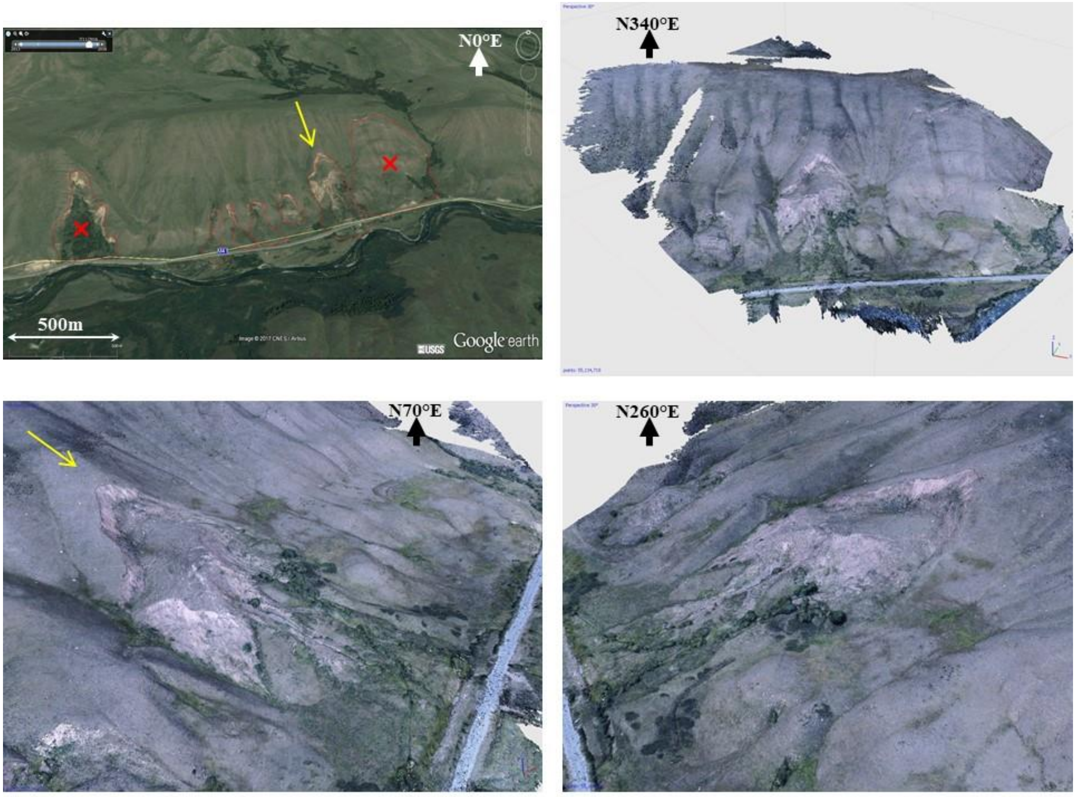


Fig. 5.10. Suusamyr landslide (coordinates: N42°12’25”, E73°36’33”) on Chet-Korumdy ridge (below yellow arrow). Top left: Google Earth view (2013 image, see also scale and view orientation); others views of 3D drone image model (completed in 2017). Note, the left and right landslides (marked by a red cross) in the top left view were not triggered by the 1992 earthquake; they existed before and have not been reactivated.

Only one large rock slope failures, the Belaldy rock avalanche, occurred on the southern slopes of the Suusamyr range (Bogachkin et al., 1997 and Korjenkov et al., 2004). It covered a shepherd's family and a flock of sheep. The situation at the rockslide site before and after the earthquake is shown in Fig. 5.11. This mass movement had formed a dam on Jalpaksu River with a thickness of about 80 m, a width of 500 m, and volume of about 30-35 x 10^6 m^3. Behind the dam, two small lakes were impounded (with an area of 200-300 m^2 in September 1992). In less than a year, the water level had increased enough to induce partial failure of the dam (Korjenkov et al., 2004). This failure resulted in a 20-km-long mud- and debris-flow, which caused a lot of damage to infrastructure of the Toktogul region. The satellite image of 1993 of the Belaldy site (Fig. 5.9) shows the upper part of the debris flow just below the dam. Currently, the dam still has a volume of about 25-30 x 10^6 m^3, as also estimated by Strom and Abdrakhmatov (2018).

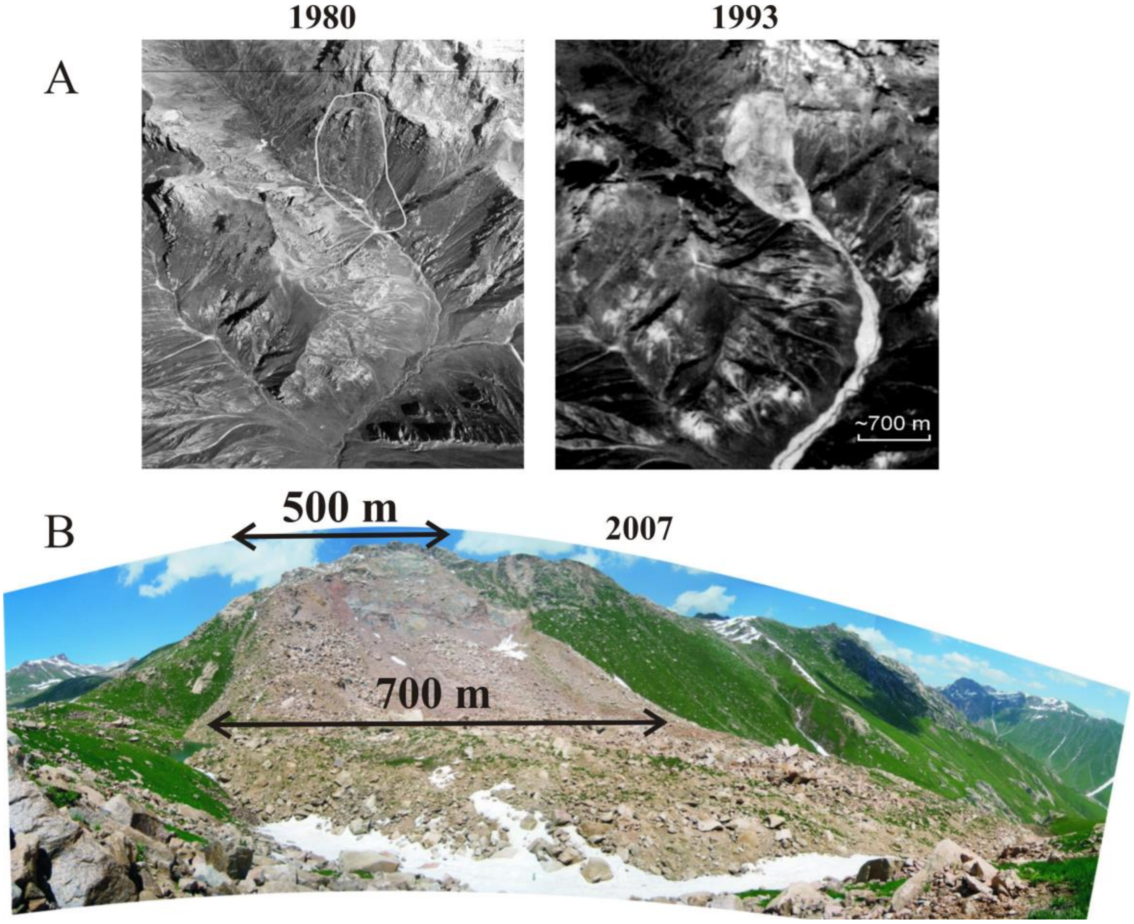


Fig. 5.11. The Belaldy rock avalanche (coordinates: N42°03’39”, E73°16’44”). A) Aerial photograph of the site acquired in 1980 (left), before the 1992 Suusamyr earthquake and satellite image of 1993 (right), after the earthquake. B) Photograph of the rock avalanche made in 2007 (by the author)

2004 Kainama landslide – delayed effect of local M = 4.5 earthquakes?

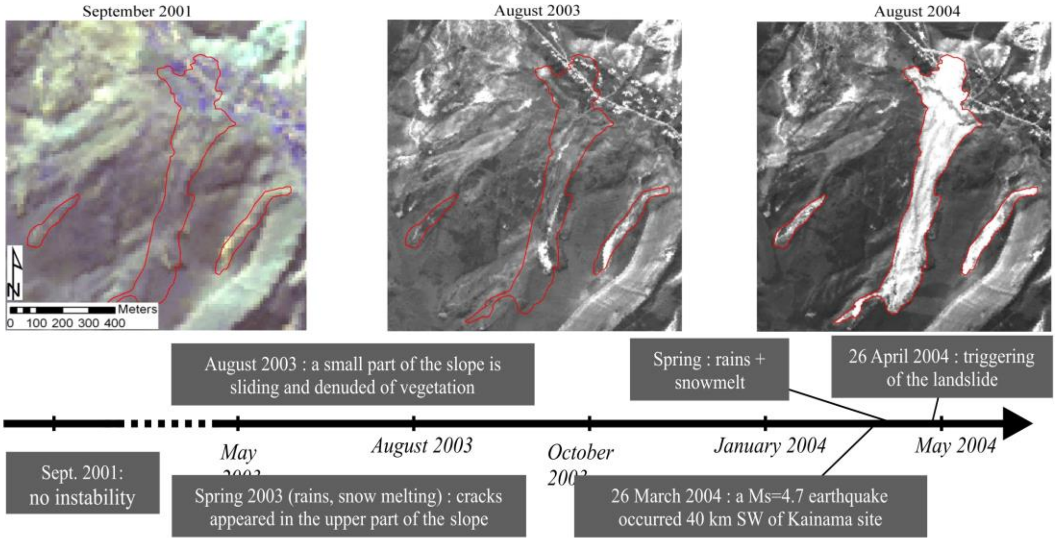
The Kainama earth-flow (220,000 m^3) of April 26, 2004, caused the destruction of 12 houses and the death of 33 people (64 families became homeless, including those living in houses with partial damage) south of the Fergana Basin (location highlighted in Fig. 5.1). This landslide had formed within the loess layer and developed into a very rapid flow with a long runout. Fig. 5.12 shows that, in 2001, no clear sign of instability could be seen. In spring 2003, several cracks appeared on the upper part of the slope.

The main failure of April 2004 was preceded by an increased seismic activity: on 2004 March 26, an earthquake of Ms = 4.7 occurred 40 km SW of the Kainama site (estimated PGA at the site ~ 0.05 g).

Two other smaller earthquakes (Ms = 4.2) were registered some 50 km NW of Kainama on April 8 and 9. New fractures were observed after these earthquakes.

The delay of massive slope failure after the earthquakes is likely to be related to changes in the local environmental conditions. At the end of March 2004, the mountains were still covered by snow and the groundwater level was low. Snowmelt and spring rains in April caused a rapid increase of groundwater level – probably enhanced by rapid water infiltration through the new fractures induced by the earthquakes.

To confirm the important role of this process-sequence for the development of many landslides in seismic areas, numerical modelling studies have been undertaken. Related results were published in Danneels et al. (2008).



Sept. 2001: no instability

August 2003 : a small part of the slope is sliding and denuded of vegetation

Spring 2003 (rains, snow melting) : cracks appeared in the upper part of the slope

Spring : rains + snowmelt

26 March 2004 : a Ms=4.7 earthquake occurred 40 km SW of Kainama site

26 April 2004 : triggering of the landslide

Fig. 5.12. Evolution of the Kainama landslide (coordinates: N40°16’22”, E73°33’51”) from 2001 (ASTER satellite image, left), to 2003 (SPOT image, middle) and 2004 (SPOT image, right)

The most recent large earthquakes in the Tien Shan and Pamirs

For more recent large earthquakes, we have almost no information on triggered landslides. For the 2008 Nura earthquake (M = 6.6) in South Kyrgyzstan we just know that there had been no failures on major highways reaching the area – as we had overviewed the region using satellite imagery taken just after the event – to indicate to authorities if emergency help could be brought by trucks to a village where 75 people had been killed (and 150 were injured) or if helicopters were needed (notably due to obstruction of main roads by rockfalls). We had confirmed that no major rockfalls had occurred along the main roads reaching the remote large Alay Mountain Valley hit by the earthquake.

Furthermore, some information may be added on the last M = 7.2 earthquake that occurred in the Pamirs in December 2015. This event triggered a few minor or partial slope failures around Lake Sarez, but massive rockslides or any serious effect on Usoy dam (besides a general lake level rise of about 20 cm) could not be identified by Ischuk and Strom (2016).

Case histories of possible earthquake-triggered landslides in the Lesser Caucasus (Armenia and neighboring regions)

1679 Garni earthquake

The 1679 Garni earthquake was one of the most destructive earthquakes to have occurred in Armenia. According to historical sources, the intensity was between VIII and X and its magnitude was estimated, accordingly, between 5.5 and 7 (Guidoboni et al., 2003). It is likely that this earthquake reactivated a series of large landslides, including the giant ancient Garni landslide. The scarp is composed of breccia with some fractured large pebbles (Fig. 5.13, left). Those neatly fractured pebbles within the breccia inside the scarp hint at a rapid massive triggering of slope failure, as can be expected during seismic shaking. According to the observations in the field, our primary interpretation and explanations by Dr. Arkady Karakhanian in September, 2016, the landslide evolution is likely to be related to local/regional extensional tectonic deformation. The (possible seismic) triggering of the main part of the landslide, with development of rotational movements and the formation of gravitational grabens, might have occurred 2000 to 3000 years ago. The age of the landslide is quite difficult to determine due to the arid climate, which preserves the landslide morphology (the age could be easily underestimated). However, horizontally lying foundations of an ancient farm of Roman times (Lat: 40.1513 – Long: 44.6860), dated near 0 AD (that apparently did not move) are still visible on the landslide body (A. Karakhanian, personal communication). They indicate that the main mass movement most likely predates the Roman era. The presence of a small basin between the gravitational graben in the breccia and the lower main part of the old landslide might be the consequence of local extensional tectonic movements that also favoured slope instability. The flat surface of this basin might be due to the filling of the basin over the last 2000 years (or more). This could explain the structure of the Garni landslide presenting a marked relief in the upper part and a smooth topography in the lower part.

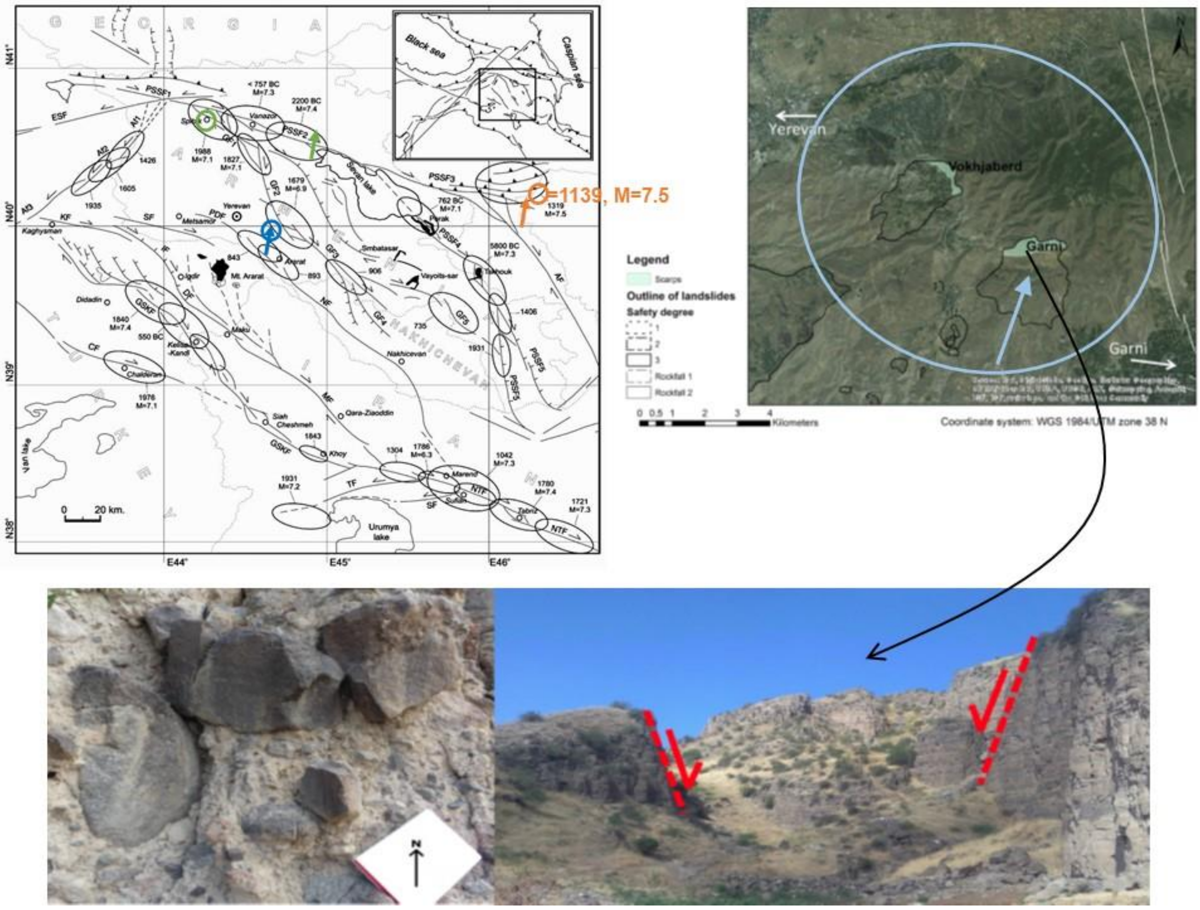


Fig. 5.13. Top left: Garni earthquake and landslide location (see blue circle and arrow); see also approximate location of the 1139 Ganja earthquake epicentral area (orange circle) and of the related seismically triggered Kapaz mountain rock avalanche (orange arrow) that dammed several lakes (map by Karakhanian et al., 2004. Note that the map probably has the wrong year for the M=7.5 event in the Eastern Lesser Caucasus, marked as 1319, which should be 1139 for the Ganja earthquake in that location). The green circle marks the epicentral area of the 1988 Spitak earthquake and the green arrow the approximate location of the Dilijan landslides. Top right: Voghjaberg and Garni landslides, likely initially triggered by earthquakes; the Garni landslide (coordinates: N40°09’03”, E44°41’09”) was apparently reactivated during the 1679 event. Below: volcanic breccia (left) and graben in the scarp area.

1840 Ararat earthquake

The 1840 Ararat earthquake, with an estimated magnitude of 7.4, occurred in the Ararat depression (Ambraseys & Melville, 1982) and created a 72-km-long surface rupture. This earthquake killed 10,000 people. A landslide was triggered from the summit of Ararat, mainly destabilized by the earthquake and, possibly, by an eruption (Stepanian, 1964; Karakhanian et al., 2002). According to historical sources and Karakhanian et al. (2002), an explosive Bandai-type phreatic eruption occurred near the Ararat summit. A cloud and pyroclastic flows would have been induced by that eruption. Some secondary volcanic effects were observed: an eruptive rain which left a blue liquid, with a harsh smell, and lahars which were triggered from the summit and travelled along the Arkory Canyon with a speed of 175 m/s (see Fig. 5.14). Added to this, the landslide destroyed the monastery of St. James (St. Jakob) and the Arkory village. The movement stopped at an elevation of 900 m and formed a natural dam. The dam broke a few days later and the resulting flood destroyed other surrounding villages. Other landslides dammed the Arax and also created floods. Liquefaction and subsidence of the ground were also generated in the Ararat depression, along the Arax, destroying some villages (Karakhanian et al., 2002).

The most damage was caused by secondary effects: the volcanic eruption triggering lahars, the landslide dams followed by floods, and earthquake-induced effects such as ground subsidence and liquefaction. The secondary effects killed 4000 people (Karakhanian et al., 2004). This earthquake destroyed many villages near the Ararat. Other cities and villages were slightly damaged, as Etchmiadzin (Armenia), Yerevan and Garni and the cities of Van (eastern Turkey), Tbilisi (capital of Georgia), Tabriz (northern Iran) and Gyumri (northern Armenia) felt the event (Ambraseys and Melville, 1982).

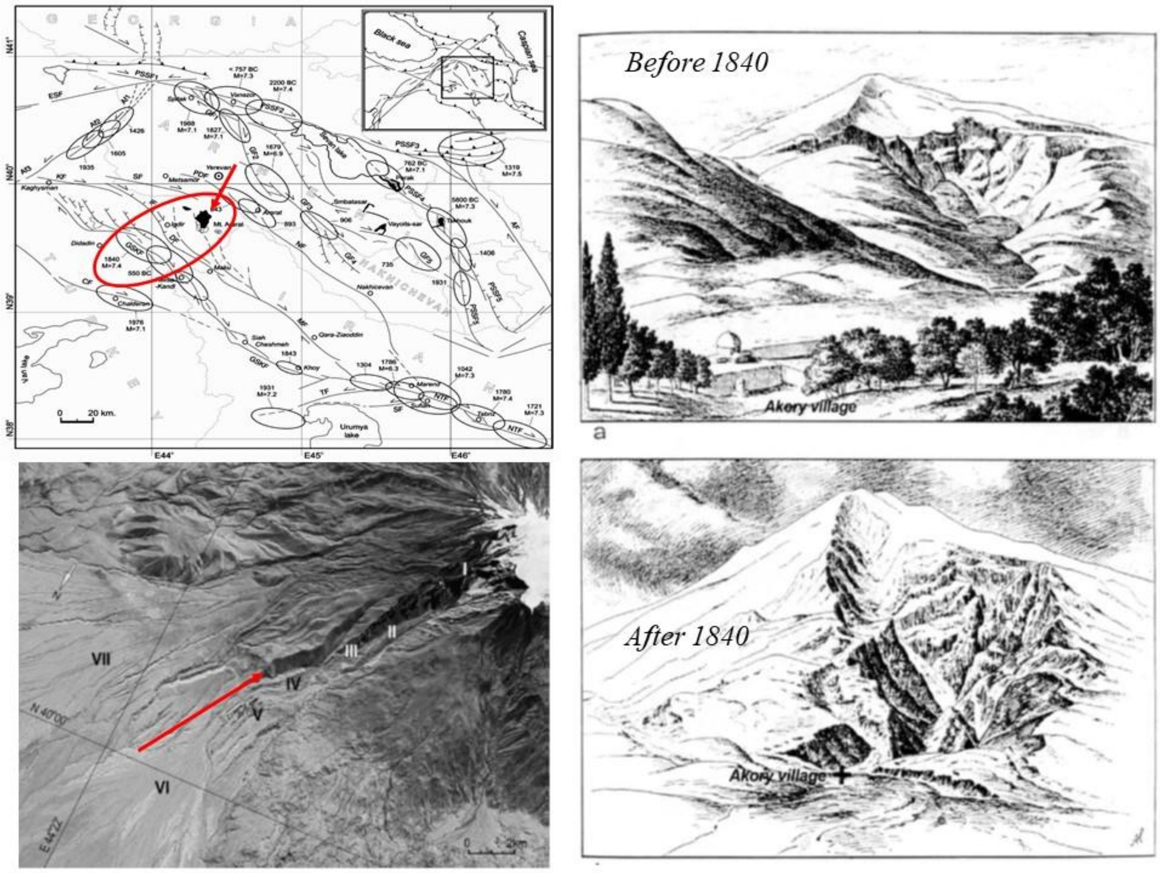


Fig. 5.14. Top left: 1840 earthquake and Arkory canyon failure on Ararat (see red arrow). Right: Drawings of Arkory canyon before and after the 1840 event. Lower left: Corona image of NE part of the Greater Ararat with Arkory canyon (coordinates: N39°44’20”, E44°19’53”). See: II - 2, deposits of the first flow-landslide of July 2, 1840; III - St. Jakob’s Monastery; IV: old village of Akory; V: today’s village; VI - deposits of the July 6, 1840, flow-landslide; VII - deposits of the earlier flow-landslides (from Karakhanian et al., 2002)

A very impressive historical event – but for which, surprisingly, little information is available in the literature – is the Kapaz Mountain rock avalanche (actually, two avalanches) triggered by the 1139 Ganja earthquake. Its location is shown by an orange arrow and circle, respectively, in Fig. 5.13); it is considered the most powerful catastrophic event in the Lesser Caucasus (Nikonov & Nikonova, 1986). The two rock avalanches dammed in total eight still existing lakes, including the two larger ones of Goy-Gol and Maral-Gol. The Google Earth view in Fig. 5.15 shows that the eastern rock avalanche part (damming Goy-Gol) is about 7 km long, while the western part (damming Maral-Gol) is almost 4 km long. The total volume of both parts would be about 500 x 10^6 m^3 (at least).

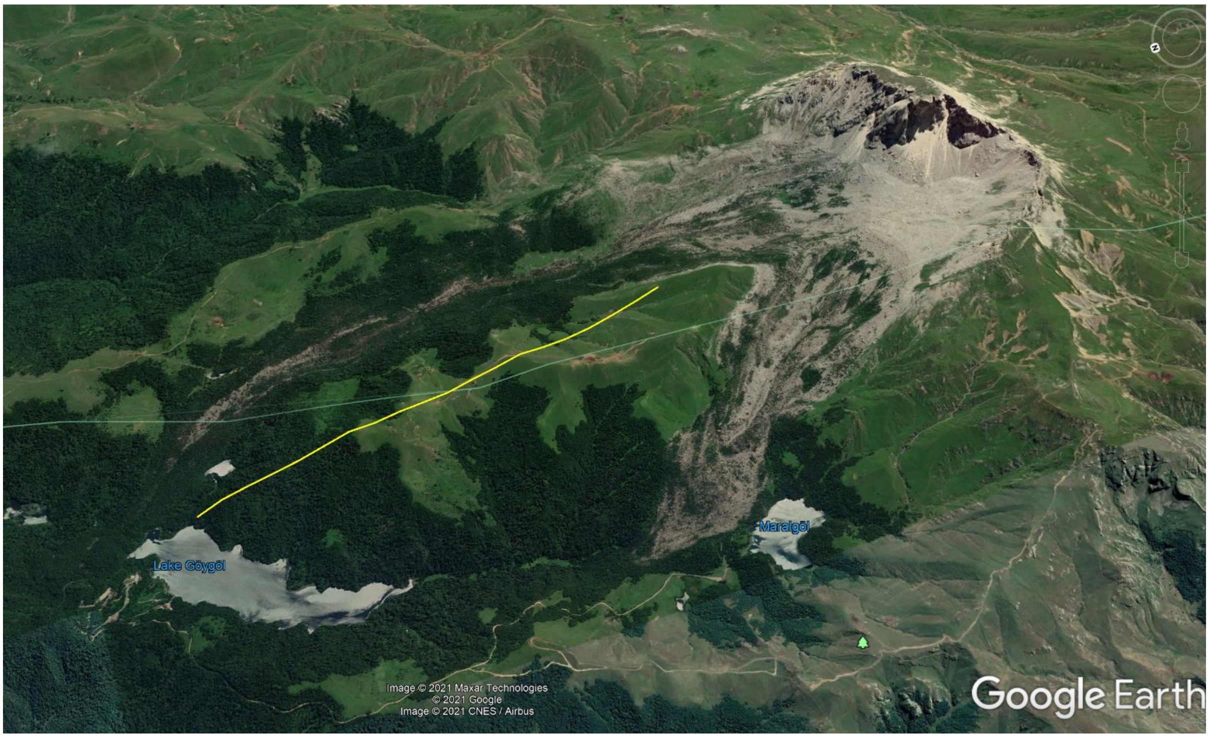


Fig. 5.15. Google Earth view from North-West of the Kapaz Mountain rock avalanche(s) (coordinates: N40°23’30”; E46°19’40”) triggered by the 1139 Ganja earthquake in the southeastern Lesser Caucasus, which dammed several lakes, including the two larger ones of Goy-Gol (lower left corner) and the Maral-Gol (middle lower right). See also yellow line of 4 km length (for scale).

The most recent disastrous earthquake in the Lesser Caucasus, the 1988 Spitak earthquake with a magnitude of 6.8 had also (re)activated larger landslides. According to Boynagryan (2009), several landslides were (re)activated in the Dilijan area (see small green arrow in upper left part of Fig. 5.13, at a distance of about 50 km from the epicentre); he also indicates that the large Voghjaberg landslide (volume of more than 100 x 10^6 m^3) shown in the Google Earth view in the right upper part of Fig. 5.13 was reactivated during the 1988 event. Boynagryan (2009) also considered the activation of the Nubarashen landslide (in the south of the capital Yerevan, directly downstream from Garni landslide) soon after the 1988 earthquake, a delayed consequence of the seismic event (see destroyed graves on the landslides in Fig. 5.16).

Fig. 5.16. Destroyed graves on the Nubarashen landslide, activated soon after the 1988 Spitak earthquake (from Boynagryan, 2009)

Case histories of possible earthquake-triggered landslides in the Carpathians (Romania)

Recent M>7 earthquakes (from Havenith et al., 2016)

The Vrancea seismic region in the South-Eastern Carpathian Mountains is known as the area producing the largest deep focal earthquakes in Europe. Four earthquakes with M_w>7.4 have been recorded in this region during the last two centuries. According to Georgescu (2003), the 1802 earthquake (‘*the Great Quake’*) is considered to be the most severe one ever recorded in this area in terms of magnitude (Mw 7.8-7.9, 150 km depth) and among the most important in terms of intensity (I_{0I}=IX-X MSK). Historical earthquakes in Vrancea are known to have triggered landslides at very large distances (250-300 km). As a consequence of the November 1940 earthquake (M_w=7.7, 150 km depth), Radu and Spânoche (1977) reported numerous geohazards (ground fracturing and at least 40 shallow and medium-seated landslides accompanied by ground-water level disturbances), favoured by the wet conditions induced by the overall very humid 1937-1940 time period (annual mean precipitation exceeded by 13-38%). The very large majority of the above-mentioned processes was recorded within an elliptical zone (300 by 200 km) elongated along a NE-SW direction and marked by the 8 degrees MSK intensity isoline. Angelova (2003) states that all the M>5.5 Vrancea earthquakes have left ground effects and damage throughout Bulgaria. In particular, the 1977 event (M_w=7.4, 94 km depth) was marked by numerous coseismic processes like cracks and fissures (also at epicentral distances of 160-290 km), falls (from coastal cliffs, caves, steep river banks, limestone ridges, at epicentral distances of up to 270-380 km) and slides (at epicentral distances of 210-260 km). Most of the landslides (12 coseismic cases are confirmed with a surface area of 1-10 ha) occurred during the earthquake or immediately after it, while only a few (namely 4) were post-seismic failures (24 hours to 5 weeks). The relatively small number of landslide events induced by the 1977 earthquakes can be attributed to the relatively dry climatic conditions during that period, marked by a pluviometric record that was 40% below the monthly average values of 30-90 mm.

Ancient possible M8+ events

As indicated above, recent earthquakes in Vrancea are known to have triggered landslides at very large distances (250–300 km), e.g. in 1940 and 1977, but none exceeding 1 million m^3 in volume. The Balta and Eagle’s Lake landslides (both with a volume of about ~ 5-10 million m^3) that we have been investigating for several years represent deep-seated mass movements with the most pronounced concave and steep scarps in this area. Furthermore, they are marked by a massive body, rock structures (rock layering) favouring static stability, a scarp initiation from the mountain top and with no river at the base of the initial slope that could have eroded the mountain toe before massive failure. Below (Fig. 5.15) we present some views of those two ancient rock slope failures which have most likely been triggered by very large, possibly M>=8, earthquakes in the SE Carpathian Mountains (see e.g. Mreyen et al., 2021). For these landslides we have also collected drone images, and 3D models are now being processed.

DISCUSSION and CONCLUSIONS

Extensive studies of earthquake-triggered landslides have been carried out in the Central Asian mountain regions. Those show that related events occur on a regular basis – with a return period that is close to the one of M>7 earthquakes (as very large landslides in these areas are typically triggered by those earthquakes). If we combine the Tien Shan and Pamir Mountains, M>7 events potentially triggering landslides occur once every 15 years. Over the past 130 years of well-known seismic hazard history in Central Asia (in practice starting with the 1885 Belovodsk event), just several large earthquakes (in 1887, in 1911, in 1949) caused massive activation of landslides. Among them the M=7.4 Khait event in 1949 was most disastrous, as it triggered numerous large slope failures that killed several thousands of people. All other cases are marked by only a few larger (> 10^7 m3) seismically triggered landslides. The main reason for this is that the areas that are most prone to landslide activation, i.e. the areas covered by thick loess deposits, are generally not marked by the highest seismic hazard. However, there are a few exceptions: the seismically very active southern border of the Tien Shan where thick loess deposits also can be found (and where the Khait earthquake occurred) and the northern and eastern border of the Fergana Basin. Around the Fergana Basin, no large earthquakes occurred in recent historic times (since 1885); the largest known events had magnitudes smaller than 6.5 - though our former seismic hazard estimates (Abdrakhmatov et al., 2003) clearly showed that NE Fergana is marked by a high seismic hazard. The probably most severe event would be an M>7 earthquake along the central segment of the Talas-Fergana Fault, in the East of Babash-Ata Mountain (to the SE of the site where a prehistorical earthquake had, most likely triggered the Karasu rock avalanche directly within the fault zone). This densely populated eastern rim of Fergana Valley is covered by thick loess deposits and extremely prone to landslides. It is also relatively close to the Tala-Fergana Fault (~40 km) and thus could be hit by a massive activation of landslides in loess deposits that may have extreme impacts (similar to those of the 1949 Khait earthquake).

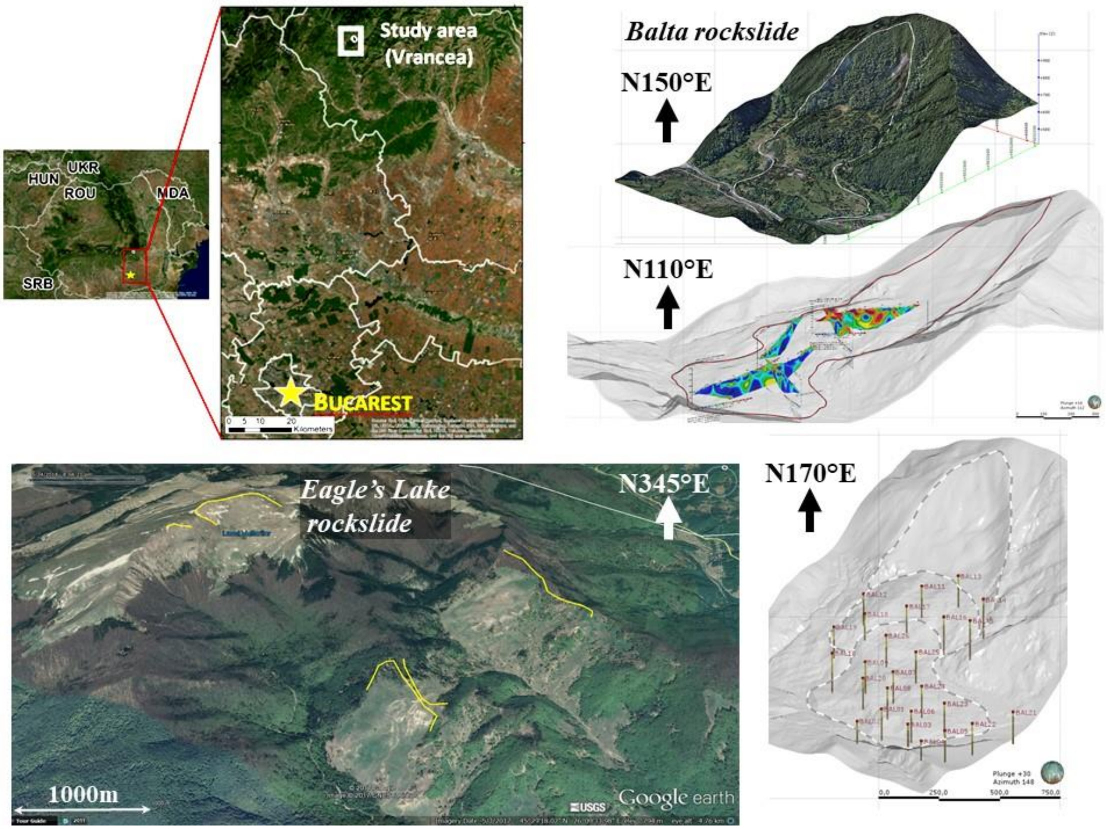


Fig. 5.15. Top left: Vrancea-Buzau seismic region location. Right part: Balta rockslide views and geophysical models (from Mreyen et al., 2017). Lower left: Google Earth view of Eagle's Lake rockslide and other ancient, likely earthquake-triggered slope failures in the Siriu Mountains (same area).

Currently, loess landslides are mainly triggered by climatic influences around the Fergana Basin and in the Tajik Depression south from the Gissar Range. We also know of earthquake effects on slope stability that prepare a later massive failure – see the Kainama case. There are also proven and monitored seismic activations of slope fractures that many years later were at the origin of large landslides. Earthquakes along the Talas-Fergana Fault are extremely rare (return period of > 1000 years for M>>7 earthquakes). More frequent activations of loess landslides (combined with other soft materials) by earthquakes can also be expected from local M~6 events. Even though less massive and extended, the Gissar case history showed that M<6 earthquakes also can trigger widespread liquefaction and slope failure in loess deposits. Furthermore, Niyazov and Nurtaev (2009) showed that loess landslide activation along the western border of the Tien Shan could be triggered by distant deep foci earthquakes (in the Hindukush or Pamir). In 1997, there is also a proved distant activation of a landslide in the Kyrgyz part of the Fergana Basin rim. Therefore, we believe that most final climatically triggered slope failures in loess deposits are just the result of accumulated strain caused by previous seismic shaking (combined with long-term climatic influences).

Finally, it is just a question of time that a Khait-type event will also occur in Southern Kyrgyzstan, possibly affecting areas in Uzbekistan as well. Along the eastern Fergana Basin rim we have identified at least 3 slopes that could fail massively during an M>7 event earthquake (with volumes exceeding 100 million m^3) which could occur along the central Talas-Fergana Fault segment. A massive rock slope failure could be triggered on Babash-Ata Mountain (where a prehistoric >1 km^3 failure has already occurred (coordinates: N41°23'41" E72°56'12"), and one >200 million m^3 soft sediment landslide (coordinates: N41°14'41" E72°03'12") could be triggered from an unstable slope in front of the village of Oogan-Talaa, and one from a landslide-prone slope in the east of Taran-Bazar (approximate coordinates: N41°06' E73°25'). An example of giant mass movements likely to have been triggered by a Talas-Fergana Fault earthquake is the prehistoric Sary-Chelek rockslide with a volume of >5 km^3 damming Sary-Chelek Lake.

In addition to the possibly large impacts of a M>=7 earthquake in Eastern Fergana within the densely populated loess-covered area, what would be the consequences of an earthquake and related triggered extremely large rock slope failures in the higher mountains (e.g., Babash-Ata in the Tien Shan or a new 'Usoy-type' rockslide in the Pamirs)? The direct consequences would probably be more limited as fewer people live in the higher mountains. But nobody could predict the later consequences if a large dam forms on a river, just as now for Usoy.

For the Tien Shan and the Pamirs, future research should focus on the potential of massive loess landslide activations by earthquakes near the northern and eastern Fergana Basin rim and along the southern border of the Tien Shan. In the higher mountain areas (with minor loess cover), it cannot be easily predicted where the next Usoy-type rockslide failure would occur (in the Tien Shan or Pamirs). Therefore, research should first focus on the total hazard assessment for the already existing Usoy-type rockslide – thus, on the landslide dam stability! At the same time, other large rockslide dams should be studied in these regions, such as Sary-Chelek, Kara-Kul and Kutman-Kul (located at the head of Mailuu-Suu Valley). Serious hazard studies (including extensive dating of ancient events and identification of zones prone to large future massive failures) would certainly require investment of more than 10 million USD. The two other regions presented here, the Lesser Caucasus and the SE Carpathians are clearly less affected by earthquake-triggered landslides than the Tien Shan and Pamirs. However, such phenomena also exist there and should not be neglected. The particularity of the Lesser Caucasus is the presence of ancient volcanoes. At present, there is no sign that those structures increase regional landslide susceptibility – but, the 1840 Ararat earthquake showed that a massive slope failure can occur at least on that volcano (the highest mountain in that region that presents also the steepest slopes). For instance, the Armenian part of the Lesser Caucasus (most studied by our team) is covered by hundreds of large rockslides, but none occurred in recent history as a consequence of an earthquake. The Garni and Voghjaberg rockslides, which have most likely been triggered by an earthquake more than 1000 years ago (together or by different events?), and certainly also the Kapaz Mountain collapse in 1139 (in the Azerbaijani part of the Lesser Caucasus), indicate that case histories similar to those known from Central Asian mountain regions could also occur in the Lesser Caucasus – though less frequently. Here, more focus should also be on landslides that could be triggered along the Pambak-Sevan-Syunik Fault bordering Sevan Lake in Eastern Armenia. In Kyrgyzstan there is practically no hazard related to subaquatic landslides in Issyk-Kul Lake or to subaerial landslides impacting the lake (due to the gentle slopes bordering the lake). However, there is clearly a much higher hazard related to such phenomena in the eastern part of Sevan Lake, where it is bordered by the Pambak-Sevan-Syunik Fault that creates very steep subaerial and subaquatic slopes. Here, full cascading hazard scenarios should be studied, including the triggering of tsunami waves by subaerial or subaquatic mass movements.

An interesting aspect of studying possibly earthquake-triggered landslides in the SE Carpathian Mountains is that, compared to other regions in Europe affected by similar high seismic hazards, very little is known about the impacts of very large earthquakes in this region. The region is known to produce the largest intracontinental earthquakes in Europe, but their effects are mainly studied for the city of Bucharest, not for the mountainous areas which are actually relatively densely populated. We have mainly highlighted the importance of ancient large rockslides for estimating the maximum possible earthquake magnitude for the SE Carpathians, as the studied rockslides are much larger than the landslides known to have been triggered by the last century's M7.4-7.7 events. High uncertainties exist around the maximum possible earthquake magnitude, due to the fact that classical paleoseismology cannot be applied in the SE Carpathians, as the activated faults are too deep and do not create surface ruptures. Therefore, an adapted paleoseismological approach is needed – working with giant rock slope failures – if it can be proven that they really had been triggered by seismic shaking: this is what we are doing now. And, once this work is advancing well, the effects of M~8 earthquakes should also be estimated for the mountain regions (in addition to the areas bordering the mountains, and to Bucharest). Inside the area marked by the highest seismic hazard is the city of Nehoiu, as well as the Siriu dam directly upstream. In the past a large rockslide has already occurred within the dammed lake area. An M~8 earthquake could cause problems to both the dam and to slope stability in the lake area, both representing an extreme risk source for the city of Nehoiu and the neighboring relatively densely populated downstream areas.

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