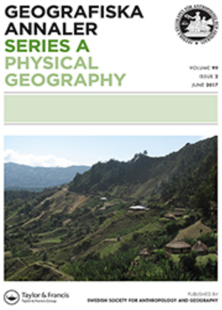

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The origin and evolution of Iskanderkul Lake in the western Tien Shan and related geomorphic hazards

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ABSTRACT
The origin and evolution of Iskanderkul Lake are studied in relation to geomorphic hazards within a broader area of interest. It is shown that the giant Kchazormech rockslide with its volume of masses of approximately 1 km^3 entirely blocked the Iskanderdarja river valley, likely in the Middle Holocene, impounding thus the palaeolake of Iskanderkul. Geomorphological evidence indicated that the palaeolake suddenly decreased its volume by 83% and its areal extent by 65% and released 0.84 ± 0.1 km^3 of water. The present-day Iskanderkul Lake is therefore considered as a remnant of a much larger palaeolake of Iskanderkul. Recent slope movements, incision and backward erosion of rockslide accumulation leading to the formation of a bypass gorge are documented. Current geomorphic hazards are outlined and the near-future evolution of Iskanderkul Lake is discussed with respect to the ongoing climate change suggesting a relatively low longevity of lakes in the Tien Shan.

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Iskanderkul Lake; rockslide dam; outburst flood; Tien Shan

1. Introduction

Giant rockslides, rockslide dams and associated rockslide-dammed lakes are common in tectonically active high mountains worldwide, including in those of Central Asia (e.g. Ischuk 2006; Korup et al. 2006; Strom & Korup 2006; Strom 2010; Chen et al. 2013). These entities are of high importance, because: (i) rockslide dams significantly influence complex geomorphological processes such as erosional-accumulation interactions between slope evolution and fluvial system (e.g. Hewitt 2006, 2009; Ouimet et al. 2007; Korup et al. 2010); (ii) floods and/or debris flows following sudden failures of natural dams are considered among the most significant sediment transport events in the environment of high-mountain rivers (e.g. Costa & Schuster 1988; Kalvoda 1993; Richardson 2010; Korup 2012) and they represent a threat for society (e.g. Eisbacher & Clague 1984; Evans & Clague 1994; Dong et al. 2011; Peng & Zhang 2012); (iii) their deposits can serve as a valuable source of proxy data for palaeoenvironmental reconstructions as well as indicators of environmental change (e.g. Kalvoda & Nikonov 2006; Hewitt et al. 2008; Sanhueza-Pino et al. 2011; Huggel et al. 2012).

Rockslide-dammed lakes of the western Tien Shan are not explored in detail, compared to other regions worldwide (e.g. Hewitt 1999; Hewitt et al. 2008). An inventory and overview of historical landslide-dammed lakes all over the globe has been provided by Costa and Schuster (1991) who mention nine landslide-dammed lakes within the area of Kyrgyzstan and Tajikistan and later by Strom (2010) who mentions 32 landslide dams in Central Asia region. An overview of selected rockslide dams and rockslide-dammed lake outburst floods in mountain ranges of Central Asia has also

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been compiled by Delaney and Evans (2011), Schneider et al. (2013) and Havenith et al. (2015). There are only scarce detailed case studies in the region, as for instance the famed Lake Sarez (Usoy dam) in Pamir (e.g. Schuster & Alfold 2004; Ischuk 2006; Risley et al. 2006), or Shewa Lake (Schroder & Weihs 2010).

Despite the fact that Iskanderkul Lake is the largest high-mountain lake in the western part of Tien Shan (Figure 1; see Section 2 for more details), only limited field data are available and the origin of the lake is still under debate. Based on the analysis of remotely sensed images, Lavrusevich (1990) concluded that the source of the material forming the dam is on the right bank of Iskanderdarja River. The author simultaneously rejected a possible glacial origin of Iskanderkul Lake. Strom (2010) indicated that the dam of Iskanderkul Lake consists of a rockslide accumulation originating in Palaeozoic sedimentary rocks on the right bank of Iskanderdarja River and estimated the volume of this accumulation to be nearly 1 km^3. On the other hand, Ischuk (2013a) stated that Iskanderkul Lake is associated with glacial processes. This statement is in accordance with the conclusion of Zech et al. (2013) who found geomorphic evidence of previous glacial activity (GA) in the adjacent area of Iskanderkul Lake. However, our observations give strong evidence for rockslide origin of the lake dam (see Section 4.1.1). The extent of the lake is successively reduced by the glacifluvial (GF) and fluvioglacial material transported from formerly or still glaciated valleys situated upstream.

The main objectives of this study are: (i) to investigate and explain the origin of Iskanderkul Lake and its recent evolution with special attention paid to the evolution of predecessor Iskanderkul Palaeolake; (ii) to outline ongoing geomorphological processes with a special emphasis given to the hazardous ones; and (iii) to discuss the near-future evolution of Iskanderkul Lake with regard to the ongoing climate change.

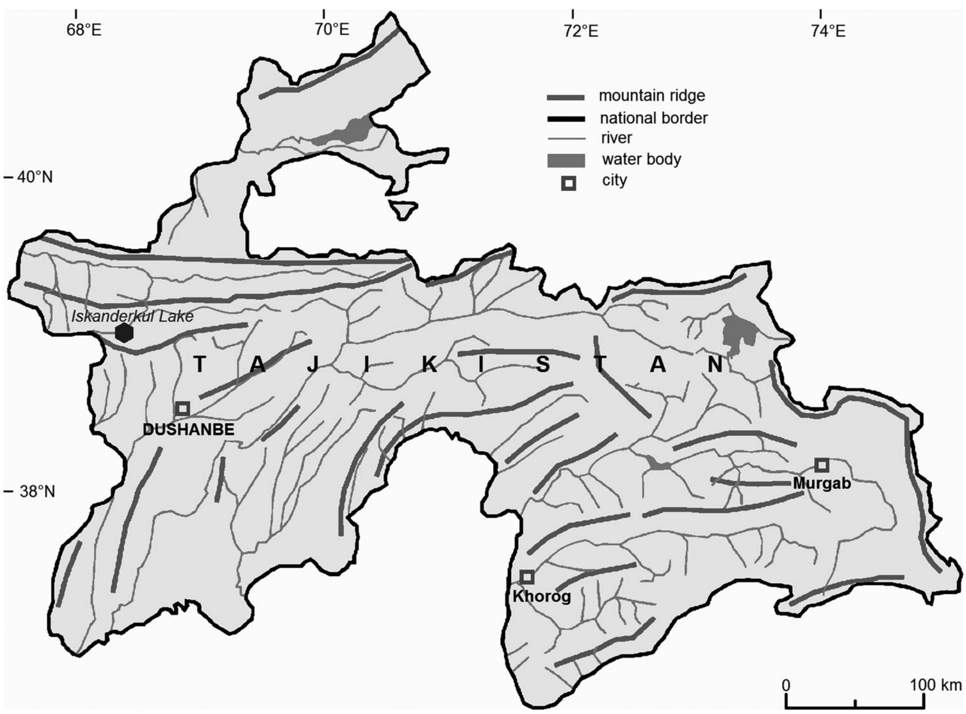

Figure 1. Geographical position of the Iskanderkul Lake in the western Tien Shan (base map modified from Narzikulov & Stanjukovich 1968; Nowak & Nobis 2010).

2. Data and study area

For this study, varied data sources were used: (i) high resolution optical remotely sensed images covering a broader area of Iskanderkul Lake surrounding (CNES/Astrium images taken on 17 May 2013 and 26 August 2013); (ii) topographical map 1:25,000 with basic contour interval 20 m and digital elevation model (DEM) available on Google Earth Pro for middle-scale analysis; and (iii) data and documentation gathered during geomorphological field survey. The present-day Iskanderkul Lake (see Figure 1 and Table 1) is the largest high-mountain lake in the SW part of Tien Shan (Strom 2010). Geological survey of Tajikistan (http://www.geoportal-tj.org/) showed that geological structures of this part of Tien Shan are of Palaeozoic age and are partially covered by Mesozoic and Cenozoic sediments. Iskanderkul Lake is located in an active tectonic region whose main fault zones have latitudinal direction, parallel with that of the main Zeravshan and Gissar ridges (Ischuk 2013b). The Gissar range is mostly formed by intrusive rocks (so-called Gissar Pluton), while the Zeravshan range is built by dike zones with basic and ultra-basic intrusive rocks. The present-day dissected mountainous relief around Iskanderkul Lake (Figure 2) was substantially influenced by active tectonic processes and variable climate-morphogenetic conditions during Late Quaternary. It is characterized by occurrence of various types of slope movements including rapid landslides and rockslides (sturzstroms).

Iskanderkul Lake has two significant water influxes – the Kchazormech stream draining the SE part of the lake catchment and the Sarytag stream draining the SW part of the catchment. The lake has a surface outflow (Iskanderdarja River) and closes the catchment with the total area of 752 km^2 which is a part of the Zeravshan river catchment. The highest mountain in the catchment is Chimtarga (5489 m a.s.l.) whose upper parts (above *c.* 3700 m a.s.l.) are glaciated. The vertical difference of the catchment is almost 3300 m. Based on balance equations, Konovalov (2007) estimated the maximum snowline altitude to be between 4480 and 4520 m a.s.l. The climate of the area is characterized as distinctly continental with year variation of air temperature between −20° C and +35°C and with very low precipitation. Melting of glaciers (Mergili et al. 2012) is the most significant component of river outflow in the broader Zervashan region (Olsson et al. 2010) and also the main source of water for Iskanderkul Lake.

3. Methods

Geomorphological analyses of remotely sensed images and field survey data were performed to describe the origin and recent evolution of Iskanderkul Lake. Areas and volumes of the lake and landforms were measured and calculated from topographical map 1:25,000 in combination with geomorphic evidence-based reconstruction of the extent of the studied features. To estimate the peak discharge following the dam breach, we used height-based and escaped volume-based regression empirical equations developed by Costa (1985)

$$Q_{\max} = 6.3 \cdot H^{1.59},\ r^2 = 0.74; \quad (1)$$

$$Q_{\max} = 672 \cdot V^{0.56},\ r^2 = 0.73; \quad (2)$$

$$Q_{\max} = 181 \cdot (HV)^{0.43},\ r^2 = 0.76; \quad (3)$$

Table 1. Basic characteristics of the present-day Iskanderkul Lake (summarized from Buzrukov et al. 2006; Strom 2010).

Location	Water level elevation	Lake area	Maximal lake depth	Lake volume	Catchment area	Outflow	DBI
39°04′30″N 68°22′00″ E	2195 m a.s.l.	3.4 km^2	72 m	0.17 km^3	752 km^2	Iskanderdarja river (Q = 18.6 m^3 s^{-1})	2.21

Note: DBI, dimensionless blockage index (see Section 3).

Figure 2. Dissected alpine-type ridges around Iskanderkul Lake originated mainly on Palaeozoic crystalline rocks of the western Tien Shan. Present-day relics of glaciers are protected only above 4000 m a.s.l. (GA). Strongly weathered crests (IW – intensive weathering) and various slope deposits (SD) as a result of intensive periglacial processes and rapid rockslides are conspicuous. Photo: J. Kalvoda.

where Q_{max} is peak discharge in m^3 s^{-1}, H is dam height in m and V is volume of released water in 10^6 m^3. Classifications by Costa and Schuster (1988) and Hermanns et al. (2011) were used to classify the dam of the lake and the dimensionless blockage index (DBI) as defined by Ermini and Casagli (2003)

$$\mathrm{DBI} = \log\left(\frac{A_b \cdot H_d}{V_d}\right), \tag{4}$$

where A_b is catchment area in m^2, H_d is dam height in m and V_d is dam volume in m^3, was used to quantify the stability of the dam. DBI < 2.75 refers to stable domain, 2.75 < DBI < 3.08 refers to uncertain domain and DBI > 3.08 refers to unstable domain (Ermini & Casagli 2003). Regionally suitable procedure developed by Mergili and Schneider (2011) for analysing outburst flood hazard of lakes in the southwestern Pamir was used. Four internal parameters of outburst susceptibility (dam material, lake drainage, lake area development, downstream slope of the dam) and four external parameters of outburst susceptibility (topographical susceptibility to slope movements, calving into the lake, seismic hazard, dam freeboard) are assessed using pre-defined classes for each parameter and summary rating matrix in this approach (see Mergili & Schneider 2011).

During geomorphological analysis realized in parts since 1986, a special attention was given to identification of landforms of variable origin and age, including signatures of rapid relief-forming processes and events such as rapid slope movements. Complex interpretation of these observations, using their comparisons with remotely sensed images and above described measurements based on topographical maps, allowed to determine main landform patterns related to the evolution of Iskanderkul Lake.

4. Results

4.1. Main morphogenetic stages of Iskanderkul Lake area during the Holocene

Considering field geomorphic evidences, which are described in detail in this section, the chain of events of Iskanderkul Lake area evolution is documented as follows: (i) deposition of a giant Kchazormech rockslide blocked the Iskanderdarja River valley (see Section 4.1.1); (ii) Iskanderkul Palaeolake was retained behind the deposition (see Section 4.1.2); (iii) the dam of the palaeolake breached producing a 0.84 km^3 outburst flood (see Section 4.1.3) forming a 3.5 km long bypass gorge (see Section 4.1.4). The present-day Iskanderkul Lake (see Section 4.2) is considered to be a remnant of Iskanderkul Palaeolake. Selected field documentation and other input particulars were arranged with intention of optimal presentation and evidence of above-mentioned rapid events and processes.

4.1.1. The Kchazormech rockslide

Based on the analysis of geomorphic evidences using remotely sensed images and field works, we consider the Iskanderkul Lake dam to be a deposition of a giant rockslide (sturzstrom) from the right bank of Iskanderdarja River (see Figure 3). The Kchazormech rockslide is, according to the morphological landslide dam classification presented by Costa and Schuster (1988), classified as Type III, that is a dam filling the valley from side to side and reaching considerable distances upvalley and downvalley from the failure. Strom (2010) pointed out that the Kchazormech rockslide is not the only large rockslide within this region. The cluster of rockslides has been detected in the adjacent region, which could be an evidence of earthquake triggers. We can support this opinion regarding circumstances that rapid slope movements are significant concomitant phenomena of numerous seismic events in the Tien Shan and the Pamirs (e.g. Kalvoda et al. 1987; Kalvoda 1993; Kalvoda & Nikonov 2006).

According to the three-step classification of rockslide dams proposed by Hermanns et al. (2011), we classified the Kchazormech rockslide dam as Type IVa/iii/2 rockslide dam before the breach. It was the single rockslide barrier in the confined topographical setting depositing a several hundreds metres high dam allowing formation of a large lake (2) and affecting the confluence of valleys (IVa), where the lowest part of the dam does not correspond to the deepest part of the valley (iii). The rockslide dam after the breach is classified as Type IVa/iv/2, because the deposition is not crossing the valley in its entire width, hence diverting the river to flow around the distal rim of deposition; drainage is not established over the dam (iv).

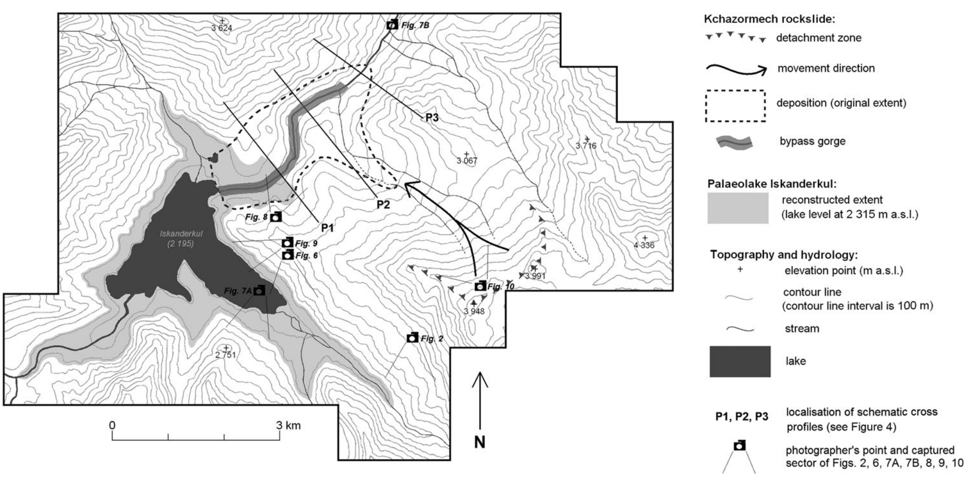

Figure 3. Geomorphic sketch-map of the Kchazormech rockslide (base map modified from topographical map 1:25,000). Areas of the giant rockslide, cross-valley profiles (Figure 4) and landscape shown at photographies (Figures 2 and 6–10) are drawn.

Table 2. Basic morphometrical characteristics of the Kchazormech rockslide deposition.

Area of deposition	Deposition height	Effective dam height for the Iskanderkul Palaeolake	Deposition length	Deposition width	Vertical drop	Deposited volume (before the breach)	Deposited volume (after the breach)
3.10 ± 0.20 km^2	>400 m	305 m	3700 m	1200 m	1980 m	0.92 ± 0.15 km^3	0.76 ± 0.15 km^3

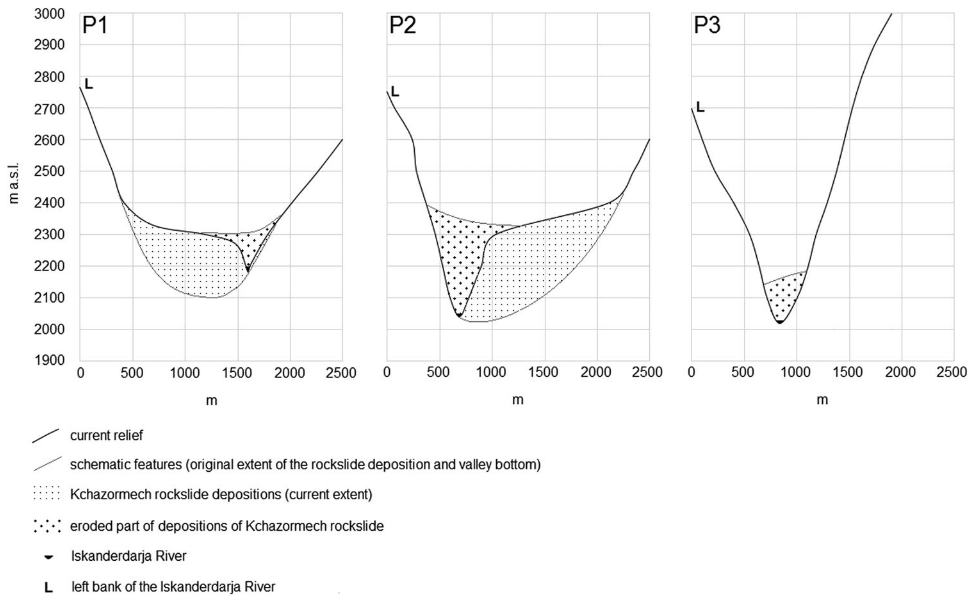

Figure 4. Schematic cross-valley profiles through depositions of the Kchazormech rockslide (profiles P1, P2 and P3; see Figure 3). Buried valley bottom and bypass gorge of the Iskanderdarja River are shown at profiles P1 and P2.

The highest point of the Kchazormech rockslide headscarp lies at 3990 m a.s.l. and the lowest point of the deposition toe at 2010 m a.s.l., the resulting vertical drop being of 1980 m (see Table 2) and the maximum travel distance of 6700 m. Considering these figures, the maximum velocity of downslope movement probably exceeded 100 m s^{-1} (sensu Erismann & Abele 2001). The mean slope of the transport zone varies from 45° in the steep upper part to 20° in the more gentle lower part, where a thin layer of deposit is still accumulated. The reconstructed mean slope of Iskanderdarja River valley is <1.5° which has resulted in the deposition of the majority of the material there. Planar dimension of large boulders on the top of the deposition is >15 × 15 m. The volume of the Kchazormech rockslide deposition deposited within the Iskanderdarja River valley (Figure 4) was roughly estimated to be of 0.92 ± 0.15 km^3 before the breach and of 0.76 ± 0.15 km^3 after the breach. Considering the relation between the deposited volume and the travel distance according to Hsü (1975), the Kchazormech rockslide is classified as moderately mobile ‘sturzstrom’.

4.1.2. Iskanderkul Palaeolake

Baratov and Novikov (1984) indicated that the present-day Iskanderkul Lake is a remnant of a much larger palaeolake, whose water level was 120 m above the current water level, i.e. at an altitude of 2315 m. This opinion is confirmed by field morphological evidences – the breached dam of Iskanderkul Palaeolake and the clearly visible horizontal line encircling the lake (partly interrupted by local slope movements and gullies) – indicating the former water level (Figure 5). After mapping of the areal extent of this line situated at 2315 m a.s.l., the area of Iskanderkul Palaeolake was

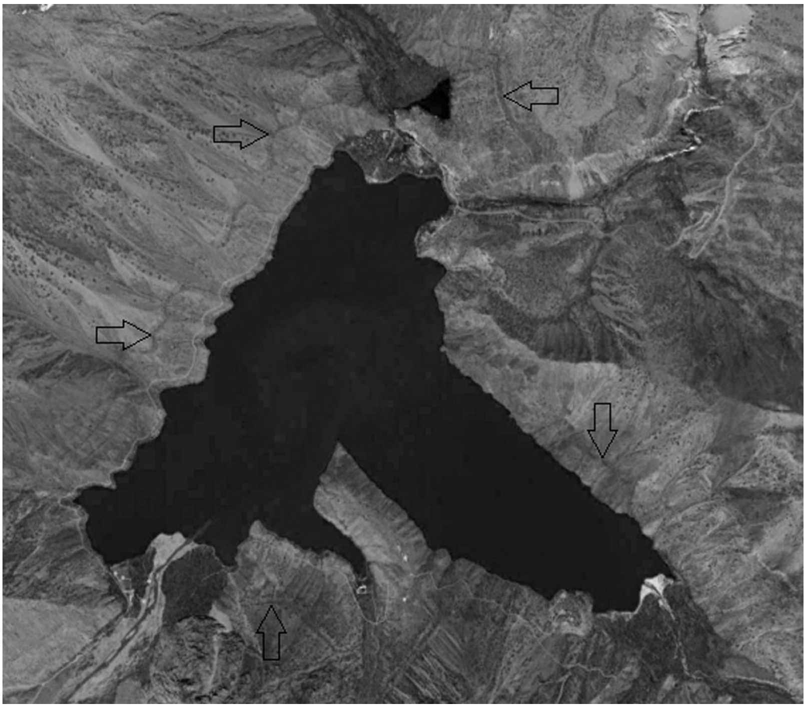

Figure 5. Horizontal line at an altitude of 2315 m (highlighted by arrows) can indicate the former water level of Iskanderkul Palaeolake (compare also its reconstructed extent at Figure 3). The satellite image (with shown area of approx. 4 × 4 km) was taken on 17 May 2013 (Google Earth Digital Globe).

estimated to be 9.8 ± 0.5 km^2, its maximum depth to at least 192 m and its volume to 1.01 ± 0.1 km^3 (Table 3).

Assuming the present-day mean discharge of Iskanderdarja River ($Q = 18.6\ m^3\ s^{-1}$) and no piping through the dam, it emerges that filling of the lake basin by water would have taken more than 560 days. However, more humid climate has been documented in Central Asia during the Middle Holocene (Chen et al. 2008; see Section 5.2), which is estimated period of Kchazormech rockslide (see Section 5.1). Lake filling, therefore, could have been more rapid. We suppose that the lowest point on the dam crest at an altitude of 2315 m (or slightly above) lead to the initiation of surface outflow from the lake and to a temporal fixing of the water level of Iskanderkul Palaeolake.

Table 3. Reconstructed characteristics of Iskanderkul Palaeolake before its draining.

Palaeolake level altitude	Palaeolake area	Maximal palaeolake depth	Palaeolake volume	Outflow	DBI
2315 m a.s.l.	9.80 ± 0.50 km^2	>192 m	1.01 ± 0.1 km^3	Surface	2.39

Note: DBI, dimensionless blockage index (see Section 3).

4.1.3. Dam breach and outburst flood

Morphological features do not provide clear evidences about the cause of the dam breach, nevertheless, the mechanism is considered to be backward erosion of the river (gradual or triggered by rapid mass movement into the lake; see Section 4.2). Conspicuous bank line of the palaeolake water level at an altitude of 2315 m a.s.l. indicates that the dam did not breach directly after the rising water level had reached the dam crest, which is a common feature of landslide dams (the vast majority of landslide-dammed lakes failed within the first year of their existence; Costa & Schuster 1988), but apparently stayed at this level for a longer period (10^2–10^3 yrs).

Table 4. Peak discharge calculated on the basis of empirical equations (Equations (1)–(3)) and mean discharge calculated for different scenarios (defined durations) of the dam breach.

Peak discharge Q_{max} ($m^3 s^{-1}$)			Mean discharge ($m^3 s^{-1}$)				
			Breach duration				
Equation (1)	Equation (2)	Equation (3)	6 (h)	24 (h)	3 (days)	30 (days)	100 (days)
12,740[a]	29,120 ± 1950	25,610[a] ± 1320	38,910 ± 4630	9740 ± 1160	3260 ± 390	340 ± 40	120 ± 10

[a]Dam height H = 120 m (breach depth) was used in calculations.

The volume of the water escaped during the dam breach of Iskanderkul Palaeolake was estimated to be 0.84 ± 0.1 km^3 (84% lake volume reduction; 65% areal reduction) which is comparable with the largest events originating in landslide-dammed lakes documented worldwide (e.g. Costa & Schuster 1988; Korup & Tweed 2007; Delaney & Evans 2011). The peak discharge during the dam breach was calculated with the help of Equations (1)–(3). The calculated peak discharge is overcomming the mean discharge of Iskanderdarja River by 680 times in the case of the most conservative result and by 1670 times in the case of less conservative results. However, the breach duration may vary from 10^{-3} to 10^{0} yrs in cases of landslide-dammed lakes (Costa & Schuster 1988), and may directly influence peak as well as mean discharge. Mean discharge was calculated for five different breach scenarios and durations accordingly (see Table 4).

It is not known whether the breach of Kchazormech rockslide dam was a single event (one-off decrease of the lake water level by 120 m, regardless the breach duration), or a successive event composed of several breaches with a step-like decrease of lake water level. The westernmost part of the lakeshore shows conspicuous water level mark also at an altitude of 2270 m. This could result from (i) a two-phases breach of the dam of Iskanderkul Palaeolake, temporarily fixing the water level at this elevation or (ii) further temporal damming of the Iskanderdarja River valley, leading to a temporal increase in the water level.

4.1.4. Bypass gorge

The amount of material eroded from the Kchazormech rockslide deposition during the breach was estimated to be 0.16 ± 0.05 km^3. Depth incision through the rockslide deposition during the dam breach led to the origin of so-called *epigenetic bypass gorge* (Korup et al. 2006), which functionally substituted the buried Iskanderdarja River channel. The Iskanderdarja River bypass gorge is approximately 3.5 km long and up to 250 m deep. Its geomorphic significance is given by the incision of Iskanderdarja River into the bedrock bottom (Figure 4), which fixes the Iskanderkul Lake water level at an altitude of 2195 m, while the earlier (that is deeper) river bottom remains buried beneath the Kchazormech rockslide deposition.

4.2. Kchazormech rockslide, Iskanderkul Lake and related geomorphic hazards

Palaeogeographical history of Iskanderkul Lake was substantially influenced by orogenetic processes and variable climate-morphogenetic conditions during the Late Quaternary (see Section 5.2). The present-day dissected mountainous relief around Iskanderkul Lake is characterized by occurrence of various types of slope movements including landslides and rockslides (Figure 6). Geomorphic hazards in the region are determined by active seismotectonics and extreme climatic events as impulses originating new large-scale slope movements (Kalvoda et al. 1987; Kalvoda & Nikonov 2006), formation and failure of landslide dams and rapid erosion processes.

DBI (see Section 3) calculated for Iskanderkul Lake (DBI = 2.21) indicates that its present-day dam is characterized as a stable domain (Strom 2010). The highest result of the calculation for the dam of Iskanderkul Palaeolake (DBI = 2.47) did not suggest as well any increased possibility of dam breach, which, however, evidently occurred. Strom (2010) pointed out that the gorge eroded

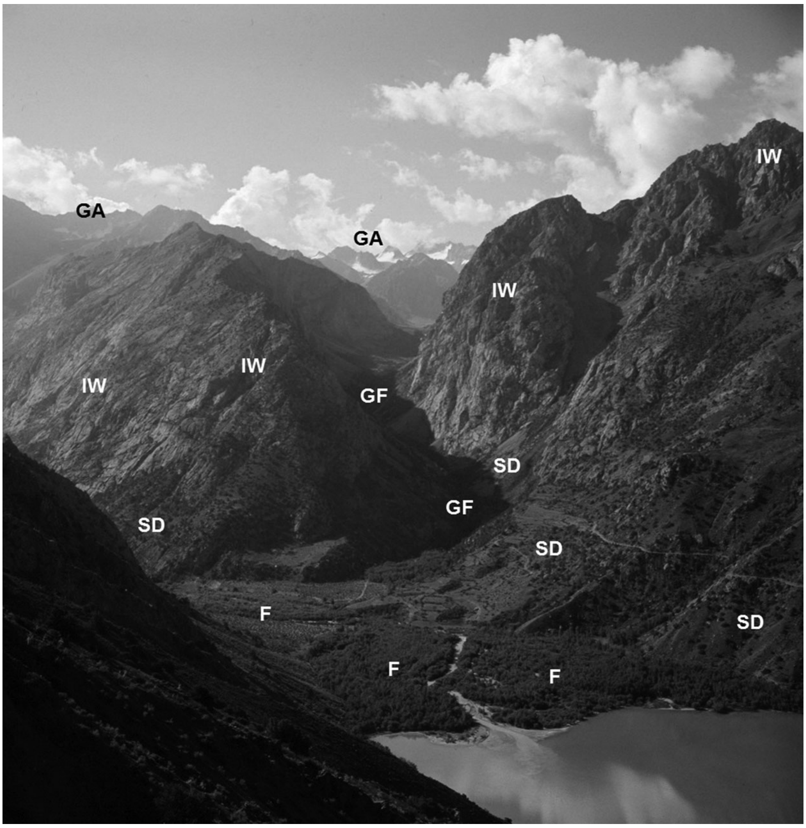

Figure 6. Iskanderkul Lake is substantially supplied by recent fluvial (F), GF and SD. These recent sediments accelerate reduction of the lake volume and of its areal extent. For the explanation of abbreviations GA and IW see captions to Figure 2. Photo: J. Kalvoda.

through the Kchazormech rockslide deposition indicates intensive backward erosion of dam body which could lead to a further breach and lake level drawdown in the near future. We, however, found no evidence that a further breach could happen, because Iskanderdarja River already incised into the bedrock bottom in the bypass gorge fixing the lake water level at 2195 m a.s.l. This opinion is in accordance with a similar one presented by Ischuk (2006) who considered the lake dam as a temporarily stable natural structure.

Using the procedure presented by Mergili and Schneider (2011) we assessed the susceptibility of Iskanderkul Lake to outburst flood as moderate reflecting the increased topographical susceptibility of lake surrounding to slope movements and seismic hazard of the region. The lake outlet being considered as stable (see Section 4.1.4), the only possible mechanism of flood from Iskanderkul Lake is an increased discharge resulting from a high-volume rapid slope movement into the lake, triggered for example by an earthquake and producing displacement wave(s). We documented morphological evidences of historical sliding into the lake indicating the described activity (Figure 7(a)). An increased discharge, however, should not lead to a further depth incision of the bypass gorge and to decreasing of the Iskanderkul Lake water level. Steep slopes of the deeply incised bypass gorge are more susceptible to lateral erosion which may lead to an undercutting-triggered collapse and to the origin of temporal blockages of Iskanderdarja River (Figure 7(b)). These blockages of Iskanderdarja River could be also induced by an earthquake-triggered reactivation of landslides and rockslides (compare Figure 8) as well as by a movement of the Kchazormech deposition.

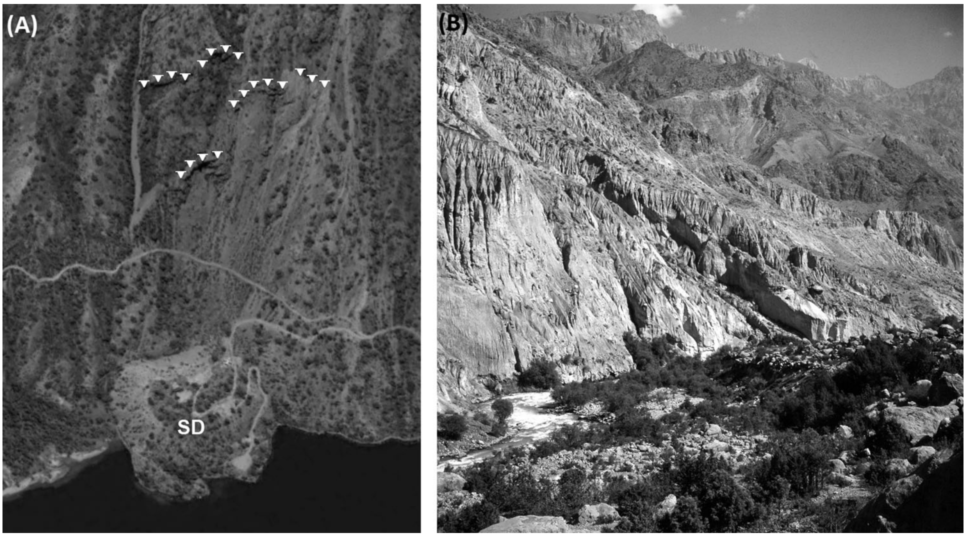

Figure 7. Various slope processes and related events substantially influence hazardousness of the present-day Iskanderkul Lake. Part (a) shows deposition of recent slope movements from the southern bank into the lake. The SD is approximately 260 m wide and the upper line of the headscarps (dashed line with triangles) is situated at 2500 m a.s.l., i.e. 300 m above present-day Iskanderkul Lake water level (satellite image Google Earth Digital Globe taken on 17 May 2013). Part (b) demonstrates undercutted parts of the Kchazormech rockslide deposition which are susceptible to reactivation of slope movements. It is the cause of occasional local blockage of the Iskanderdarja River (Photo: J. Kalvoda).

5. Discussion

5.1. The age of Iskanderkul Lake

Dating of the Kchazormech rockslide as well as of the Iskanderkul dam breach has not been performed yet. Age estimation based on general assumptions is made in this section. Costa (1985) and later Ermini and Casagli (2003) showed a generally low longevity of landslide-dammed lakes of different types by documenting failures of the majority of landslide dams within the first year of their existence. Korup et al. (2006) pointed out that longevity of large rockslide-dammed lakes could be much higher, in order of 10^1–10^4 yrs, before they are drained or infilled. Therefore, it is suggested that all existing rockslide-dammed lakes are of Holocene or rarely of Late Pleistocene age. Considering the areal extent of the catchment of Iskanderkul Lake (752 km^2), the average sediment yield in the Tien Shan being 10^2–10^3 t km^{-2} yr^{-1} (Korup et al. 2006) and the amount of material deposited within the present-day lake (roughly estimated to be 0.05 km^3), we assume the upper age limit of the Kchazormech rockslide and of Iskanderkul Lake being of Middle Holocene age. This estimation, based on calculation of the lake filling, could be, however, influenced by the origin of another 200 m high rockslide dam which had been damming Sarytag stream situated 2 km upstream of Palaeolake Iskanderkul (Strom 2010).

The only 'historical' information about Iskanderkul Lake indicates that the lake bears its name (Iskanderkul = Alexander Lake) in honor of Alexander III of Makedon. His troops probably visited the lake area during a military campaign to Central Asian and Indian regions between 329 and 327 BC. This somewhat speculative figure can be considered as the lower age limit of Iskanderkul Lake. Since the horizontal line indicating the water level of palaeolake is still clearly visible (Figure 5), it can be assumed that the dam breach occurred not earlier than 10^2–10^3 yrs BP. According to recent geographical expeditions, the lake was visited and described in the second half of the nineteenth century by an expedition led by A. Fedtschenko (Warncke 1989).

Figure 8. Distinctive areas of rockslides and landslides originated on strongly weathered complex of Palaeozoic and Mesozoic sediments in the Iskanderdarja River valley. These landform patterns of rapid slope movements are situated at the left side of the valley 2–3 km below the present-day outflow of water from the lake dammed by Kchazormech rockslide deposits. Photo: J. Kalvoda.

5.2. Late quaternary climate changes and their implications for landform evolution

Chen et al. (2008) indicated significant climate changes in Central Asia during Holocene by studying lacustrine, fluvial and aeolian sediments at 11 localities (lakes). Cold and arid climate in the Early Holocene was altered by humid climate between 8000 and 4000 BP (~Middle Holocene; Walker et al. 2012). The aridity of the climate raised again thereafter. Humid climate and/or increased melting of glaciers in Central Asia during the Middle Holocene was attributed to the increased humidity of summer monsoon convection (warm oceanic convection; W, SW and S direction) related to weakening of the Siberian anticyclone compared to the Iranian anticyclone. The highest lake water levels and volumes of lakes as well as river discharges were indicated in mountain valleys of Central Asia during this period. These findings are in concordance with opinions of other authors. It was shown that Issykkul Lake had surface outflow to Chu River 7800–6000 BP (Ricketts et al. 2001), then the lake has turned to endorheic condition, its water level lowered, salinity increased and rate of lacustrine sedimentation decreased.

Implications for the near-future evolution of Iskanderkul Lake (Figure 9) are noticeable especially in the context of decreasing extent and volume of glaciers in the upper part of the catchment. The majority of these glaciers are cirque glaciers with areas <1 km^2. Reflecting present-day trends in climate change and glacier retreat in the Tien Shan (Bolch 2007; Konovalov 2007; Mergili et al. 2012), these glaciers are expected to disappear within decades (sensu Zemp et al. 2006), or even years in some cases. Water influx into Iskanderkul Lake may significantly decrease during dry seasons changing thus hydrological conditions of the lake from 'lake with permanent surface outflow' (current state) to 'lake with occasional (episodic) surface outflow' during wet season or 'lake without surface

Figure 9. Dissected relief on the mountaineous environment above western banks of the Iskanderkul Lake (2195 m a.s.l.) and conspicuous dejection cone around present-day mouth of the Sarytag stream into the lake. Photo: J. Kalvoda.

outflow' (endorheic condition). An example of lake which turned due to the climate change to endorheic condition is Issykkul Lake (see above; Ricketts et al. 2001).

The total amount of water influx and of discharge fluctuation is closely tied with the amount of material transported from the catchment into the lake basin. Considering the average sediment yield 10^2–10^3 t km^{-2} yr^{-1} estimated for Tien Shan by Korup et al. (2006), the current lake basin volume and the average lacustrine sediment density 1,5 t m^{-3} (Rutkowski et al. 2007), the rough longevity of Iskanderkul Lake based on sediment filling is estimated in orders of 10^2–10^3 yrs. However, this opinion does not reflect climate-driven general environmental changes such as changes in hydrological regimes of tributary streams, geomorphological aspects such as temporal damming(s) upstream of the lake caused by landslides or direct accumulation of material of slope movements into the lake (see Figure 6; see also Passmore et al. 2008), and it also does not reflect regional changes in average sediment yield (Kirchner et al. 2001; Morche & Schmidt 2012). Extinction of a lake by filling is common process in the Tien Shan and several examples of infilled lakes were found within the catchment of Iskanderkul Lake, e.g. an infilled rockslide-dammed lake at the Sarytag valley.

Comparisons of the Iskanderkul Lake origin and geomorphic phenomena associated with recent environmental change in the Tien Shan can be improved by radiometric dating of the Kchazoremech rockslide (Figure 10) and/or lake sediments (e.g. Prager et al. 2009; Pánek 2015; Guo et al. 2016). Detailed engineering-geological survey on stability of slopes around Iskanderkul Lake (Figures 2 and 8) could also specify a range of actual geomorphic hazards (sensu Chu-Agor et al. 2008; Zangerl et al. 2010).

Figure 10. Polygenetic landform patterns of the western Tien Shan in semi-arid area of the Iskanderkul Lake (on the left) with relics of the giant Kchazormech rockslide and recent landslides in the Iskanderdarja River valley. Rocky massifs of the Zeravshan range (on the horizon, up to 5000 m a.s.l.) originated in glacial and/or periglacial zones, extensive steep denudation and erosional slopes in lower parts of the mountains are dissected by various slow and rapid slope movements. These dynamic climate-morphogenetic processes in the Tien Shan are strongly supported by long-term tectonic uplift and intensive seismic activity. Photo: J. Kalvoda.

6. Conclusions

Iskandertkul Lake is a remnant of a much larger palaeolake, likely of Middle Holocene age, which was dammed by depositions of the giant Kchazormech rockslide originated on the right bank of Iskanderdarja River. On the basis of morphological evidences, the areal extent of Iskanderkul Palaeolake was estimated to be 9.80 ± 0.5 km^2, while its volume was calculated to be 1.01 ± 0.1 km^3 with maximal lake depth above 190 m. The rockslide dam breached in the past decreasing the water level of the palaeolake by 120 m and releasing a volume of water of about 0.84 ± 0.1 km^3 (84% volume reduction and/or 65% areal reduction). It is one of the most voluminous landslide-dammed lake outburst flood, however, it is not known whether this release was an one-off event or a successive set of events. Water incision through the rockslide deposition did not follow the original direction of the now buried Iskanderdarja River channel. Fluvial erosion created an approximately 3.5 km long epigenetic bypass gorge. Bedrock bottom exposed in the bypass gorge fixed the elevation of water level of the present-day (remnant) lake at 2195 m a.s.l.

Since the bypass gorge has been incised, a further dam breach is no more probable and the only mechanism of a sudden water release from the lake could be a rapid slope movement into the lake producing displacement wave(s). Another potential threat consists in a temporal damming of the Iskanderdarja River and in sliding of river banks, for example by earthquake-triggered re-activation of deeply eroded Kchazormech rockslide deposits. Reflecting ongoing climate change trends and the successive glacier retreat in the Tien Shan, Iskanderkul Lake may turn to episodic surface outflow condition or endorheic condition in the near future. High mean rates of sediment yield also suggest the possibility of lake filling and indicate a relatively low expected longevity of the lake up to several thousand years.

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