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Reconstruction of glacial lake outburst floods in northern Tien Shan: Implications for hazard assessment

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ABSTRACT

Glacier lake outburst floods (GLOFs) and related debris flows are among the most significant natural threats in the Tien Shan Mountains of Kyrgyzstan and have even caused the loss of life and damage to infrastructure in its capital Bishkek. An improved understanding of the occurrence of this process is essential so as to be able to design reliable disaster risk reduction strategies, even more so in view of ongoing climate change and scenarios of future evolutions. Here, we apply a dendrogeomorphic approach to reconstruct past debris-flow activity on the Aksay cone (Ala-Archa valley, Kyrgyz range), where outbursting glacier lakes and intense rainfalls have triggered huge debris flows over the past decades.

A total of 96 *Picea abies* (L.) Karst. trees growing on the cone and along the main channel have been selected based on the evidence of past debris-flow damage in their trunks; these trees were then sampled using increment borers. The dating of past events was based on the assessment of growth disturbances (GD) in the tree-ring records and included the detection of injuries, tangential rows of traumatic resin ducts, reaction wood, and abrupt growth changes. In total, 320 GD were identified in the tree-ring samples. In combination with aerial imagery and geomorphic recognition in the field, reactions in trees and their position on the cone have allowed reconstruction of the main spatial patterns of past events on the Aksay cone.

Our findings suggest that at least 27 debris flows have occurred on the site between 1877 and 2015 and point to the occurrence of at least 17 events that were not documented prior to this study. We also observe high process activity during the 1950s and 1960s, with major events on the cone in 1950, 1966, and 1968, coinciding with phases of slight glacier advance. The spatial analyses of events also point to two different spatial patterns, suggesting that quite dissimilar magnitudes probably occurred during glacier lake outburst floods and rainfall-induced debris-flow events. The results presented here represent the longest, annually resolved GLOF series in the region, which in turn has key implications on risk assessment, not just in the Ala-Archa valley, but also in the entire Kyrgyz range (northern Tien Shan).

1. Introduction

Debris flows are rapid mass movements in which a combination of loose debris, rocks, organic matter, air, and water mobilizes as a slurry which then flows downslope (Varnes, 1978; O'Connor et al., 2001). This natural process is considered one of the most common natural hazards in mountain environments and is responsible for significant damage to infrastructure and even loss of life (Fuchs et al., 2013; Borga et al., 2014). The causative factors of debris flows as well as their behavior, rheology, and geomorphic imprint have been described extensively in the literature (e.g., Costa, 1984; Rickenmann, 1999; Jakob and Hungr, 2005; Wu, 2015). Very huge debris flows can form as a result of glacial lake outburst floods (GLOFs; Richardson and Reynolds, 2000), which are typically formed from the breakage (e.g., seepage, piping) or the overflowing of moraine- or ice-dammed lakes (Worni et al., 2012, 2013a, 2014). These extreme events are able to shape debris cones and to produce intense changes in depositional forms (Breien et al., 2008) but also to affect environments located a long distance downstream of the source area of flows by disrupting networks and causing damage to populated valleys (Erochin and Cerny, 2009; Jansky et al., 2010; Schwanghart et al., 2016).

Over the past decades, numerous GLOFs have been documented in many mountain ranges worldwide. Examples of recent and large GLOF events are found in the Andes (Reynolds et al., 1998; Hegglin and Huggel, 2008), Central Asia (Aizen et al., 1997; Narama et al., 2006,

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2010; Mergili and Schneider, 2011), the Himalayas (Richardson and Reynolds, 2000; Allen et al., 2009; Xin et al., 2009; Worni et al., 2013b), the Rocky Mountains (Jakob and Bovis, 1996; Clague and Evans, 2000; Kershaw et al., 2005), the European Alps (Haeberli et al., 2001), and in the Mount Everest region (Cenderelli and Wohl, 2001, 2003). It is believed that the occurrence of these phenomena may increase over the next decades in many of the high mountain environments caused by (i) the formation of new unstable glacial and subglacial/englacial lakes as a result of glacier retreat and/or (ii) increasing slope destabilization in the cryosphere domain as a result of changes in the precipitation and temperature patterns (Aizen et al., 1996; Stoffel and Huggel, 2012; Stoffel et al., 2014). In the northern Tien Shan region, the IPCC projects a moderate increase in temperatures (IPCC, 2007), which is supposed to contribute or even to intensify current glacier retreat (Sorg et al., 2012, 2014). These changes may also cause significant modifications of the cryosphere (Sorg et al., 2015) and related instabilities at or around glacier termini and may thus impact on the actual formation or outburst of glacier lakes (Stoffel and Huggel, 2012). The widespread lack of long-term observations and more robust projections of climate change at the regional level have so far prevented more robust conclusions about possible changes in GLOF activity in the region.

Therefore, an improved understanding of past GLOF occurrences and their magnitude could indeed be a valuable baseline against which hypotheses about their relations with glacier dynamics could be tested and from which potential hazard zones at the level of fans and farther downstream in the valley could be drawn (Worni et al., 2014). So far, however, efforts have been focused primarily on the description of impacts of specific events causing disasters and not on hazard potential; and a longer-term perspective on the process has been clearly missing, such that the capacity of local authorities to perform sustainable hazard and risk assessments has been rather hampered.

Here, we combine an assessment of time series of aerial pictures, a detailed study of historical archives, field-based surveys, and tree-ring analyses to build the longest, annually resolved history of GLOF and debris-flow activity in northern Tien Shan. This paper therefore aims at improving our knowledge about the spatiotemporal dynamics of these processes on the Aksay fan, as a basis for future hazard assessments, at the site and within the larger study region. The well-preserved forest covering the Aksay fan allows studying impacted trees with dendrogeomorphic approaches (Stoffel and Corona, 2014). This approach has been used widely to analyze past debris flow events (see Bollschweiler and Stoffel, 2010b for a recent review) at local and regional scales (Bollschweiler and Stoffel, 2007; Mayer et al., 2010; Stoffel et al., 2010; Procter et al., 2012; Šilhán et al., 2015) but has not been applied to understand GLOF activity in the past. In an attempt to distinguish GLOFs from debris flows, we hypothesize that the signs left and the spatial patterns would be different (Bollschweiler and Stoffel, 2007) and that the position of trees on the cone would help us in distinguishing dissimilar events with quite dissimilar magnitudes but operating in the same catchment. The hypothesis was first tested with available historical records.

2. Study site

The Aksay cone (42°33′N; 74°29′E) is the largest debris-flow fan in the Ala-Archa National Park (Fig. 1). It is located on the northern slope of the Kyrgyz range at only 35 km from Bishkek. The catchment size is ca. 28.3 km^2, and ranges from 4895 to 2250 m a.s.l. In the upper part of the catchment (above 3600 m a.s.l.), two valley glaciers can be found: (i) the Uchitel Glacier with an accumulation area on the western slopes of the Semenov Tianshanskiy (4895 m a.s.l.) and Korona (4691 m a.s.l.) summits; and (ii) the Aksay Glacier, with an accumulation area located on the southwestern slopes of Korona and the western slope of Dvurogaya (4814 m a.s.l.) summits. The terminus of Uchitel Glacier is located at 3640 m a.s.l. and that of Aksay Glacier is at an elevation of 3330 m a.s.l. The lower parts of both glacier snouts are debris covered and seem to be stagnant. Roughly 1 km upslope of its terminus, Aksay Glacier exhibits an icefall with a slope of 52% and a vertical drop of up to 200 m.

The debris-flow cone extends from 2200 to 2350 m a.s.l. and is covered by *Picea abies* in the areas where somewhat older sediments predominate and *Betula* in those sectors which have been affected by

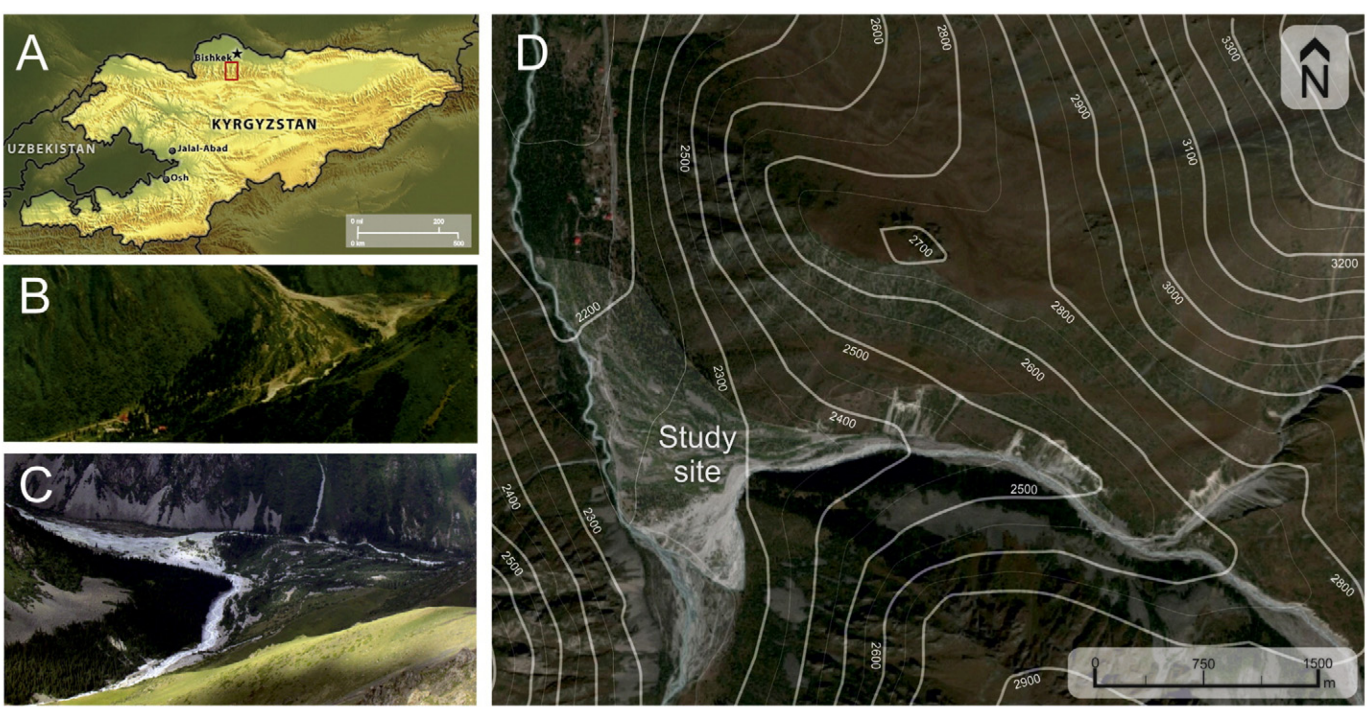

Fig. 1. (A) The study area is located close to the Kyrgyz capital Bishkek, north of the main divide of the Kyrgyz range, within the Ala-Archa National Park, Aksay valley. (B) View of the cone from west to east and (C) from east to west. (D) Satellite image (QuickBird, 2014) of Aksay cone; distance over main contours is 100 m.