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Recent increase in debris flow activity in the Tatras Mountains: Results of a regional dendrogeomorphic reconstruction

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ABSTRACT

Debris flows are very frequent geomorphic agents that form relief of the High Tatras Mountains, which are the highest mountain range in the Carpathian arc. The knowledge of their history is based on lichenometric dating, historical orthophotos and incomplete archival records. Nevertheless, complete chronologies of debris flows at an annual resolution for the High Tatras Mountains have not yet been reconstructed. In this paper, we present results of dendrogeomorphic research in the southern region of the mountains (the Great Cold Valley and Small Cold Valley). The research was undertaken to reconstruct regional year-to-year chronologies of debris flows, which would present unique perspectives on the debris flow activity. A total of 474 scars on the stems and branches of 414 *Pinus mugo* were dated with a seasonal precision (the best tool for distinguishing debris flow scars from snow avalanche scars) in 12 debris flow tracks. 22 debris flows over the last circa 30 years (the valid chronological range) in six event years were reconstructed. A significant increase in debris flow activity (verified using historical orthophotos) has occurred since AD 2007 (21 of 22 events occurred during the last decade). Two basic spatial patterns of debris flow activity were identified: regional events with at least five debris flows in one or both valleys and local events with a maximum of two debris flows per year.

Based on reports by several authors, increase in extreme precipitation events during the last decade has been observed, but debris flows have not occurred even during the most extreme precipitation events in the study area. Preparatory factors must play an important role at this stage. A significant increase in summer and autumn temperatures at the turn of the 21st century has been reported in the High Tatras Mountains. This could accelerate (dis)continuous permafrost thawing in the source zones, increase the amount of material for the next transport and influence the increase in debris flow activity.

1. Introduction

Debris flows, which are dangerous geomorphic process, are among the most frequently studied present-day phenomena in high mountains (Korup and Clague, 2009; Legg et al., 2014; Neumayer et al., 2014; Stolle et al., 2015). For prediction, a knowledge of past events is necessary. For example, Stoffel et al. (2014) stated an assumption of debris flow occurrence in the Swiss Alps for the next hundred years based on a dense dataset of dated past debris flow events. Moreover, the creation of debris flow chronologies is important for the analysis of temporal trends in past debris flow occurrences. A close relationship between changing frequencies of debris flows and global changes has often been observed. Jomelli et al. (2004) presented findings of a significant increase in debris flow frequency during the last 50 years in the French Alps. Similar results are presented by Pelfini and Santilli (2008) from central Italian Alps (increasing debris flow frequency with the peak in the 1970s–1980s). However, chronologies from the Swiss Alps show a peak of activity in the 1920s, and a significant decrease in debris flows occurred during the last decade (Bollschweiler and Stoffel, 2010). These changes are frequently attributed to short term changes in triggering rainfalls as well as long-term changes in climate, increasing mean temperatures and permafrost thawing in the culmination regions of the mountains (Sattler et al., 2011; Stoffel and Graf, 2015). Seasonal changes in debris flow occurrence can be observed. Stoffel et al. (2008) reported a shift in debris flow occurrence from June and July to August and September during the last 100 years. For those conclusions, high precision data of the past occurrence of debris flows was necessary to obtain.

The accessibility of such data is crucial and often the primary limitation for drawing relevant conclusions. The areas most impacted by debris flows are often very remote, and historical records are very scarce (Raška et al., 2014; Văidean et al., 2015). Under such circumstances, dendrogeomorphic methods are very helpful tools for the reconstruction of past debris flow occurrence several centuries back (Bollschweiler and Stoffel, 2010; Šilhán et al., 2015), even with seasonal precision (Stoffel et al., 2008; Kaczka et al., 2010). The only requirement is the presence of trees with distinct annual tree rings. Data based on the tree ring research are very suitable to analyze changes in the occurrence of past debris flows. According to the actual state of art, regional

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reconstructions for several debris flow torrents are necessary for a detailed understanding of debris flow behaviors (Procter et al., 2011; Schraml et al., 2015; Šilhán et al., 2015). Unfortunately, debris flows seldom occur in isolation from other geomorphic processes (Owczarek et al., 2013). In particular, snow avalanches very frequently affect the same localities. Fortunately, snow avalanches and debris flows can be distinguished in tree ring based chronologies. Dating using geomorphic signals (growth evidences within tree ring series) with seasonal precision has led to good results (Stoffel et al., 2006; Szymczak et al., 2010). E.g., Kogelnig-Mayer et al. (2011) introduced a seasonal index for distinguishing snow avalanches and debris flow events.

The High Tatras Mountains are the highest mountain range in the Carpathian arc. Their relief is formed by frequent debris flows that occasionally cause infrastructure damage (Ziętara, 2002). Although there is a long history of debris flow research for the northern slopes of the mountains, a detailed regional chronology at an annual precision has not yet been developed. Partial knowledge of past debris flow events is contained in incomplete archives or has been reconstructed using lichenometry (Kotarba, 1989, 1991) or orthophotos (Kapusta et al., 2010). Most of the past studies focused exclusively on areas above the tree line. Because the earlier debris flow research preferentially addressed the northern slopes of the mountains, there are no known debris flow chronologies for the southern slopes. Scarce information is available based on the analysis of old orthophotos, for example by Kapusta et al. (2010), but without annual resolution. Dendrogeomorphic methods for debris flow dating in this region have not yet been applied. This study focuses on the activity of debris flows in the neglected parts of slopes covered by mountain pine (*Pinus mugo* var. *mugo*). Dating debris flows in those locations can provide uniquely precise data and new perspectives on debris flow activity.

Aims of this study are to i) date debris flow events in the High Tatras Mountains using dendrogeomorphic analysis of *P. mugo*, ii) create a regional chronology of debris flows for the southern slopes of the studied mountains and iii) reveal temporal trends in debris flow occurrence and discuss their potential control.

2. Study area

The High Tatras Mountains tectonically developed during the Cretaceous to Quaternary. The highest peaks rise above 2500 m a.s.l. The main ridge is an asymmetric fault structure tilted to the north. The geology is dominated by granitoids and quartz diorites. Remnants of carbonate rocks (limestones) occur in the northern part of the mountains. The relief of mountains was sculpted by several glacial phases during the Pleistocene. According to Kotarba (1992), Klimaszewski (1988) and Engel et al. (2015), the most extensive glaciation occurred during the Würm period. However, even the culmination areas of the mountains are free of glaciers. Several authors predict discontinuous and continuous permafrost at elevations above the 1700 and 2500 m a.s.l., respectively (Gądek and Kędzia, 2008; Gądek and Leszkiewicz, 2010). Individual mountain ridges are often affected by deep-seated gravitational slope deformations (Pánek et al., 2015). The present timberline ecotone lies at altitudes of approximately 1450–1700 m a.s.l. on the southern slopes (Plesník, 1971; Kaczka et al., 2015), nevertheless its shift can be expected in the future under changing climatic conditions (Piermattei et al., 2014). A continuous belt of formations of bush-like *P. mugo* occurs up to approximately 1700 m a.s.l. The High Tatras Mountains are on the border of continental and oceanic climates. The mean annual precipitation ranges from 595 mm in the foreland (Poprad meteorological station; 690 m a.s.l.) to 1400 mm in the culmination parts (Lomnický štít meteorological station; 2653 m a.s.l.) (Niedźwiedź, 1992). The extreme precipitation totals are frequently caused by cyclones passing from the Mediterranean area through central Europe that follow Vb tracks (Van Bebber, 1881; Messmer et al., 2015; Niedźwiedź et al., 2015). According to Kotarba (2007), the rainfall intensity threshold for debris flow initiation is 1 mm/min or 25 mm/h in

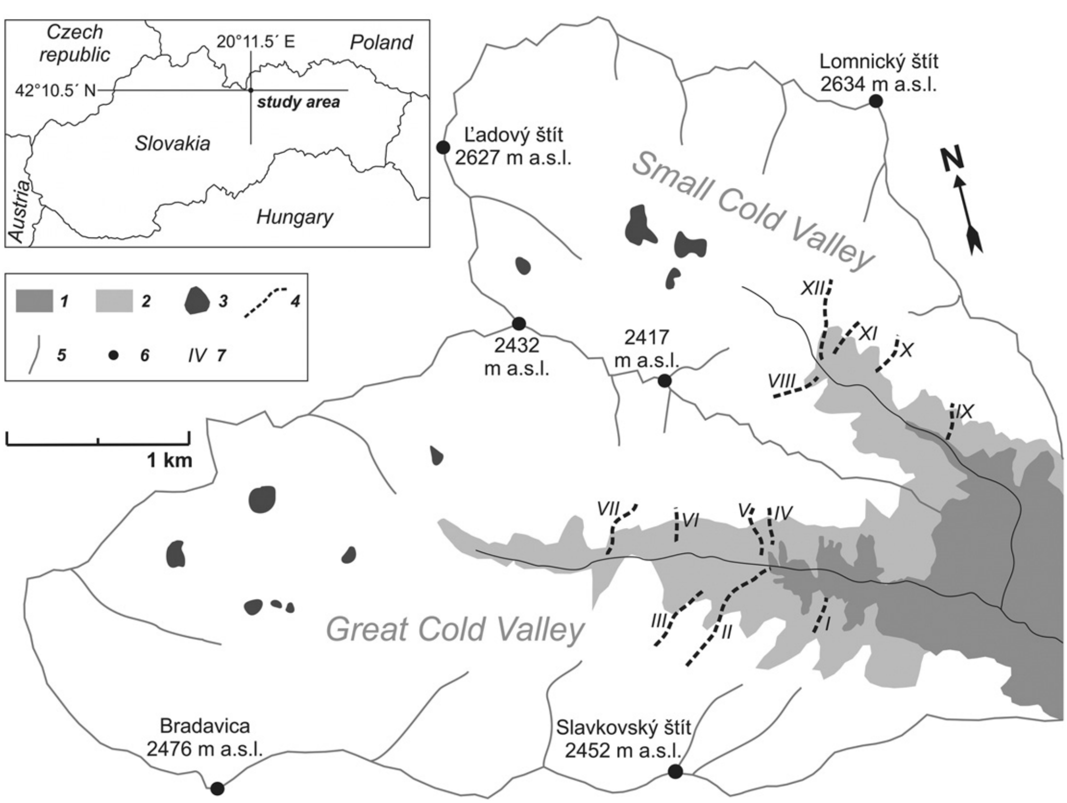

Fig. 1. Location of the study area (1 – continuous common spruce forest, 2 – continuous *P. mugo* cover, 3 – glacial lake, 4 – studied debris flow tracks, 5 – basin divide, 6 – peak and 7 – the number of debris flow tracks).