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Evaluation of growth disturbances of *Picea abies* (L.) Karst. to disturbances caused by landslide movements

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ABSTRACT

Dendrogeomorphic methods are frequently used in landslide analyses. Although methods of landslide dating based on tree rings are well developed, they still indicated many questions. The aim of this study was to evaluate the frequently used theoretical scheme based on the event–response relationship. Seventy-four individuals of Norway spruce (*Picea abies* (L.) Karst.) exhibiting visible external disturbance, were sampled on the Girová landslide (the largest historical flow-like landslide in the Czech Republic). This landslide reactivated in May 2010, and post-landslide tree growth responses were studied in detail. These growth responses were compared with the intensity and occurrence of visible external tree disturbance: tilted stems, damaged root systems, and decapitation. Twenty-nine trees (39.2%) died within one to four years following the 2010 landslide movement. The trees that died following the landslide movement were significantly younger and displayed significantly greater stem tilting than the live trees. Abrupt growth suppression was a more-frequent response among the dead trees, whereas growth release dominated among the live trees. Only two trees (2.7%) created no reaction wood in response to the landslide movement. Forty-four percent of the trees started to produce reaction wood structure after a delay, which generally spanned one year. Some eccentric growth was evident in the tree rings of the landslide year and was significant in the first years following the landslide movement. Missing rings were observed only on the upper sides of the stems, and no false tree rings were observed. The results confirm the general validity of event-response relationship, nevertheless this study points out the limitations and uncertainties of this generally accepted working scheme.

1. Introduction

Landslides rank among the most hazardous of geomorphic processes (natural hazards) and cause several thousand fatalities and great damage to structures every year worldwide (Gutiérrez et al., 2010). Therefore, the modelling of landslide activity with future changing climate conditions in terms of landslide magnitude–frequency relationships is highly important (Lopez-Saez et al., 2013). Typically, obtaining detailed information about past landslide activity is crucial for developing meaningful predictions of future landslide activity. More accurate data regarding past landslide occurrence tend to raise the possibility of identifying landslide triggers.

There are several methods used to date landslides (Lang et al., 1999; Pánek, 2015). All these methods are limited by the length of the chronology and by the accuracy of the dating. Dendrogeomorphic methods are regarded as the most precise method of landslide dating in forested areas with temperate climate (Alestalo, 1971). Tree-ring chronologies may span as much as several hundred years (Šilhán et al., 2012) with a precision as good as several months (Lopez-Saez et al., 2012). Although these methods have been used for several decades and are well developed, many unsolved questions still remain (e.g. detailed analysis and verifying of tree growth response to disturbances).

The theoretical conceptual model underlying dendrogeomorphic research was first described in 1978 by Shroder (1978). His model is usually expressed as a process–event–response sequence, which is applicable to landslide research inasmuch as the process in this sequence is landslide movement. The process–event relationship in the case of landsliding is well known and described (e.g., Carrara and O'Neill, 2003; Lopez-Saez et al., 2012). Landslides cause several events observed in trees: tilting of tree stems due to ground destabilisation or surface deformation, root damage (mostly along tension cracks or fresh scarps), burying of stems by landslide material, and wounding of stems and branches by falling trees (Carrara and O'Neill, 2003). Very intense events can kill trees. The interpretation of growth disturbance (GD) in trees in response to an event is based on the general preconditions summarized by, e.g., Shroder (1978), Stoffel and Bollschweiler (2008) and Stoffel and Corona (2014). The primary growth reaction of a tree to stem tilting is the creation of reaction wood on one side of the stem: compression wood on the lower sides of the stems of

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coniferous trees (Westing, 1965; Timell, 1986) and tension wood on the upper sides of the stems of broad-leaved trees. The creation of reaction wood can be supported by eccentric growth (Braam et al., 1987; Wistuba and Malik, 2011; Šilhán, 2016), but eccentric tree rings can also develop without the presence of reaction wood (Fisher and Marler, 2006). Tree-root damage and stem burial are followed by abrupt growth suppression (LaMarche, 1968). In certain cases, growth release can occur in the tree-ring series of live trees in reaction to new competition conditions after the deaths of neighbouring trees (Butler, 1979). Trees growing on the side of tension cracks can experience root exposure. Anatomical changes in the form of a decrease of early wood cells size usually follow exposure in the case of coniferous trees.

Nevertheless, this model does not work well every time, and certain authors have described its possible limitations and uncertainties (e.g., Shroder, 1980; Stoffel and Bollschweiler, 2009; Stoffel and Corona, 2014). One of the most serious problems is the potential delay in the growth response. This delay is observed most often in cases of growth suppression and release (Stoffel and Bollschweiler, 2009; Procter et al., 2012), but it may also be observed in other types of growth disturbances - GD (e.g., reaction compression wood; Shroder, 1978; Lopez-Saez et al., 2012). Moreover, the intensity of GD varies from tree to tree. The general practice has been to weigh GD and to focus on strong signals for dating of geomorphic processes (Kogelnig-Mayer et al., 2011; Tichavský and Šilhán, 2015). This approach, unfortunately, can lead to the neglect of minor geomorphic processes. Therefore, dendrogeomorphic chronologies are always regarded as minimal. In addition, not enough is known about the relationship between the event intensity and response intensity. Resolution of these issues is crucial for the future development of dendrogeomorphic methods and for the correct interpretation of dendrogeomorphic results.

The main goals of this study were as follows: (i) to evaluate the delay of GD after a landslide movement, and (ii) to evaluate the relationships between the intensities of external tree disturbance and growth responses. Solving of these main goals should bring data enabling to evaluate and possibly to upgrade the validity degree of Shroder's conceptual model in the specific conditions of catastrophic landslide. These goals were met using the comparison between dead trees and trees that survived the landslide event. For purposes of such an evaluation, it seemed useful to analyse trees growing on a landslide with a well-defined record of past activity. The ideal landslide is one displaying a single large-scale reactivation. This characteristic is important in that it allows for the exclusion of a potential combination of growth signals from multiple landslide movements. The May 2010 movement involving the Girová landslide, which is located in the Outer Western Carpathians, was selected for this study. The landslide is covered almost exclusively by Norway spruce (*Picea abies* (L.) Karst.).

2. Study area

The Girová landslide (Fig. 1) is the largest long-runout historical landslide in the Czech Republic. It is located in the geomorphic region of the Slovenské Beskydy Mountains (part of the Outer Western Carpathians). The landslide is situated on the southern slope of Mt. Girová (839 m a.s.l.) (Pánek et al., 2011b). The rocks of Mt. Girová are predominantly compact sandstones overlying weak claystones and mudstones. The area receives 979 mm of annual precipitation and has an annual mean temperature of 7.4 °C (Jablunkov meteorological station, 380 m a.s.l.). The maximum landslide runout is 1150 m, the maximum width is 300 m, the total vertical distance is 171 m, and the landslide area measures 20 ha. The landslide can be characterized as a translational, wedge-like rockslide with a main scarp delineated by the crossing of two normal faults. The amount of horizontal movement varies across the landslide. The blocks in the upper portion have moved as much as 80 m. The middle portion has moved 270 m horizontally, and the frontal portion has moved as much as 550 m. The upper portion of the landslide is dominated by a 25-m-high rocky headscarp and large, translationally displaced, deep-seated blocks. Compressional landslide features and lateral levees are present in the middle portion of the landslide mass. The landslide front is characterized by relatively shallow (<10–20 m) flow-like movement of a distal lobe (Pánek et al., 2011b) (Fig. 1). The landslide movement was triggered at night from 18 to 19 May 2010 after three days of intense rainfall (15–18 May 2010; >300 mm) (Pánek et al., 2011a). Minor landslide movements occurred until 29 May 2010.

3. Methods

3.1. Field sampling

Suitable trees for the analysis were located in the lowest portion of the landslide area, i.e., on the distal lobe, and above the main scarp; both areas were fully activated during the 2010 movement (Fig. 1).

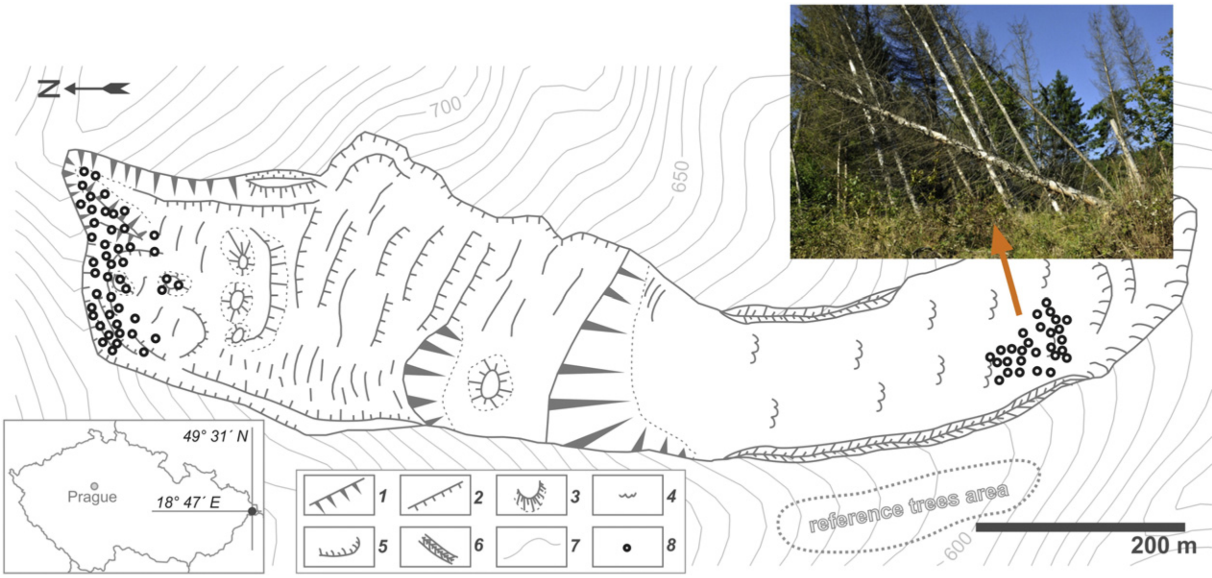

Fig. 1. Location and geomorphic map of the study area, and the view on the disturbed trees (1 – main scarp, 2 – minor scarp, 3 – partial landslide block, 4 – deformed surface of frontal lobe, 5 – border of frontal lobe, 6 – lateral levee, 7 – izoline (5 m), 8 – sampled tree).