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How different are the results acquired from mathematical and subjective methods in dendrogeomorphology? Insights from landslide movements

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ABSTRACT

Knowledge of past landslide activity is crucial for understanding landslide behaviour and for modelling potential future landslide occurrence. Dendrogeomorphic approaches represent the most precise methods of landslide dating (where trees annually create tree-rings in the timescale of up to several hundred years). Despite the advantages of these methods, many open questions remain. One of the less researched uncertainties, and the focus of this study, is the impact of two common methods of geomorphic signal extraction on the spatial and temporal results of landslide reconstruction. In total, 93 Norway spruce (*Picea abies* (L.) Karst.) trees were sampled at one landslide location dominated by block-type movements in the forefield of the Orlické hory Mts., Bohemian Massif. Landslide signals were examined by the classical subjective method based on reaction (compression) wood analysis and by a numerical method based on eccentric growth analysis. The chronology of landslide movements obtained by the mathematical method resulted in twice the number of events detected compared to the subjective method. This finding indicates that eccentric growth is a more accurate indicator for landslide movements than the classical analysis of reaction wood. The reconstructed spatial activity of landslide movements shows a similar distribution of recurrence intervals (*Ri*) for both methods. The differences (maximally 30% of the total *Ri* ranges) in results obtained by both methods may be caused by differences in the ability of trees to react to tilting of their stems by a specific growth response (reaction wood formation or eccentric growth). Finally, the ability of trees to record tilting events (by both growth responses) in their tree-ring series was analysed for different decades of tree life. The highest sensitivity to external tilting events occurred at tree ages from 70 to 80 years for reaction wood formation and from 80 to 90 years for eccentric growth response. This means that the ability of *P. abies* to record geomorphic signals varies with not only eccentric growth responses but also with age.

1. Introduction

Landslides are very broadly extended geomorphic processes that often occur in populated areas (Gutiérrez et al., 2010; Van Den Eeckhaut and Hervás, 2012), where they can present a significant natural hazard. Therefore, knowledge of the chronology of past landslide activity is important for modelling their future potential occurrence (Borgatti and Soldati, 2010). Moreover, data regarding the spatial distribution of landslide activity are necessary for safe land-use planning. Unfortunately, direct information regarding past landslide activity is often scarce, particularly in remote areas. Landslides inventory and mapping is required to better understand where and when they may occur. Nevertheless, as the dates of triggering of past events are often uncertain, the application of absolute dating methods becomes necessary (Lang et al., 1999).

Dendrogeomorphic methods represent the most precise way of dating past landslide activity in areas with forest cover located in temperate zones in the timescale up to several hundred years (Corona et al., 2014), although some limitations exist. For example, a limitation of dendrogeomorphic landslide dating is the age of the trees studied. Since the introduction of dendrogeomorphic analysis, coniferous trees have been favoured (Alestalo, 1971; Shroder, 1978; Bégin and Filion, 1988; Lopez-Saez et al., 2012a) probably due to their good visibility of tree-rings, easy sampling, or good visible growth responses. Nevertheless, many landslide areas are populated by broad-leaved trees, and studies investigating broad-leaved trees have become more frequent in recent decades (Fantucci and Sorriso-Valvo, 1999; Guida et al., 2008; Stefanini, 2004; Šilhán et al., 2014). According to Shroder (1978), the most frequent landslide-associated event affecting trees is the tilting of their stems; nevertheless, damage to the roots or burying of the stem base can occur as well (Stoffel and Corona, 2014). For coniferous trees, the dominant influence on growth following tree tilting is the formation of reaction (compression) wood on the lower side of the stem. The cells of compression wood have thicker and more rounded walls of the tracheids, which is the reason why tree rings containing compression wood are macroscopically identifiable (Timell, 1986). Nevertheless, coniferous trees do not create reaction wood in all cases of

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stem tilting, and a potential minimum tilting value for its creation had not been defined until recently (Šilhán and Stoffel, 2015). Moreover, potential delay in the compression wood formation after the tilting event can occur (Shroder, 1978). However, compression wood identification in tree ring series is a subjective approach, and results can be influenced by a researcher error. Additionally, broad-leaved trees create reaction (tension) wood on the upper side of their tilted stems. Unfortunately, this type of reaction wood is practically unidentifiable at a macroscopic scale (Westing, 1965). In spite of potential limitations regarding compression wood analysis, many recent studies of landslide dating have been based on this subjective approach (Lopez-Saez et al., 2012a,b; Šilhán et al., 2012, 2013). Another growth reaction to stem tilting is eccentric growth. Tilted coniferous trees start to produce wide tree-rings on the lower side of the stem, whereas the upper side of the stem is dominated by suppressed growth (Braam et al., 1987). The position of wide tree-rings and suppressed growth is usually opposite in the case of broad-leaved trees. Identification of a tilting event based on dating of this reaction has a mathematical base, as the eccentricity is based on the calculation from measured tree-ring widths, and subjective errors can be excluded. Unfortunately, some limitations even for the eccentric growth analysis exist. The eccentric growth can occur even as a response to non-geomorphic events (e.g. strong wind). Due to the aforementioned difficulties with identification of tension wood, the analysis of tree-ring series of broad-leaved trees is dominantly focused on eccentric growth as a reaction to stem tilting (Van Den Eeckhaut et al., 2009; Šilhán et al., 2014). To date, the resulting effect of these two different approaches (reaction wood vs. eccentric growth) on reconstructed chronologies or spatial reconstruction is not known. However, answering this question is crucial for increasing the accuracy of past events identification. Therefore, as noted above, dendrogeomorphology is characterized by some biases (while it is very accurate), so that a comparison of different methods is highly important.

Another open question is the changing sensitivity of trees to geomorphic events with increasing age. For example, Šilhán et al. (2013) found the highest sensitivity of Crimean pine (*Pinus nigra* ssp. *pallasiana*) to rockfall events at ages of 80 to 90 years. The highest sensitivity of *P. nigra* to landslides was found to be present in two phases, between the ages of 40 to 60 years and 120 to 130 years (Šilhán and Stoffel, 2015) in the dependence on the dominant growth response (reaction wood vs. eccentric growth). However, for Norway spruce (*Picea abies* (L.) Karst.), a very common tree species occupying landslides in the northern hemisphere, the most suitable ages for recording tilting events have not been determined yet.

Based on the aforementioned open questions, the objective of this study is to show the effects of using subjective and mathematical approaches (reaction wood and eccentric growth, respectively) on different aspects of dendrogeomorphic reconstruction of landslide movements. This objective will be achieved using the following strategies: (i) evaluating landslide event chronologies obtained using both

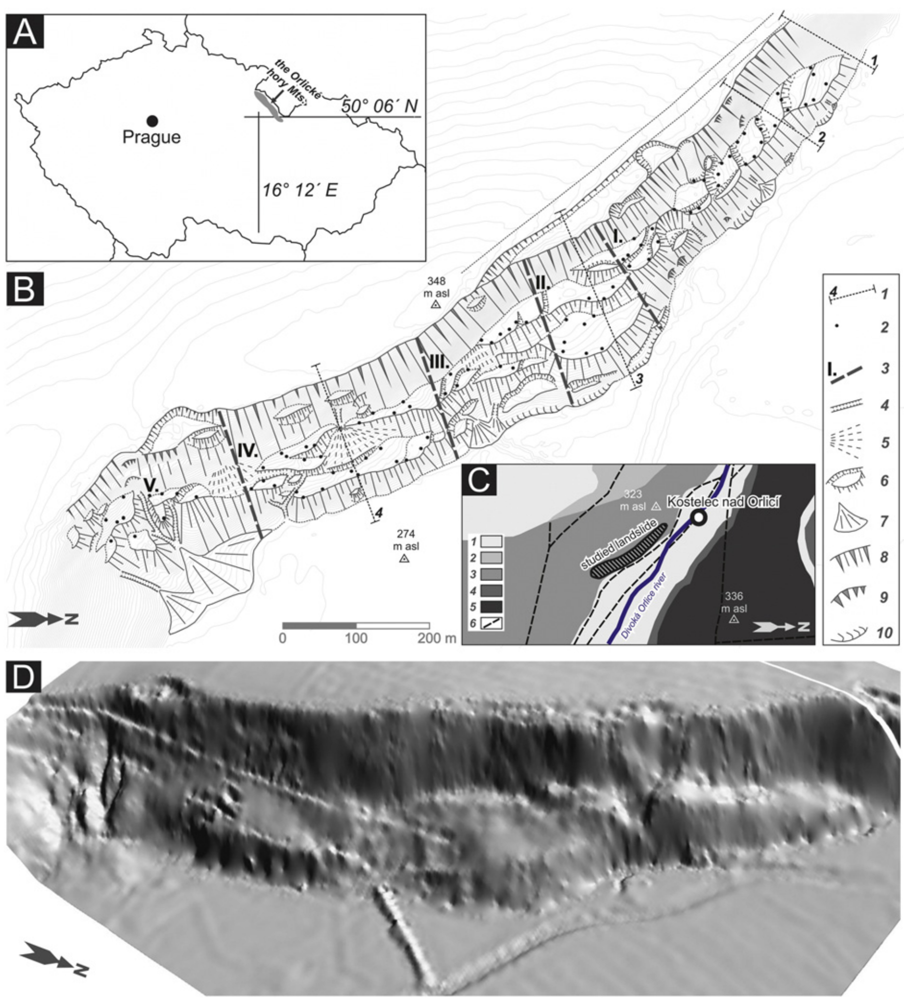

Fig. 1. Location, geomorphology, and geology of the studied area. A — location of the study area in the Czech Republic, B — geomorphic map of the studied landslide area (1 — position of the topographic profile in Fig. 2; 2 — sampled trees; 3 — border of studied domains; 4 — gully; 5 — debris talus; 6 — partial landslide block; 7 — alluvial fan; 8 — main scarp; 9 — bedrock outcrop; 10 — accumulation lobe), C — geology of the studied landslide surroundings (1 — fluvial sands and gravel, 2 — marlstone and sandstone, 3 — marlstone, 4 — limestone claystones, 5 — loess, 6 — fault), and D — LiDAR image of hillslope affected by the studied landslide.