ROMANIAN ASSOCIATION OF GEOMORPHOLOGISTS
AGR

REVISTA DE GEOMORFOLOGIE (2022) **24(2)**: 16–26
DOI: 1021094/rg.2022.147
www.geomorfologie.ro, http://revistadegeomorfologie.ro

Dendrogeomorphic reconstruction of past landslide activity in the Jablůnka village (Czech part of the Outer Western Carpathians)

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Received 28 January 2022; Revised 31 November 2022; Accepted 19 December 2022
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ABSTRACT

Landslides represent an important and possibly very dangerous natural hazard. Dendrogeomorphic methods can provide unique data on the behaviour of landslides in the past by studying the tree–ring series of disturbed trees. Knowledge about past landslide activity in the flysch part of the Outer Western Carpathians is generally very scarce or missing. The past activity of selected landslides (possibly endangering neighbouring settlements) was studied using data from 106 increment cores from 53 disturbed individuals of *Picea abies* (L.) H. Karst. to assess their past spatiotemporal activity. In total, six certain event years and 13 probable events were detected during the period between 1927 and 2017. Certain events always occurred in groups of the two following events, suggesting the inertia of landslide movements after the initial triggering. The spatiotemporal reconstruction revealed a distinctly increased activity of movements in the zone of the main scarp and particularly in the landslide front, which could possibly endanger human infrastructure during its significant reactivation. However, the reconstruction performed suggests general landslide inactivity since 1997, when the last high–magnitude reactivation occurred.

KEYWORDS Dendrogeomorphology; Landslide; Dendrometry; Outer Western Carpathians; Reaction wood

1. Introduction

Landslide movements can represent a high risk for the inhabitants living in their surroundings. Damage to buildings or roads is no exception (Kirchner et al., 2000). The activity of slope processes is currently one of the most important pieces of information for understanding these natural hazards and their triggers (Corominas a Moya, 2008). Several possibilities of landslide movement monitoring exist, i.e., installation of extensometers (Klimeš et al., 2012), repeated GNSS measurements (Wang, 2011), or digital photogrammetry (Chandler, 1999). The use of such methods can be limited by the necessity of long-term monitoring and approach precision due to the lack of obtained information.

One of the oldest known landslide events in the Hostýnsko–Vsetínská highland (Czech part of the Outer Western Carpathians – one of the most landslides–susceptible regions in central Europe (Van den Eeckhaut and Hervás, 2012)) probably originated in 1924–1929 (Bíl et al., 2014). However, the landslide movements recorded a higher interest after the landslide calamity in 1997, when the extreme precipitation total amount (re)activated slope movements in the flysch relief of the Outer Western Carpathians in the eastern part of the Czech Republic and caused extensive damage (Kirchner and Krejčí, 2002). The region around Vsetín town was one of the most heavily damaged (Kirchner and Krejčí, 2002). The main triggering factors of landslide reactivation in this region are extreme (high-magnitude) precipitation totals and intensive snow melt (often in combination with rain on snow) (Kirchner and Krejčí, 2002).

To determine past landslide activity and creation of event chronology, dendrogeomorphic methods can be used as very effective tools in situations where archival data or long-term monitoring is missing (Alestalo 1971). The length of the reconstructed chronology of past landslide movements can reach several hundred years or up to a millennium (Zhang et al., 2019), even with seasonal precision (Lopez–Saez et al., 2012a). The first mention of the term dendrogeomorphology was by Alestalo (1971), who described the basic relationships between slope movements and tree growth by Shroder (1978), who introduced the process–event–response scheme that is currently valid. Later, dendrogeomorphic methods were frequently used for studying various geomorphic processes (Stoffel et al., 2008; Bollschweiler et al., 2009), hydrological processes (Ballesteros et al., 2011; Stoffel and Wilford, 2012), or geological applications (Jacoby et al., 1988; Baillie, 2008). Dendrogeomorphic methods use the analysis of tree-ring series of trees disturbed by geomorphic processes of interest (Stoffel and Bollschweiler, 2009). The information from disturbed tree ring series can help us better understand the landslide behaviour in regions of interest (Šilhán, 2020). Moreover, data about past active landslides can be used not only for the assessment of landslide triggers but also for the modelling of landslide activities in the future (Lopez Saez et al., 2012b). Landslide movements usually cause tilting of the tree stems. The intensity and direction of stem tilting can be successfully used to assess landslide movement mechanisms (e.g., rotational vs. translational movements), as demonstrated by Šilhán (2015).

The aim of this study is to create a spatiotemporal reconstruction of past landslide movements in the forested area near Jablůnka village in the Hostýnsko–Vsetínská highland using dendrogeomorphic methods. The partial aim can be summarised as follows: i) to define the frequency and recurrence of landslide movements, ii) create the spatiotemporal reconstruction of past landslide activity in map form, and iii) verify the possible activity of the studied landslide in 1997. The obtained information can help with decisions about the extension of urbanised zones surrounding active landslides.

2. Studied locality

The studied landslide (49.38° N and 17.97° E; Fig. 1) is located at an elevation of approximately 500 m a.s.l. in the NW direction from the Vlčice Mt. (606 m a.s.l.) in the Hostýnsko–Vsetínská highland. The geological composition of the region is part of the flysch zone of the Outer Western Carpathians (the group of the Magura nappes). The area of interest is located in the Račanská unit of the Belovež layers. This structure is typical of fine flysch with dominating claystones over locally occurring sandstones of the Paleocene to Eocene age (Menčík et al., 1983). The average precipitation total amount reaches 100–130 mm during the summer half of the year and 130–160 mm during the winter half of the year (Tolasz et al., 2007). The maximal precipitation total was recorded in 1997 when the mean five–day (4–8 July) cumulated precipitation reached 300–400 mm. Several hundreds of landslides in the studied region were activated during this extraordinary event (Kirchner et al., 2000).

The landslide of interest has flow–like morphological characteristics with the expected shallow slip surface. The landslide is approximately 300 m long and 100 m wide. The height of the morphological indistinct main scarp is approximately 1 m, and the landslide front is situated on the bank of the Lýkový stream. The landslide front is morphologically very distinct, with lobate fresh morphology suggesting its recent active movements. The evidence of active landslide movements starts in the middle zone of the total landslide area with a distinct tension crack on one side of the landslide. The erosion step is approximately located in the corresponding position to the crack on the opposite side of the landslide. The frontal part of the landslide is covered by juvenile individuals of common spruce (*Picea abies* (L.) H. Karst.). The rest of the landslide area is occupied by distinctly older individuals of *P. abies*. The forest cover in the upper part of the landslide is supplemented by juvenile individuals of European beech (*Fagus sylvatica* L.). The active landslide front is located approximately 400 m above the inhabited area, on the land of an industrial company. Possible fast acceleration of landslide movements could cause heavy damages here, as already happened in several localities in the studied region (Kirchner and Krejčí, 2002).

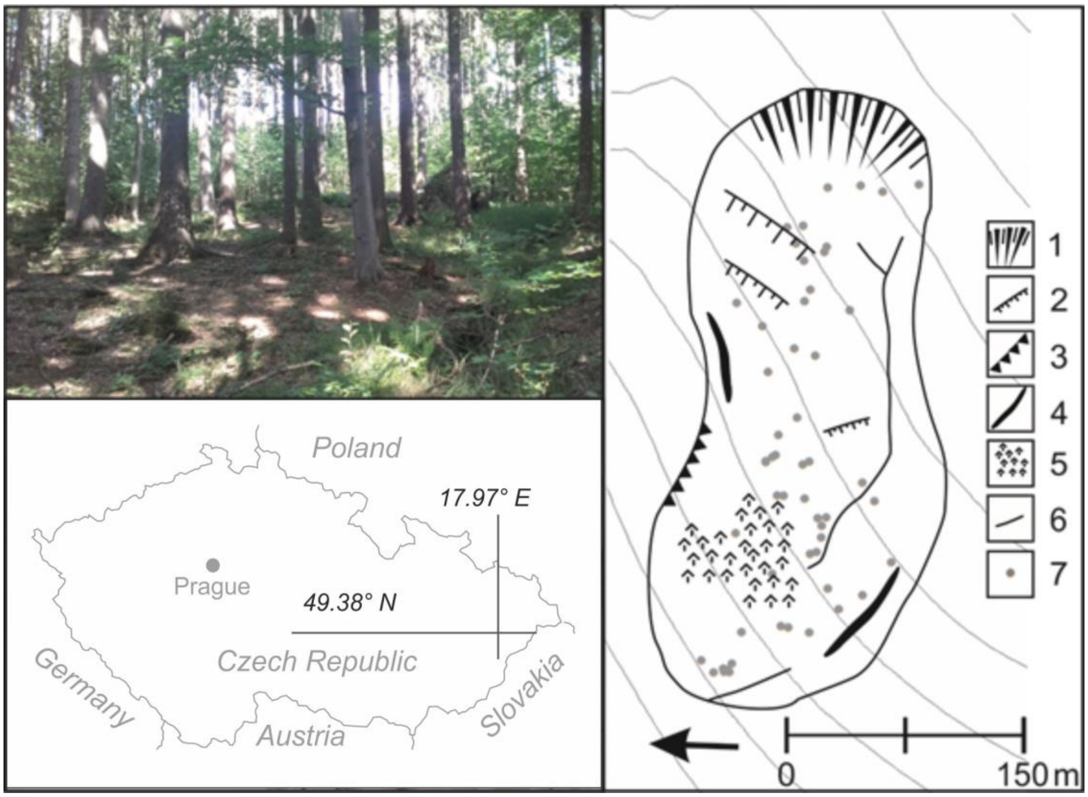

Figure 1 Location and geomorphology of the studied locality (1 – main scarp, 2 – terrain step, 3 – minor scarp, 4 – tension crack, 5 – juvenile trees, 6 – gully, 7 – sampled tree)

3. Methods

The main methodical approach used in this study was based on studying tree-ring series. Nonetheless, this method was supplemented by other approaches.

3.1 Geomorphic mapping

The first step of fieldwork included geomorphic mapping (1:100). The mapping was focused on the basic structures of the landslide area (e.g., the presence and location of the main scarp, tension cracks, gullies, lateral levees; Fig. 1). The positions of all trees occupying the landslide area were simultaneously recorded using a total geodetic station. Next, the intensity and direction of stem tilting were measured and recorded using a digital inclinometer and compass. These dendrometric parameters were recorded for all trees occupying the landslide surface (not only the sampled and analysed trees). Trees suitable for subsequent sampling and dendrogeomorphic analysis were selected during this step as well. The trees were selected according to their positions to equally cover the landslide surface, as recommended by Corona et al. (2014).

3.2 Field dendrogeomorphic sampling

All selected trees were sampled using a Pressler increment borer (maximum length: 50 cm; diameter: 0.5 cm). Only trees with evident effects on their growth by landslide movements (tilted or bent tree stems) were sampled (Kirchner and Lacina, 2004). In total, 53 individuals of *P. abies* were sampled, and their positions were recorded in the geomorphic map. Two increment cores were extracted from each tree.

The first core was taken from the lower side of the tilted stem and another from the opposite side of the stem. The sampling height was in the position of the most intensive stem bending. Next, 20 indistinguishable individuals of *P. abies* growing out of the studied landslide in the stable position but under similar microclimatic conditions were sampled for construction of the reference chronology. All reference trees were sampled in the isoline direction, and two increment cores were always taken from each tree.

3.3 Laboratory approaches

The processing of samples following standard dendrochronological procedures (Stokes and Smiley, 1968) preceded the interpretation of landslide signals in the tree-ring series of disturbed trees. Individual methodical steps included gluing the samples into wood supports and subsequent sanding of core surfaces by descending rows of sandpaper. The next analytical step was tree ring counting and measurement of their widths using the dendrochronological device TimeTable and PAST4 (VIAS, 2005) software under a binocular stereoscope.

Samples from reference trees were processed in the same way, and the resulting reference chronology was compiled in Arstan software (Holmes, 1994) using a double detrending procedure. Increment curves of reference chronology and individual disturbed trees were cross-dated to identify possible false or missing rings. Moreover, the reference curve was used to filter climatically induced growth and abrupt changes in tree growth from the geomorphic induced ones.

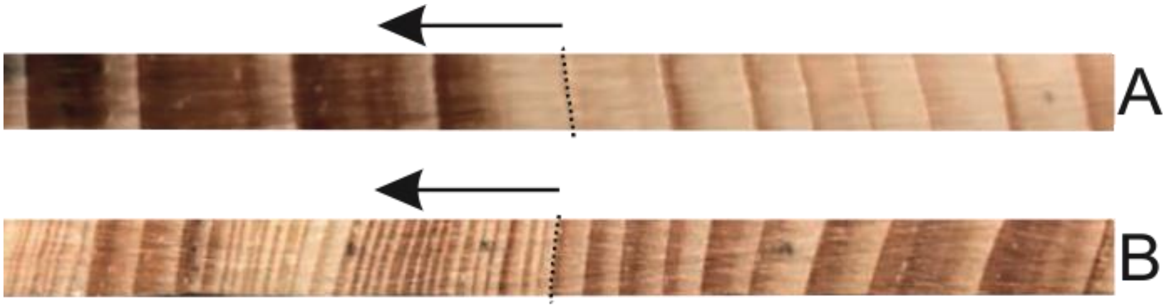

Figure 2 Dated growth disturbances. A – reaction wood, B – abrupt growth suppression

3.4 Sample analysis and identification of past landslide events

The prepared samples were macroscopically analysed for the detection of growth disturbances in individual years. The most frequent growth disturbance induced by tilting of the tree stem due to the destabilization of the tree ground via landslide movements was reaction wood (Fig. 2; Westing, 1965). The reaction wood in coniferous tree species is also called compression, whose typical characteristic is the occurrence of a wide tree ring with a distinctly darker colour on the lower side of the stem (Stoffel and Bollschweiler, 2009). The brown–reddish colour of woody material is caused by thick and well-rounded cell walls of early and late wood tracheids (Timell, 1986). The initial year of occurrence (the onset), the number of subsequent rings containing a compression wood structure and reaction wood type (mild or pronounced following the recommendation of Lopez Saez et al., 2012a) were the recorded parameters of each identified reaction wood. Mild reaction wood was defined when the typical structure occurred in less than 75% of the tree-ring width, and the pronounced reaction wood was defined as the occurrence of reaction wood structure in more than 75% or tree-ring width (Lopez Saez et al., 2012a). The next observed and recorded growth disturbance was the abrupt changes in the tree ring widths (particularly decrease) in the several following tree rings (Fig. 2). Abrupt growth suppression is usually caused by damage to the root system by subsurface landslide movements or by the decapitation of trees. The next causes of suppressed growth can lie in the burial of stems based on accumulated landslide material (Gärtner, 2007). As the landslide signal in this study, the abrupt growth suppression had to be at least approximately 50% compared with the mean tree-ring width of four previous tree rings (Schweingruber et al., 1990). Moreover, the intensity of abrupt growth suppression was evaluated and recorded according to the percentage decrease value into the two levels. Moderated abrupt growth suppression was defined as a 50–70% decrease, and strong abrupt growth suppression was defined as a 70% decrease in the tree-ring width. Next, the duration of such suppression must be detectable in at least eight subsequent tree rings (Stoffel and Corona, 2014).

Based on the identification of reaction wood and abrupt growth suppression, the activity of landslide movements was expressed by calculating the standard event–response (I_t) index following the formula of Shroder (1978) as

$$I_t = \frac{R_t}{A_t} \times 100\ (\%) \qquad (1)$$

where R is the number of trees with a growth disturbance in year t and A is the total number of sampled and analysed trees alive in year t. To prevent overestimation of values possibly causing false landslide events, two thresholds of the I_t index were defined (Stoffel et al., 2013). Probable landslide events were defined as years with I_t values between 5 and 10%, and certain events were defined as years with I_t values higher than 10% (Corona et al., 2014). Moreover, at least three trees had to simultaneously contain growth disturbances in their tree-ring series in the event year. The mentioned values of I_t thresholds were selected following the recommendation of Corona et al. (2014) based on the total number of sampled and analysed trees on landslides (sample size). The frequency of detected past landslide events in each tree was expressed by the recurrence interval (R_i), which was calculated using the following formula:

$$R_i = \frac{A_s}{\sum L_s} \qquad (2)$$

where A is the age of tree s and L is the total number of growth disturbances recorded in the tree-ring series of tree s. The calculated R_i values were subsequently spatially interpolated using the ordinary kriging method in Surfer9 software (Golden software, 2002).

4. Results

The geomorphic map was created as the first step of results processing. Next, a total of 53 trees (all *P. abies*) were sampled via 106 increment cores. The mean age of all the sampled trees was 80.6 years (stdev: 20.0 years), while the oldest trees were 107 years old and the youngest sampled tree was 34 years old.

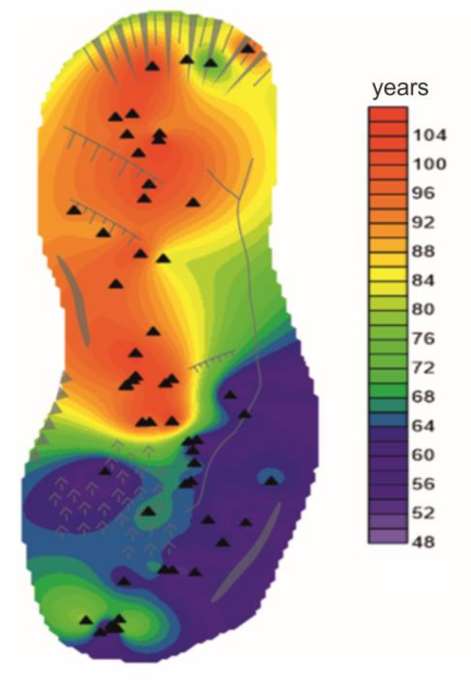

Figure 3 Spatial distribution of the tree age (black triangle – sampled tree)

The oldest trees were generally located in the zone below the main scarp, and their ages decreased towards the landslide front, where the youngest trees were detected (Fig. 3). The intensity of stem tilting ranged between 1 and 26° (Fig. 4). The trees with a maximal intensity of stem tilting were located in three zones of the studied landslide surface. Trees occupying the rest of the landslide surface expressed moderate to low tilting intensity values. The most frequent direction of stem tilting was to SSW (19 trees).

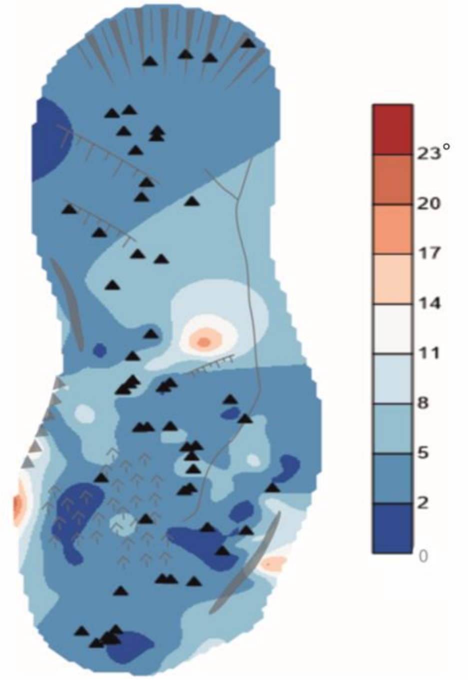

Figure 4 Spatial distribution of stem tilting direction (black triangle – sampled tree)

In general, the trees were most frequently tilted in the direction between W and S (77 trees) (Fig. 5). However, it seems that trees do not tend to cluster based on their tilting, and trees with various tilting directions are randomly dispersed across the entire landslide area. In total, 134 growth distributions (GD) were identified in all 106 tree-ring series. The occurrence of reaction wood dominated with 94 cases (70.1%) to abrupt growth suppression with 40 cases of occurrence (29.9%).

Each tree recorded 2.5 GD on average (stdev: 1.4 GD; minimum: one GD; maximum seven GD). The onsets of reaction wood occurred with a frequency of 1.8 cases per tree (stdev: 0.9 cases), and abrupt growth suppression occurred with a frequency of 0.8 cases per tree (stdev: 0.9 cases). The mild type of reaction wood dominated (75 cases; 79.8%) above the pronounced type (19 cases; 20.2%). The mean duration of reaction wood was 18.2 years (stdev: 17.5 years), with a minimal duration of two years and a maximum detected duration of 76 years. Strong reaction wood occurred in 11 trees in 1941, 1966 and 1997. Other years with the occurrence of strong reaction wood provided only one or two trees with this reaction wood type. Moderate abrupt growth suppression (GS) occurred in 29 cases (72.5%) and a strong intensity of GS occurred in 11 cases (27.5%). The maximal frequency of strong GS in one year was two cases.

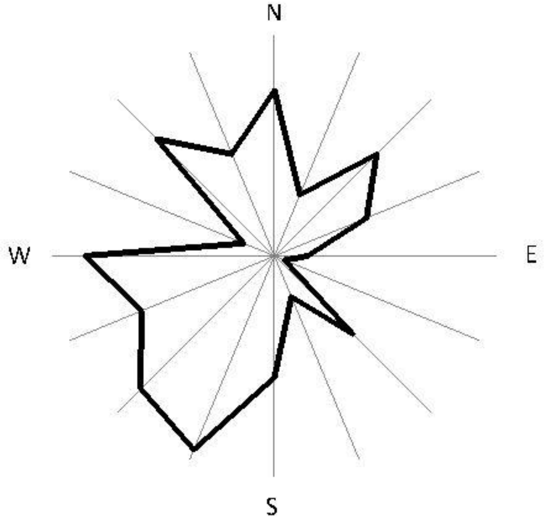

Figure 5 Graphical presentation of stem tilting direction frequency

The total chronology length covers the period of 91 years between 1927 and 2017. The oldest GD was recorded in 1927, when 26 sampled trees were alive. The youngest GD was detected in 2013. Reaction wood was recorded at a mean tree age of 29.2 years (stdev: 20.7 years) and abrupt growth suppression at a mean tree age of 52.6 years (stdev: 23.5 years). Based on the I_t index values, six years (1941, 1942, 1965, 1966, 1996, and 1997) can be assumed to be certain events of landslide movements with $I_t \geq 10\%$ (Fig. 6). The highest I_t values were reconstructed in 1997 (14 GD; I_t=26.4%). The next highest I_t values were reached in 1966 (9 GD; I_t=17.3%), 1941 (4 GD; I_t=13.8%), 1965 (6 GD; I_t=11.8%), 1996 (6 GD; I_t=11.3%) and 1942 (3 GD; I_t=10.3%). If we consider the probable events with I_t thresholds between 5 and 10%, the chronology of events increases by more than three times (Fig. 6). In total, 19 years can be supposed as event years with certain or probable events. The lowest I_t values were reached in 1953 (5.2%). The mean R_i value for each tree was 39.5 years (stdev: 19.9 years; minimal: 14.3 years; maximal: 101.0 years). The spatial interpolation of R_i values discovered the most and the least active landslide zones (Fig. 7). The zone of the main scarp and the landslide front expressed the highest frequency of past landslide events, and thus these are considered the most active. In contrast, the generally middle part of the landslide seems to be typical with the lowest intensity of landslide activity. Based on the event–response maps (Fig. 8) in each certain event year, the spatial development of landslide activity can be observed. The first detected reactivation was located in the middle part of the landslide and in the zone below the main scarp. The second phase of movement between 1965 and 1966 shifted closer to the landslide front. Finally, the last detected events in 1996 and 1997 were localised exclusively in the front part of the landslide.

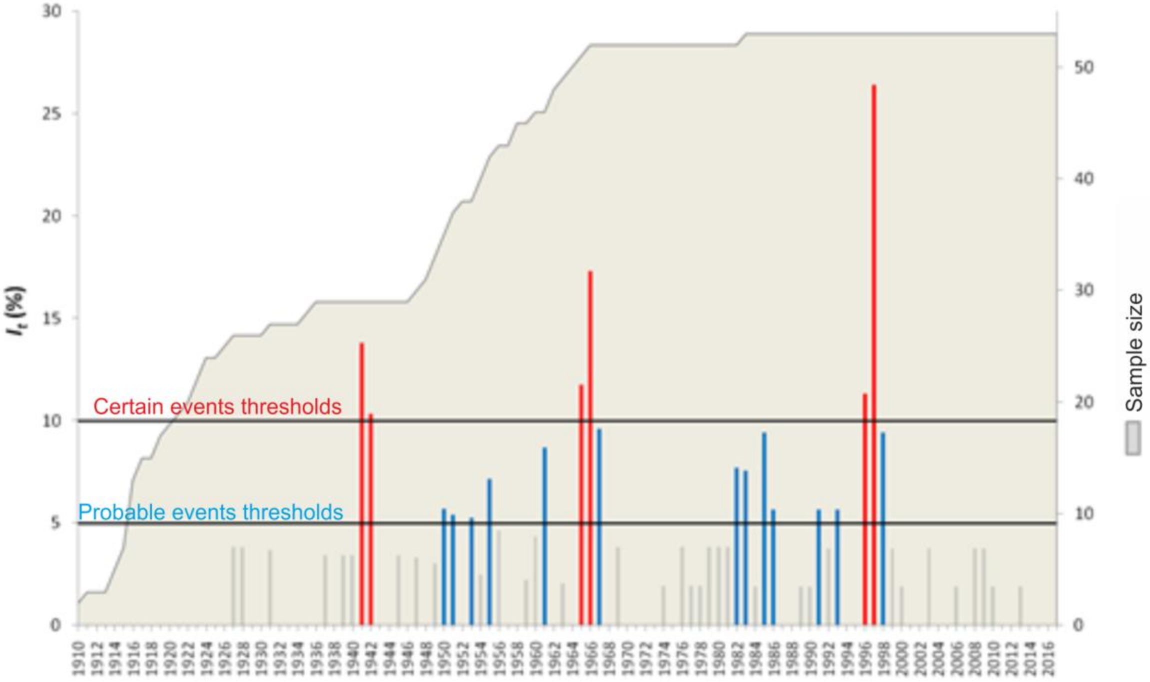

Figure 6 The chronology of dated landslide events ($I_t \geq 10\%$ – certain events; $10\% > I_t > 5\%$ – probable event

5. Discussion

The flysch relief of the Outer Western Carpathians is a region with frequent occurrences of various slope deformations (Kirchner and Krejčí, 2002). Unfortunately, data about their past historical reactivations are extremely scarce or fully missing. The zones with the occurrence of ancient slope failures are the most frequently affected by new reactivations (Pánek et al., 2011).

This study helped with the collection of knowledge about past landslide activity in the case of the selected landslide close to the Jablůnka village in the Hostýnsko–Vsetínská highland, using dendrogeomorphic methods. Although the studied landslide is located close to the inhabited area and thus possibly expresses a risk, no information about its reactivations or installed monitoring exists.

With the use of 106 increment cores from 53 disturbed trees (*P. abies*) occupying the studied landslide, the chronology of its past reactivation was created. The chronology was based on the identification of reaction wood and abrupt growth suppression. The presence of these GDs and tilted tree stems suggests the recent activity of the studied landslide (Stoffel and Bollschweiler, 2009). An important factor that could possibly affect GD creation is the age-dependent sensitivity of trees to landslide movements. According to Šilhán and Stoffel (2015), the ability of trees to record landslide signals in their tree-ring series is highest between the ages of 60 and 70 years and the second peak is between 110 and 130 years. In the case of this study, the mean age when the recorded trees contained the onset of reaction wood was 29.2 years, but we used different tree species compared to the mentioned study. Moreover, the mean age of trees in this study was only 80.6 years. The very dispersed direction of stem tilting fully corresponds with the flow-like morphological character of landslides, when according to Šilhán (2021a), such a landslide does not tend to induce a one- or bi-modal distribution of stem tilting direction. Flow-like movements of landslides probably cause very irregular destabilization of the ground without any laws compared to landslide movements with rotational characteristics (Šilhán, 2015).

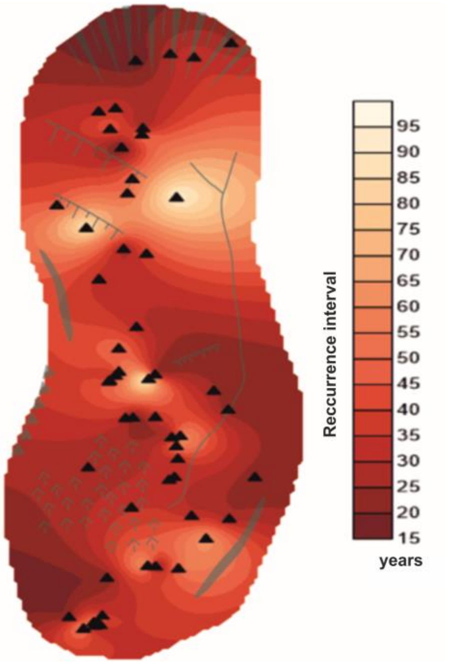

Figure 7 The spatial distribution of the recurrence interval of past landslide reactivations (black dot – sampled tree)

The I_t threshold for the landslide event definition was 5% for probable events for our sample size of 53 trees following the recommendation of Corona et al. (2014). Using this threshold enabled us to reconstruct the past 19 landslide event years (probable and certain) during the last 91 years. However, it is necessary to note that in eight cases, the detected events followed one another (e.g., 1941 and 1942 or 1950 and 1951). In contrast, when the I_t threshold was increased to 10%, the number of detected events decreased to six cases, but all of them were grouped in pairs. Such a detected chronology can suggest the specific behaviour of the landslide body when the reactivation can be strong enough to have some inertia or can be followed by the next minor events even several months after its initiation. This assumption even corresponds with the observation of Krejčí et al. (2002) after the landslide calamity in 1997, when the secondary reactivations occurred even several months after the main landslide phase in the studied region. A case with such a situation is, for instance, in 1941 with the occurrence of a strong type of reaction wood and the following year (1942) with the occurrence of a mild type of reaction wood. For instance, Stoffel and Corona (2014) suggest using the occurrence of reaction wood with a weak intensity only for verification of events, but not for direct dating. The other dated event years are typical of the initial occurrence of reaction wood with a mild intensity followed by the event year detected by reaction wood with a strong intensity. Thus, the occurrence of landslide events at the turn of the vegetation period can be expected. Comparing the results of dating in this study with results published by Šilhán (2021b) from the wider region, event years are confirmed to be 33.3%. Nevertheless, when considering even probable events, the agreement with landslide events in the wider region reaches 42.1%. It is well known that GDs in the form of compression tree and abrupt growth suppression exhibit a certain measure of inertia and therefore cannot be used to date annual landslide events within a tree-ring series of a single tree (Stoffel and Corona, 2014). Thus, the aforementioned successive event years were always reconstructed from different trees, which allowed the detection of recurrent events.

Unfortunately, the dendrogeomorphic approach used could not distinguish whether several recurrent landslide movements occurred during one event year. Thus, it is even possible and likely that landslide movements were repeated in an event year, but tree-ring based methods only captured one event year at a time.

Another important aspect of dendrogeomorphic dating of landslides is the possible delay in GD formation (Stoffel and Bollschweiler, 2009), which is especially true for abrupt growth release (Chalupová et al., 2020), but was not used in this study. Nevertheless, the influence of this factor on the resulting chronology cannot be completely ruled out. However, the number of trees with delayed GD is not very high (Šilhán, 2017), and thus, due to the high number of trees with GD in consecutive years, it can be attributed to real recurrent landslide events. This behaviour for landslides in the study region has been noted by Kirchner and Krejčí (2002).

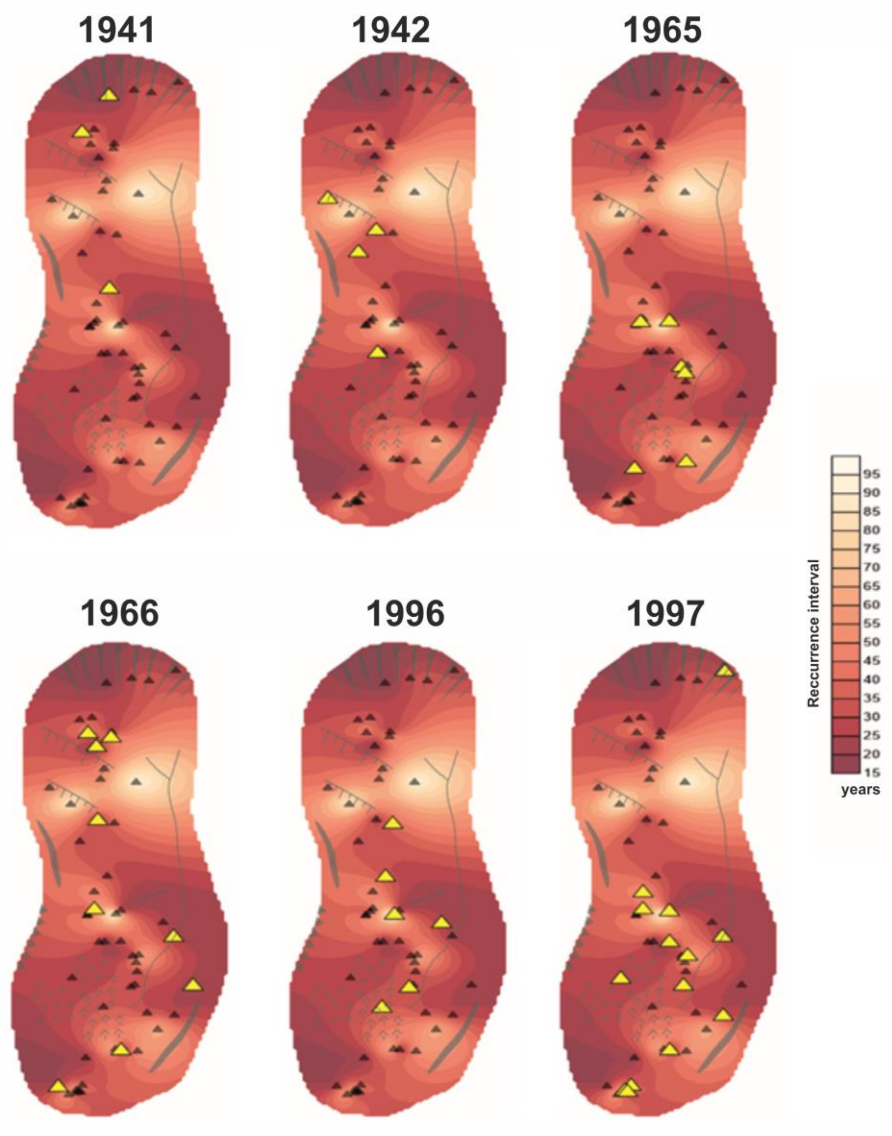

Figure 8 Event-response maps in certain individual event years (yellow dot – tree with GD, black dot – sampled tree without GD)

The reconstructed development of landslide reactivations from event-response maps (Fig. 8) corresponds to the spatial distribution of the recurrence interval (Fig. 7) and field observations in the zone of the landslide front, where the activity of landslide movements can be assumed to be the highest. This zone is simultaneously covered by the youngest trees (40–60 years). Such an age structure could lead to an increased sensitivity of trees in this zone to landslide movements. In contrast, the zone of the main scarp is typical of the presence of low recurrence intervals and older trees. Thus, the age structure of trees and the different sensitivities of trees could affect the reconstruction results (Šilhán and Stoffel, 2015).

The last year with the detected landslide event was 1997 and there was a probable landslide event in 1998. No other years with I_t values higher than 5% were detected after these two years. Moreover, no strong type of reaction wood or strong abrupt growth suppression was detected in this period. As the occurrence of most cases of strong reaction wood occurred in years defined as a certain event, it is possible to suggest that the landslide activity in the recent period after 1996 was minimal. Although no analysis of triggers was performed in this study, the dated years suggest a strong effect of extreme precipitation on landslide reactivation. For instance, 1940, 1996, and 1997 are well known for this (Štekl et al., 2001). Thus, future studies should focus on a comparison of dated landslide events with hydrometeorological extremes.

6. Conclusions

This study represented chronological data (based on dendrogeomorphic research) of landslide reactivation from the extended area of Jablůnka village in the Hostýnsko–Vsetínská highland during the period between 1927 and 2017. The reconstruction was performed using data from 106 increment curves from 53 disturbed individuals of *P. abies*. Two I_t thresholds were used for the past landslide event definition. In general, six certain and 13 probable landslide reactivations were detected. The mean recurrence interval of landslide reactivations was 39.5 years, and the most active landslide zones were detected in the area of the landslide front and main scarp. Recently, landslides seem to be stable after the last certain event in 1997, which was highly likely triggered by extreme precipitation totals.

Acknowledgements

The Czech Science Foundation project 22-12522S and the University of Ostrava project no. SGS02/PřF/2019–2020 supported this study. The language was reviewed by the American Journal Experts. David Řeha, Matěj Kaloč and Radek Tichavský are warmly acknowledged for their help with the field work.

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