Landslides (2020) 17:615–626
DOI 10.1007/s10346-019-01300-w
Received: 29 May 2019
Accepted: 27 September 2019
Published online: 28 October 2019
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Tree ring evidence of slope movements preceding catastrophic landslides

Abstract Catastrophic landslides represent one of the most dangerous natural hazards. Detailed knowledge about the pre-landslide behaviour of the affected slope is crucial for effective modelling of the landslide origin in the future or even for creating an early warning system. As precise retrospective reconstruction of slope movements in the pre-landslide period is very limited, dendrogeomorphic methods can be effective tools for these purposes due to the high sensitivity of trees to slope movements and the spatial aspects of data provided by the position of affected trees. This study presents the results of tree ring-based analysis of slope movements preceding three selected catastrophic landslides of different types in the Outer Western Carpathians (Girová 2010—translational rockslide; Brodská 1997—earthflow; Hluboče 2006—rotational rockslide). Three aspects of pre-landslide slope movements were analysed in detail (frequency, intensity, spatial distribution). In total, 300 tree ring series from 150 trees disturbed by pre-landslide movements were used for these purposes. The Girová landslide was preceded by an increasing frequency and intensity of movements but without any spatial pattern. The Brodská landslide was preceded by a low frequency of low-intensity movements without any temporal trends but with significant clustering several years before the landslide. The Hluboče landslide was preceded by a decreasing frequency of movements with increasing intensity and concentration in the source zone. The character of pre-landslide movements is probably influenced by the presence of old landslide structures on the affected slope and by the mechanism of the movements themselves.

Keywords Catastrophic landslide · Dendrogeomorphology · Predisposition · Outer Western Carpathians

Introduction

Landslides are dangerous natural hazards that cause severe damage to human infrastructure and even fatalities each year (van Westen et al. 2006; Grahne and Jaldell 2017). In particular, catastrophic landslides can totally change the landscape character or destroy whole villages (Kilburn and Petley 2003; Chigira et al. 2010). Remediation measures are very expensive and annually cost billions of Euros (Sassa and Canuti 2009; Klose et al. 2016). The application of suitable susceptibility models could eliminate landslide-induced damage. In general, various approaches to determining landslide susceptibility exist (analysis of landslide inventories, physically based numerical modelling, geomorphic mapping, statistically based methods, etc.; Brabb 1984; Guzzetti et al. 1999; Alvioli and Baum 2016; Reichenbach et al. 2014). The main limitation of all approaches is the quality and accessibility of input data.

The past chronological development of landslide behaviour is one of the most important factors possibly indicating future landslide activity. Catastrophic landslide activation is often preceded by minor slope movements connected with deep weathering, disruption and subsidence of bedrock, acceleration of episodic creep movements, pressure release or preparatory minor movements themselves (Petley and Allison 1997; Pánek et al. 2011a, 2011b). Detailed knowledge of the character of these movements regarding their frequency, magnitude or spatial extent can be crucial for possible prediction of catastrophic landslide events or even for suitable early warning system proposal and application. Unfortunately, studying the characteristics of slope movements preceding catastrophic landslide activation is very difficult because it is difficult to predict where and when such events occur. Long-term field instrumental monitoring can provide very precise point data about the slope behaviour; nevertheless, the monitored time period usually does not directly precede the catastrophic reactivation. The determination of pre-landslide slope behaviour can be performed in cases of existing past catastrophic landslides via retrogressive slope movement reconstruction. Absolute dating approaches (Lang et al. 1999) are used for this purpose, but their temporal resolution (on the order of several decades) is usually too rough to provide some detailed pre-landslide scenario of slope development. The use of historical orthophotos can provide more detailed information; nevertheless, their ability to detect some minor movements on the order of cm or even mm is limited. Time series of LiDAR-based DEM could provide very precise information, but their accessibility, time density or even existence in the pre-landslide period is very limited.

Dendrogeomorphic (tree ring-based) approaches are very precise methods of absolute dating (Alestalo 1971). Their use for retrospective detection of minor slope movements preceding catastrophic landslide activation seems to be a very precise and cost-effective approach (Pánek et al. 2011a; Wistuba et al. 2019). Their principle is based on the scheme presented by Shroder (1978) that geomorphic processes (minor slope movements in this case) affect the growth of trees (e.g. tilting of tree stems). Subsequently, tree response by specific growth disturbance can be detected in tree ring series and dendrochronologically dated (Stoffel et al. 2013). The length of reconstructed slope activity can extend, depending on tree age, up to several hundred years (Šilhán et al. 2012; Zhang et al. 2019) with even sub-annual resolution (Stefanini 2004; Lopez Saez et al. 2012a). The chronology of past landslide events (Corominas and Moya 1999), the spatial extent of landslide activity (Lopez Saez et al. 2012b) or even regional reconstruction (Šilhán et al. 2018) can be realized. Corominas and Moya (2010) even tried to estimate the magnitude-frequency relationship for landslides using tree ring analyses. The character of slope movements preceding catastrophic landslide activation can differ (particularly in magnitude) from landslide reactivation events. Nevertheless, as demonstrated, e.g. by Pawlik et al. (2013), the sensitivity of dendrogeomorphic approaches is high enough to detect even periodic creep movements.

This paper aims to discover and present slope movements preceding three catastrophic landslides in the flysch Carpathians using dendrogeomorphic methods. The study verifies three hypotheses regarding the character of such movements. Tree ring methods are used for (i) creation and analysis of slope movement chronology (Are there any changes in the frequency of movements in the pre-landslide period?), (ii) estimation and analysis of the intensity of pre-landslide slope movements (Are there any changes in trends of movement intensity in the pre-landslide period?) and (iii) reconstruction of the spatial distribution of slope movements (Are there any trends to the cluster of movements or are they getting closer to the source zone during the pre-landslide period?).

Study areas

Three recent catastrophic landslides in the flysch Outer Western Carpathians (Girová, Brodská, Hluboče; Fig. 1) were selected for the reconstruction and analysis of pre-landslide slope behaviour. The Outer Western Carpathians (OWCs) comprise mainly the folded transition of sandstone and claystone layers of Mesozoic to Tertiary age (Menčík et al. 1983). The flysch part of the OWC is a nappe system thrust onto the Carpathian foredeep during the Palaeogene and early Neogene periods. Each of the selected landslides expresses different morphology, mechanism of movement and precipitation triggers.

The Girová catastrophic landslide (49°31.5′N; 18°47.5′E; Fig. 1b) is a reactivated part of the old complex slope deformation on the southern slope of the Girová Mt. (839 m a.s.l.). The mean annual precipitation reaches approximately 1000 mm, and the mean annual temperature is ca. 7 °C for this area. The upper part of the affected slope is created by almost horizontally inclined sandstone-dominated flysch (up to 100 m thick). Weak claystone/mudstone rocks underlie the more rigid upper structure. The catastrophic landslide originated during the night from 18 to 19 May 2010 following precipitation totalling > 300 mm over 4 days (15 to 18 May) (Pánek et al. 2011b). Due to practically no settlements in the area of the landslide, only forest roads were destroyed. The landslide is defined as a translational long-runout rockslide (Cruden and Varnes 1996). The rockslide evolved in the upper part of the slope, where a 25 m-high wedge-like rocky headscarp originated. The position and shape of the headscarp were most likely influenced by the presence of two crossing faults with azimuth/dip of 250°/50° and 110°/55°. The landslide is approximately 1150 m long and covers 20 ha (Pánek et al. 2011a). Practically all of the trees growing on the landslide surface were destroyed. The area along the headscarp is forested dominantly by Norway spruce (*Picea abies* (L.) Karst.) and European beech (*Fagus sylvatica* L.).

The Brodská catastrophic landslide (49°22.5′N; 18°12.0′E; Fig. 1c) is situated on the western slope of the Zadní Kyčera Mts. The mean annual precipitation reaches 1000–1100 mm, and the mean temperatures range from 5° to 6° on the summits (Tolasz et al. 2007). The slope is built by almost vertical dipping sandstone layers and thick claystone and shale beds. The main scarp with a height up to 15 m expresses a strictly wedge-like morphology that is controlled by the intersection of the steep bedding planes of the bedrock and the presence of a normal fault in the ENE–WSW direction. The source zone of the catastrophic landslide is not part of some ancient landslide area, but in its lower part, it intersects an old deep-seated landslide (Baroň et al. 2014). The landslide is defined as earth flow with a length of approximately 690 m and an estimated volume of 300,000 m^3. The catastrophic landslide evolved on 7 July 1997 after 3 days of extreme precipitation totals reaching more than 350 mm (Kirchner and Krejčí 1998). As the landslide evolved in the forested area, the damage is only to forest management. All trees growing on the active landslide were destroyed. The border area along the main scarp is covered by individuals of *P. abies*.

The Hluboče catastrophic landslide (49°3.8′N; 18°3.1′E; Fig. 1d) is situated within a larger deep-seated slope failure on the southern slopes of the Tratihušť Mt. The mean annual precipitation reaches 900–1000 mm in this area. The slope is built by 20–50° inclined claystone and shale rocks with a thick weathering mantle. The affected ridge is crossed by several faults in the N–S direction. The active landslide was created by two fault branches in the upper part. Only the eastern branch occurred in the forest; thus, it was studied in detail. The landslide is defined as a rotational rockslide that transitions into earth flow in its lower part. The headscarp is 9 m high, and several minor scarps of ancient landslide areas are presented above it. The landslide is approximately 770 m long and covers 6 ha. The landslide occurred during the night from 2 to 3 April 2006 after more than 140 mm of total precipitation during the 2006 snow thaw period (Klimeš et al. 2009). Thus, the landslide trigger was a combination of above-average precipitation and fast thawing of above-average snow cover (Bíl and Müller 2008). The catastrophic landslide destroyed three buildings and access roads. All trees growing on the eastern branch of the landslide were destroyed. The zone along the main scarp is covered by individuals of *P. abies*.

Methods

General dendrogeomorphic approaches

The dendrogeomorphic sampling was exclusively focused on trees growing along the main source zone (headscarp) of each studied landslide. As trees growing on the moved body of the landslide were totally destroyed (due to the catastrophic character of the landslides), only trees growing above the main scarp were studied. Preferably, trees with signs of past slope movement effects on their growth (tilted or bent stems) were sampled. The position of each sampled tree was recorded using a GPS device and identified using orthophotos. The shortest distance to the tree from the upper line of the main scarp was measured using a laser rangefinder. Selected trees were sampled following standard procedure in the height of the maximal stem bending. Two increment cores were extracted from each tree using a Pressler increment borer (length 40 cm; diameter 0.5 cm). Moreover, at least 30 trees growing out of the affected area but in similar microclimatic conditions were sampled for construction of the reference chronology. This was realized only in the case of the Hluboče landslide because in other cases, the reference chronology was already known from previous studies.

Extracted samples were processed following standard dendrochronological procedures (Bräker 2002; Stoffel and Bollschweiler 2008). Increment cores were stabilized by gluing them into woody supports. Next, the sample surfaces were sanded until individual woody cells were clearly visible under a microscope. Tree rings were counted, and their widths were measured under a stereoscopic microscope using the dendrochronological device

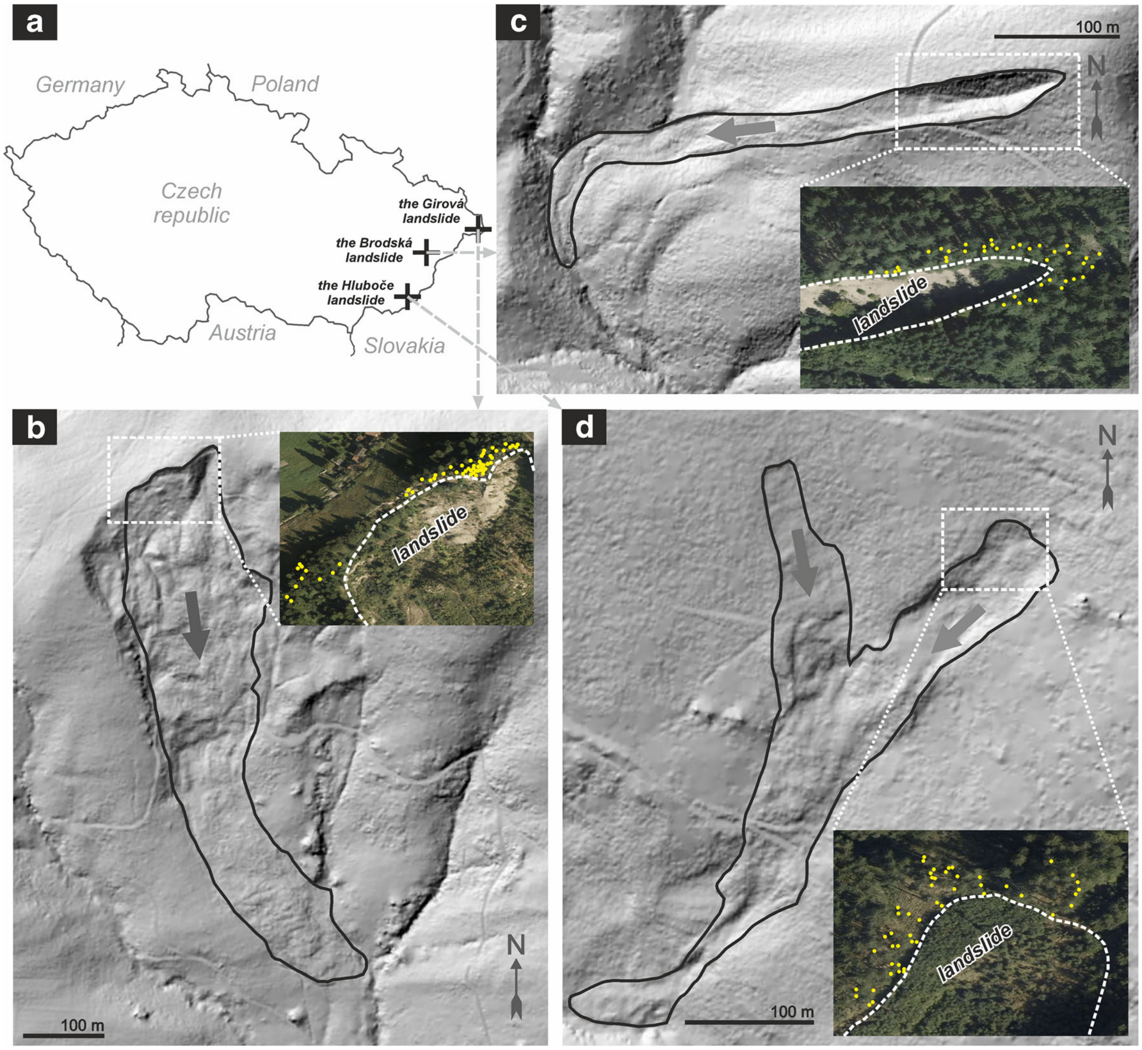

Fig. 1 Position and morphology of studied catastrophic landslides and the position of sampled trees (**a** location within the Czech Republic, **b** the Girová landslide, **c** the Brodská landslide, **d** the Hluboče landslide)

TimeTable and PAST4 software (VIAS 2005). The reference chronology was built in Arstan (Cook 1983) using a double detrending procedure. Tree ring series from disturbed trees were cross-dated against the reference chronology to identify and correct false, missing or wedging rings. After all samples were chronologically corrected, growth disturbances (GDs) were identified and dated. In general, two types of GD were taken into account based on the analysis of prepared sample surfaces and increment curves. Reaction wood (compression form in the case of coniferous tree species) is the specific woody tissue forming on one side of the stem following stem tilting. It is clearly macroscopically distinguishable due to its brown-reddish colour caused by rounded thick-walled tracheids (Westing 1965). Another detected type of GD was abrupt growth suppression. Trees create this type of GD as a response to damage of their roots caused by subsurface movements or spreading of tension cracks (Lopez Saez et al. 2012a). Only growth suppression greater than 70% in comparison with the mean width of the four previous tree rings was assumed to be significant DG (Schweingruber et al. 1990). Moreover, to eliminate possible false signals caused by different environmental disturbances (insect attacks, droughts etc.), only GDs not presented in the reference chronology simultaneously were assumed to be slope movement-induced ones. The following approaches followed the verification of the main hypotheses summarized in Fig. 2.

Analysis of slope movement frequency

Identified GDs were counted and assigned to individual years. Due to the decreasing number of alive trees with increasing age of the chronology (the development of sample size), the number of GD was negatively weighted by the number of living trees in each year according to the formula presented by Shroder (1978) in the form of the event-response (I_t) index:

$$I_t = \sum R_t / \sum N_t \times 100\% \tag{1}$$

where R_t is the number of trees with a GD in year t and N_t is the number of all sampled trees alive in year t. The length of the chronology was limited by the number of ten living trees. In

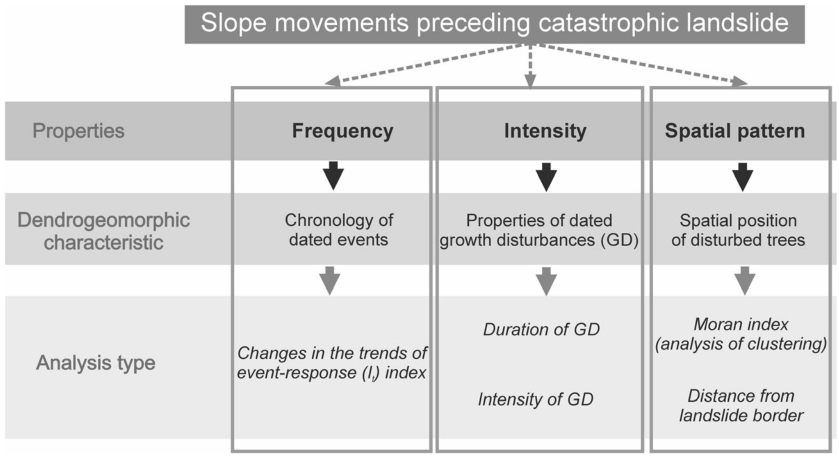

Fig. 2 The basic scheme of the analysed pre-landslide slope movement properties, used dendrogeomorphic characteristics and applied methods of analysis.

contrast to the classical reconstruction of landslide events from disturbed trees growing directly on the surface of the landslides, no I_t thresholds were applied in this study. Pre-landslide movements express lower magnitude compared to landslide events itself (Petley and Allison 1997); thus, the limiting of I_t values could cause omission of minor pre-landslide slope movements. Possible trends in the total chronology of I_t values were then tested using a non-parametric Mann-Kendall trend test. This analysis enables detection if variables are significantly decreasing or increasing over time (for linear or even non-linear trends).

Analysis of slope movement magnitude

The magnitude of pre-landslide slope movements (meaning the intensity of local surface changes in this case) was expressed only using proxy characteristics of GD. Supposing the direct relationship between surface deformation intensity and the intensity of tree growth response (Šilhán 2017), the slope movement magnitude could be approximately expressed by the characteristics of the GD. Two characteristics of the GD were analysed for this purpose. The duration of the GD was calculated as the number of tree rings containing the structure of reaction wood or the number of suppressed tree rings in a row. The second characteristic of the GD was its intensity. In the case of reaction wood, the proportion of reaction wood within the tree ring width was assumed to be the GD intensity (Fig. 3a). In the case of abrupt growth suppression, the intensity was expressed as the percent change in the tree ring width compared to the previous ones (Fig. 3b). The intensity and duration of all DGs were summarized for all

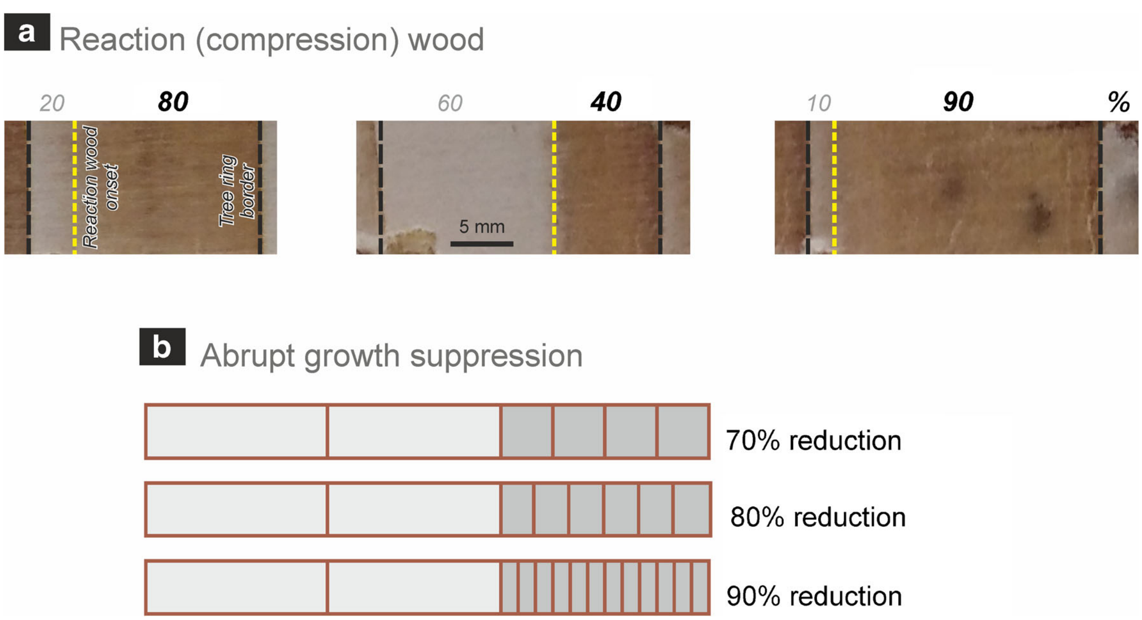

Fig. 3 The cases of growth disturbance intensity estimation (**a** intensity of reaction wood as the proportion of reaction wood structure within the total width of the tree ring; **b** intensity of abrupt growth reduction as the percentage decrease of tree rings compared to widths of previous rings)

Table 1 Number and age of sampled trees in individual localities

	Trees	Samples	Mean age (st. dev)	Maximal age	Minimal age
Girová	61	122	53.8 (26.3)	119	21
Brodská	40	80	78.5 (12.9)	128	61
Hluboče	49	98	84.5 (13.1)	98	47

decades preceding the catastrophic landslide events. The significance of time trends in mean values of both characteristics over all decades was tested by a non-parametric Mann-Kendall test.

Analysis of the spatial distribution of slope movements

The spatial distribution of pre-landslide slope movements was reconstructed and analysed based on the position of the trees with a signal in decadal periods. The mean distance of the affected trees from the main scarp was collected for individual decades. Moreover, the tendency of affected trees in individual decades to cluster was tested using Moran indices (Moran 1950). Moran index values close to 1 point to clustering, whereas values close to − 1 point to a dispersed pattern. The significance of the Moran index was verified using the Z score and p values. The trends of the mean values of affected tree distances from the main scarp and the values of the Moran index in individual decades were tested using a non-parametric Mann-Kendall test.

Results

In total, 150 disturbed trees were sampled at all three localities. The only sampled tree species was *P. abies*. The highest number of trees was sampled in Girová (61 trees), and the lowest number of trees was sampled in Brodská (40 trees) (Table 1). The number of sampled trees always corresponded with the maximal number of possibly usable trees. The oldest trees were sampled in Hluboče (mean age 84.5 years), whereas the youngest trees were sampled in Girová (mean age 53.8 years) (Table 1). The youngest tree was sampled in Girová (28 years), whereas the oldest tree was sampled in Brodská (128 years).

Chronology of pre-landslide slope movements

The oldest pre-landslide chronology (limited by 10 alive trees) of slope movements was built for the Hluboče landslide (82 years), whereas the shortest was built for the Brodská landslide (57 years). A 79-year-long chronology was built for the Girová landslide. In total, 241 growth disturbances were detected in all the sampled trees. In general, reaction wood dominated (78.6 %) above the abrupt growth suppression (21.4 %), although differences between localities exist (Table 2). The mean number of GD per tree was lowest for Brodská (1.1 GD.tree^{-1}), whereas 1.8 GD.tree^{-1} was detected for both Girová and Hluboče. Growth disturbances were grouped into 49 individual years in Girová with a mean recurrence interval of 1.6 years. Twenty-three individual years expressed the presence of GD in Brodská (mean recurrence interval 2.5 years) and 48 years in Hluboče (mean recurrence interval 1.7 years). The mean values of the I_t index were highest in Girová (5.4 %), whereas 4.2% was the mean value in both Brodská and Hluboče. The I_t values through the total reconstructed chronology expressed a significant positive increasing trend ($r = 0.25$) only in the case of Girová (Fig. 4). This trend was particularly distinct between the 1970s and 2000s. There was generally no significant decreasing or increasing trend in the case of Brodská (Fig. 4). The general trend of I_t values was not detected in Hluboče; nevertheless, a significant decreasing tendency was found between the 1970s and 2000s (Fig. 4).

The intensity of pre-landslide slope movements

The intensity of pre-landslide slope movements was expressed via proxy indicators of GD properties (duration and intensity of DG). The longest duration of GD was in Hluboče (mean duration 4.7 years) and the shortest was in Brodská (mean duration 3.1 years). The most intensive GDs were again in Hluboče (mean intensity: 55.2 %), and the lowest intensity was detected for GDs in Brodská (50.2 %). The mean duration and intensity of GD in Girová were 3.9 years and 53.1 %, respectively. No trends in the mean decadal values of duration and intensity in all localities were found with two exceptions (Fig. 5). A positive significant trend ($r = 0.58$; p value = 0.02) was found for the duration of GD in Girová. Another very significant increasing trend ($r = 0.79$; p value = 0.00) was detected for the intensity of GD in Hluboče (Fig. 5).

The spatial distribution of pre-landslide slope movements

The spatial distribution of slope movements was expressed by the position of trees containing some GD during a particular decade preceding the catastrophic landslides. The density of affected trees was visualized via Kernel density for each studied locality (Figs. 6, 7, and 8). Two zones in the case of Girová express the concentration of slope movements (northern and western part of the headscarp). The western part was affected primarily during the first half of the covered time period (up to ca. 1960s). Since this period, the activity clearly moved to the northern part of the headscarp (particularly between the 1980s and 2000s; Fig. 6). The activity of slope

Table 2 Type and number of dated growth disturbances

	Reaction wood	Abrupt growth suppression	Growth disturbances	GD.tree^{-1}
Girová	98 (88.3 %)	13 (11.7 %)	111	1.8
Brodská	34 (80.9 %)	8 (19.1 %)	42	1.1
Hluboče	79 (89.7 %)	9 (10.3 %)	88	1.8

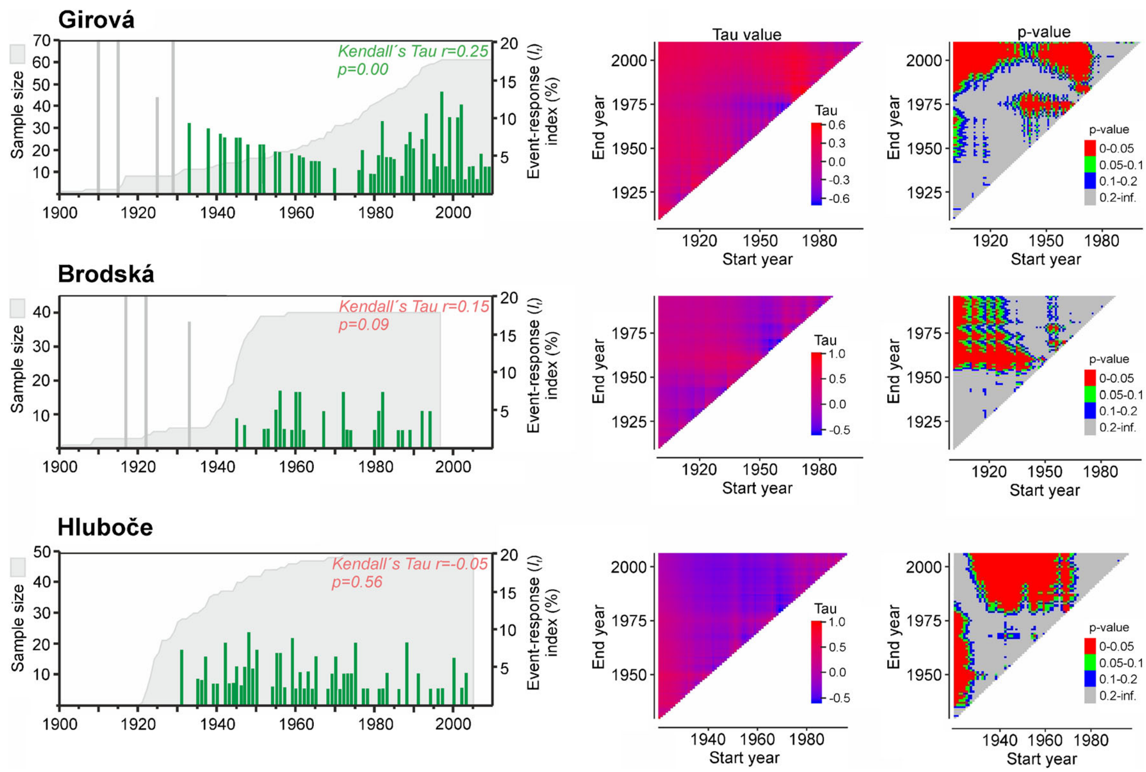

Fig. 4 Chronologies of pre-landslide slope movements for all studied landslides expressed as the chronological development of event-response index values. Chronologies were assumed to be relevant since at least ten trees were alive. The analysis of trends and their significance was tested using the non-parametric Mann-Kendall test and expressed in the form of a spatial matrix

movements was located mostly in the southern part along the headscarp during the first three reconstructed decades in the case of the Brodská landslide. Since the 1930s, the activity has moved to the northern zone (Fig. 7). Finally, the activity was dispersed between the northern and eastern parts of the source zone during the last three decades preceding catastrophic reactivation. The activity of slope movements in the case of the Hluboče landslide was dispersed across the northern and western parts of the source zone.

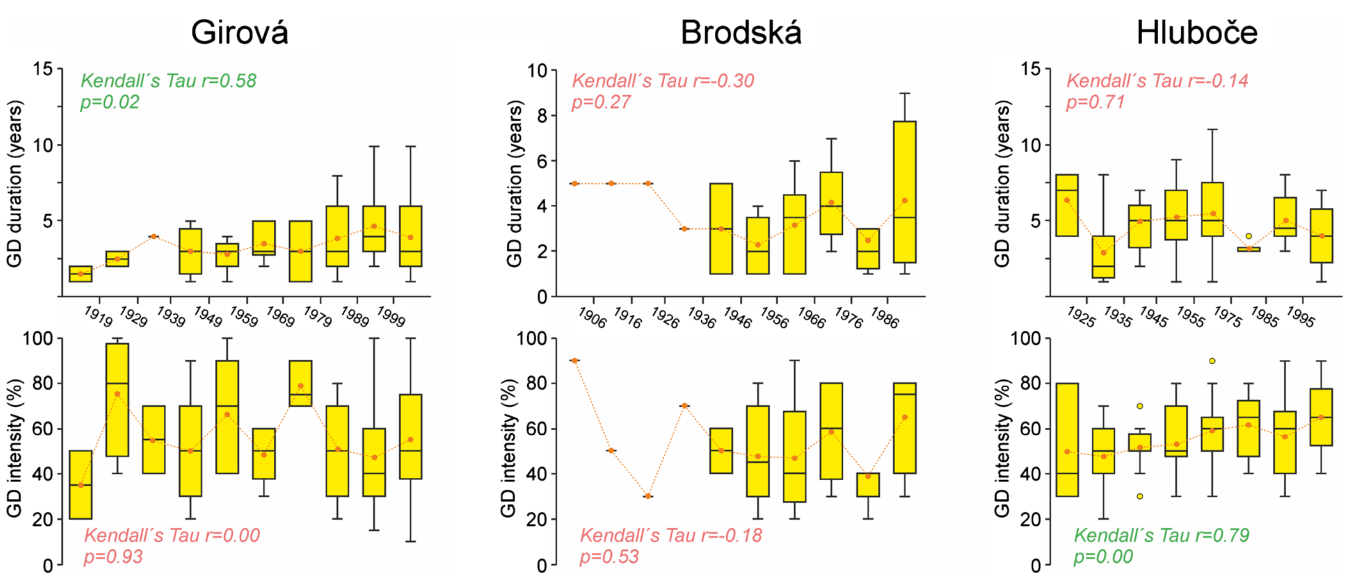

Fig. 5 The intensity and duration of growth disturbances (GDs) induced by pre-landslide slope movements as proxy indicators of their intensity. The dashed line connects the mean values. The testing of the trend of the mean value was performed using the Mann-Kendall test

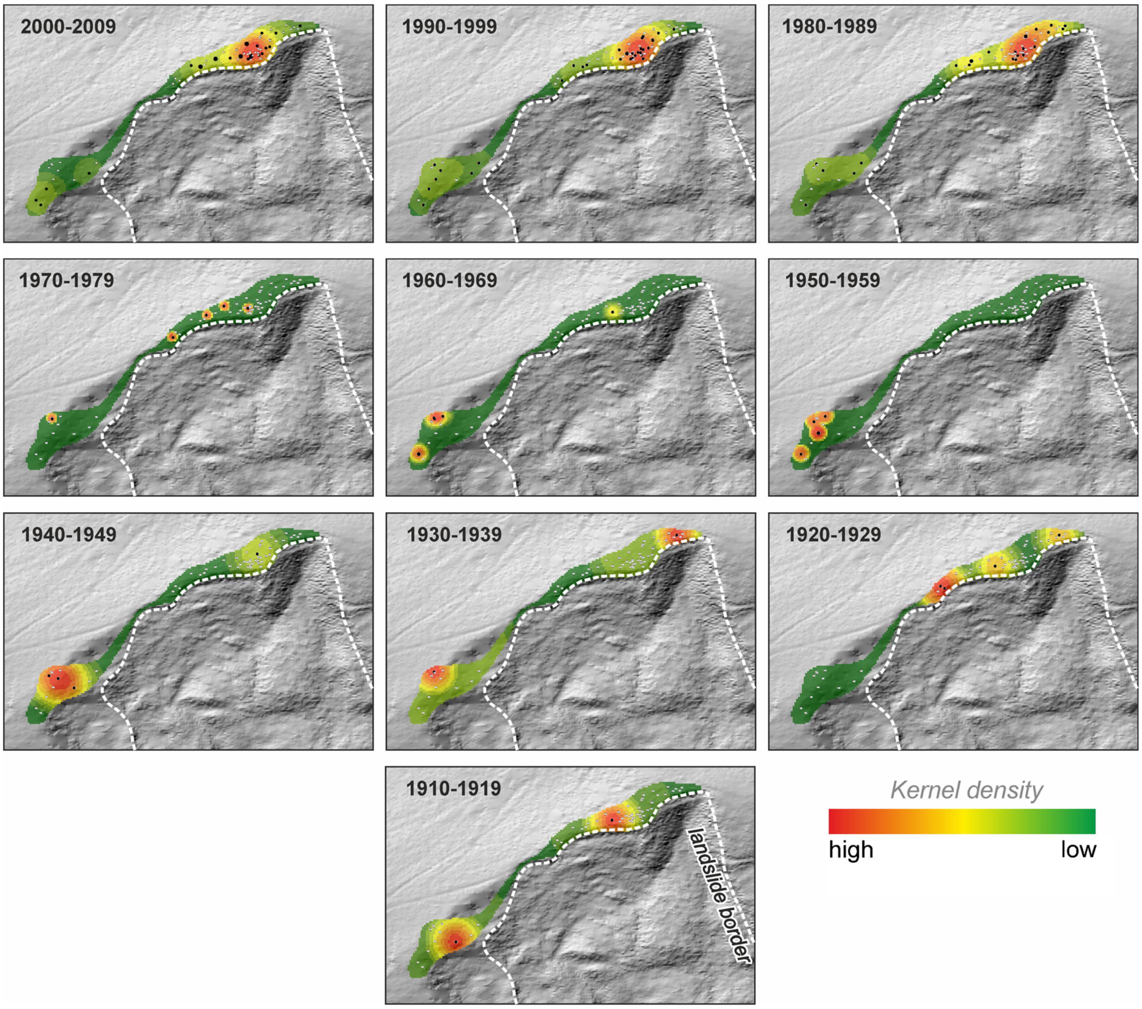

Fig. 6 The spatial distribution of trees affected by pre-landslide slope movements and the visualized Kernel density for individual decades preceding the catastrophic activation of the Girová landslide in May 2010

Nevertheless, some decades with concentrated activity only in the northern zone (e.g. 1996–2005) or only in the western zone (e.g. 1986–1995) exist (Fig. 8).

The Moran index and the mean distance of affected trees during each decade were calculated and tested. No significant trend was detected for all the studied localities with two exceptions (Fig. 9). A significant increasing trend leading to a clustering of slope movements was detected for Hluboče (r = 0.69; p value = 0.03). Very distinct clustering of slope movements (although without any long-term trend) was found for the last decade preceding the catastrophic activation of the Brodská landslide (Moran I statistics provided the significant value 0.22). The mean distances of affected trees from the headscarp do not express any significant trends. Only in the case of Hluboče did the dispersion of distance values significantly decrease (Fig. 9).

Discussion

Slope movements preceding catastrophic landslides were studied at three localities in the Outer Western Carpathians using dendrogeomorphic methods. Three aspects connected with the pre-landslide slope movements (chronology, intensity, spatial pattern) were studied using 300 tree ring series from 150 disturbed trees. The idea of studying pre-landslide development of the slope is not frequently applied in the analysis of catastrophic landslides. Wistuba et al. (2019) studied the eccentricity of tree rings from trees growing on the surface of active landslides in years preceding and following large landslide events. Pánek et al. (2011a) reconstructed the frequency of creep movements preceding large landslide reactivation. Nevertheless, the attempt to realize a detailed analysis of various aspects (not only chronological) of slope movements preceding catastrophic landslides is unique. Detailed knowledge of pre-landslide slope behaviour could serve as a basis for an early warning system in the future, as suggested by Wistuba et al. (2019).

Dendrogeomorphic aspects of pre-landslide slope movement detection

Tree ring-based approaches are commonly used for the analysis of past landslide movements (Bégin and Filion 1985; Fantucci and Sorriso-Valvo 1999; Lopez Saez et al. 2012a; Šilhán et al. 2013; Bekker et al. 2018). Their use is often interpreted as limited to

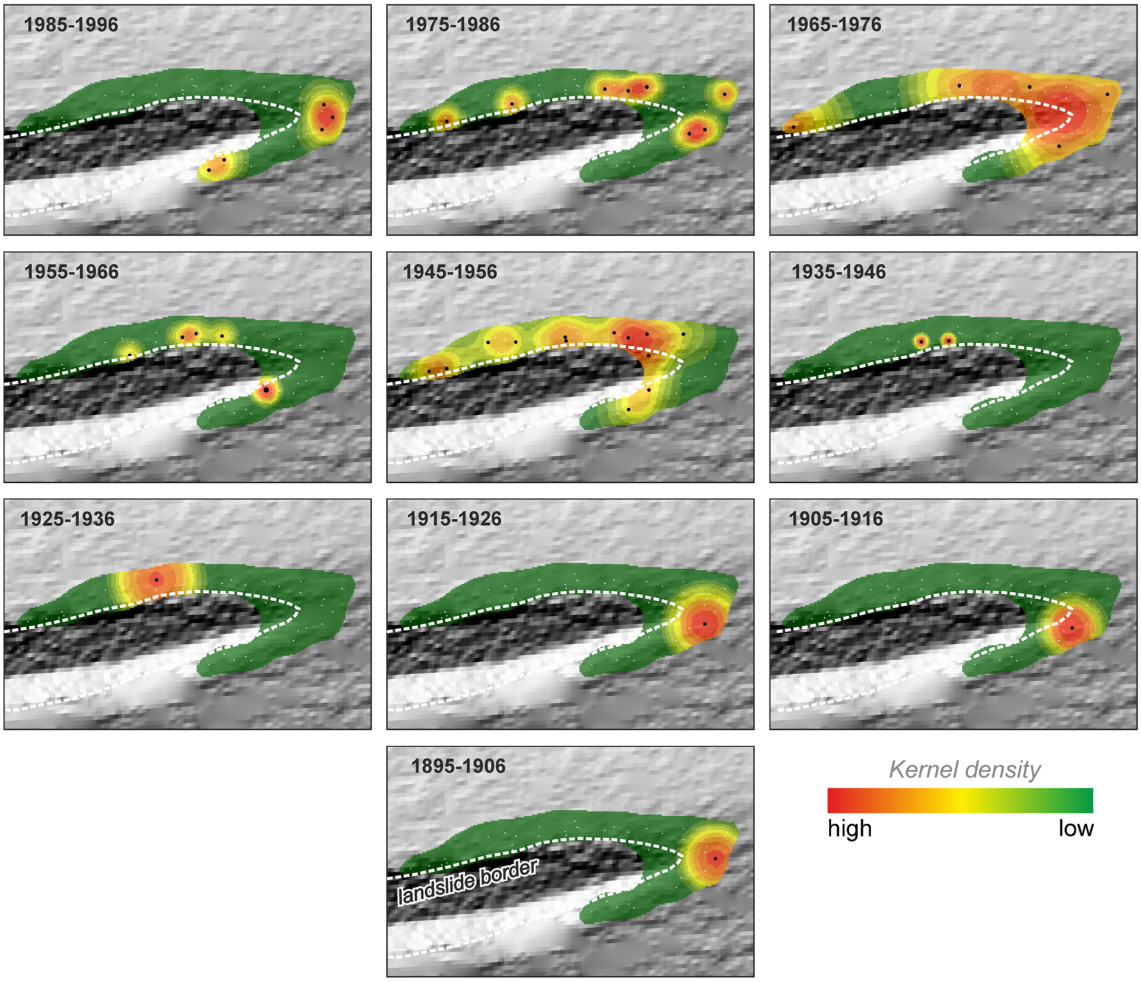

Fig. 7 The spatial distribution of trees affected by pre-landslide slope movements and the visualized Kernel density for individual decades preceding the catastrophic activation of the Brodská landslide in July 1997

rather moderate landslide movements because large catastrophic events destroy all trees, and too small movements can be ignored by tree responses (Corona et al. 2014). Nevertheless, as suggested by Pawlik et al. (2013), Migoń et al. (2014) and Wistuba et al. (2018), trees (particularly *P. abies*) can be very sensitive and able to record slope movements on the order of several millimetres. This assumption was recently verified by Šilhán et al. (in press) on monitored landslides. Thus, it is highly probable that tree rings are a relevant and valuable source of data about very minor pre-landslide movements. Regarding the relatively limited reconstructed values of the event-response (I_t) index (Fig. 4), meaning that only a low proportion of studied trees were affected by slope movement, the magnitude of pre-landslide movements in this study is lower compared to proper landslide movements (compare to Stefanini 2004; Corominas and Moya 1999; Šilhán 2012).

The intensity of pre-landslide slope movements was expressed as a proxy using intensity and duration of growth disturbances. One can suppose that slope movement of a particular intensity induces appropriate intensity of external growth disturbance (e.g. the more intensive the movement and surface deformation, the more tilted the tree stem; Šilhán et al. 2019). Next, as evidenced by Wistuba et al. (2015) and Šilhán (2017), the intensity of external growth disturbance (e.g. stem tilting) induces the correspondingly intensive growth response (e.g. intensity of reaction wood). Thus, the expression of slope movement intensity via properties of induced GD seems to be logical and reasonable.

The type and proportion of detected GD (reaction wood and abrupt growth suppression) can signal the character of causal slope movements (Stoffel and Bollschweiler 2008; Šilhán et al. 2016). Reaction wood is the dominant growth response of trees to tilting (Westing 1965) of their stems induced preferably by intensive surface deformations. In contrast, abrupt growth suppression is a typical growth response to damage to the root system induced by rather hidden subsurface movements. Although the presence of reaction wood dominated compared to growth suppression in all case localities (Table 2), its ratio was almost twice as low in the case of Brodská. The Girová and Hluboče catastrophic landslides are situated within the area of ancient deep-seated slope deformation. Thus, surface deformations are expected to be more intensive due to the weakened slope mass due to old failures, resulting in a higher proportion of reaction wood among GDs. In contrast, the Brodská source zone is surrounded by a relatively stable slope without the presence of other slope failures. Thus, the movements can be characterized as creep-like in this locality.

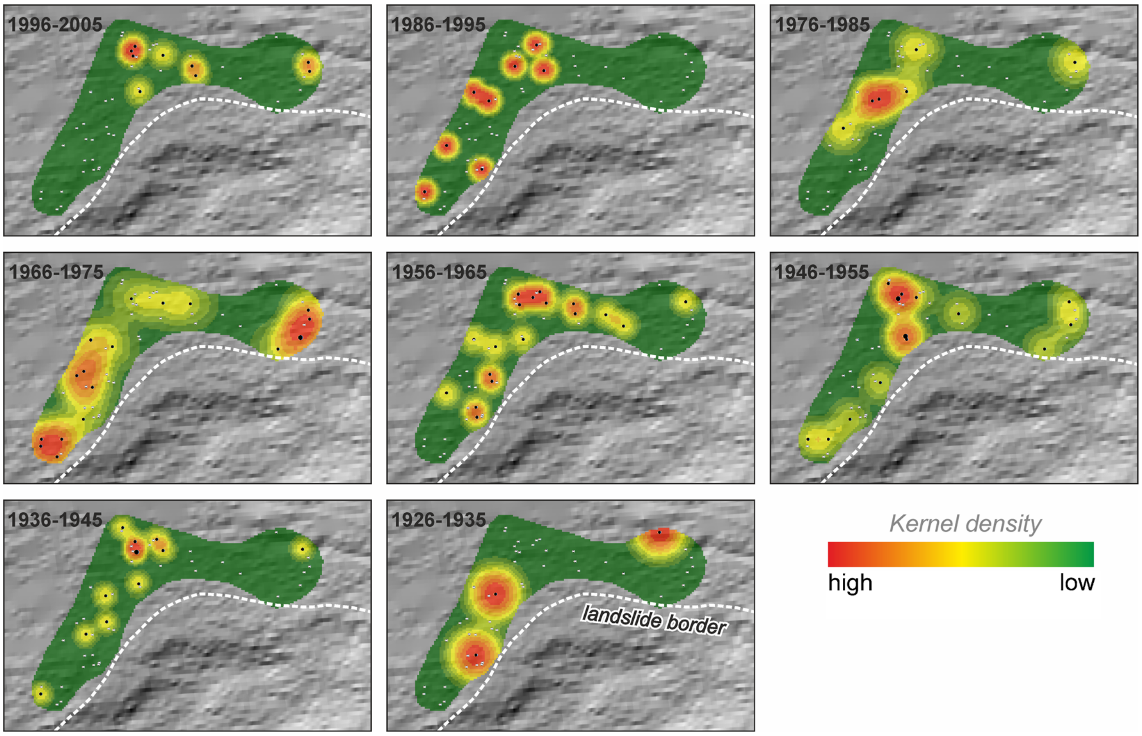

Fig. 8 The spatial distribution of trees affected by pre-landslide slope movements and the visualized Kernel density for individual decades preceding the catastrophic activation of the Hluboče landslide in April 2006

These movements do not intensively deform the slope surface, and their effect is instead probably subsurface, inducing intensive tree root damage and resulting in a higher proportion of abrupt growth suppression among the GDs.

The reconstructed patterns of pre-landslide slope behaviour

Three studied catastrophic landslides were typical of different movement mechanisms (translational, flow, rotational). Each landslide expresses specific behaviour of the slope preceding the catastrophic reactivation. The general overview of reconstructed slope development based on the tree ring indices is presented in Fig. 10. Nevertheless, an important aspect of presented study is necessary to mention here. Tree ring-based data about past slope behaviour come just from trees actually growing out of the area of catastrophic reactivation. Due to catastrophic character of landslide movement, all trees occupying the original landslide area

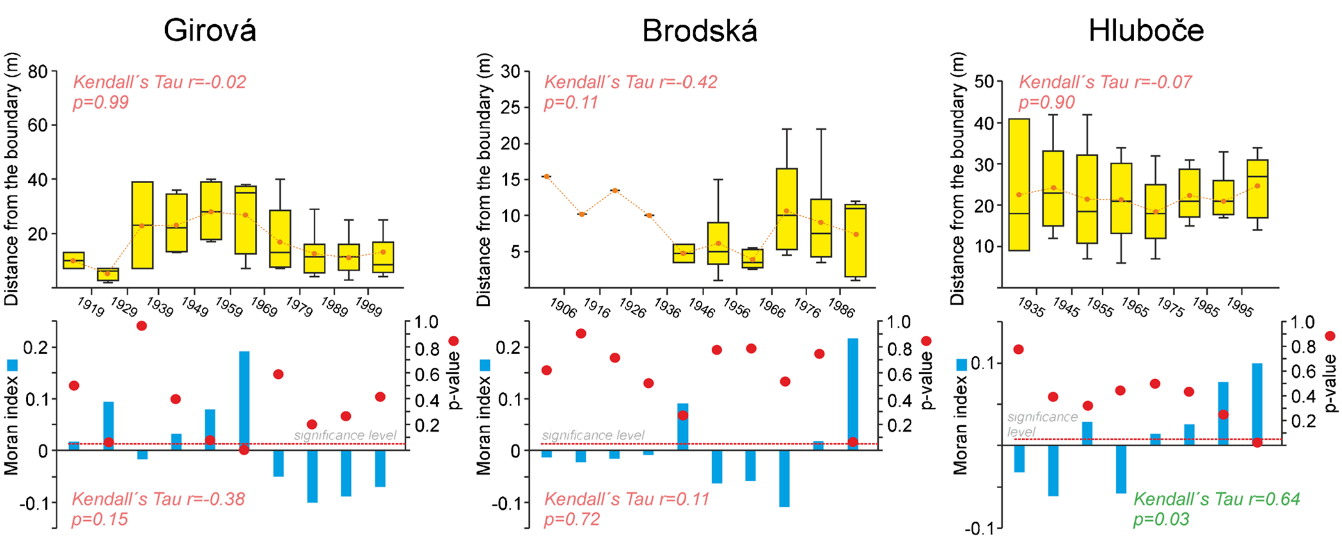

Fig. 9 The chronological development of the spatial indicator (the distance of affected trees from the headscarp and the Moran index) of distribution of pre-landslide movements in individual decades. The dashed line connects mean values. The testing of the trend of the mean value was performed using the Mann-Kendall test

were destroyed. Thus, the presented data and results provide information only about the development of frontal zone along the main landslide source areas, and the movement history and character on the landslide surface itself could be different.

The translational Girová landslide was preceded by a high frequency of movements with moderate intensity. Moreover, the high frequency significantly and gradually increased before the catastrophic event in May 2010. The significant increase in dated GD duration indicates the increasing intensity of slope movements. This concept is in agreement with generally assumed pre-landslide slope behaviour as suggested by Bigot-Cormier et al. (2005). In contrast, the catastrophic Brodská earth flow from July 1997 was preceded by only minor slope movements with generally low frequency. The spatial distribution of movements significantly clustered just in the decade immediately preceding the 1997 activation. This behaviour suggests that movements had the character of locally and occasionally accelerated creep movements (Petley and Allison 1997). This assumption is supported by the fact that the slope surrounding the source zone is free of other slope failures. Years with the most active movements (e.g. 1961, 1972, and 1982; Fig. 4) are generally known from the wider region as years with intensive slope movements induced by extreme precipitation totals (Špůrek 1972; Štekl et al. 2001; Krejčí et al. 2002; Šilhán et al. 2018). Creep movements of clay-rich weathered slope material were probably accelerated during these precipitation events as well. The rotational catastrophic Hluboče landslide from April 2006 was preceded by different patterns of pre-landslide slope movements. The frequency of movement events was relatively high; nevertheless, during several decades before 2006, it significantly decreased. Nevertheless, a decrease in frequency was compensated for by a significant increase in the movement intensity, as suggested by a significant increase in the high intensity and duration of detected GDs in the tree ring series. Moreover, these strengthening movements were gradually clustered in the source zone. The most intensive GDs detected in Hluboče compared to other cases can be explained by the character of the movements. The rotational character of the movements is assumed to cause the most intensive surface deformation (in contrast to, e.g. translational movements; Cruden and Varnes 1996). Thus, the resulting intensity of tree stem tilting followed by appropriate growth response is very intensive as well.

In general, the character of slopes affected by catastrophic landslides is a significant factor influencing the character of pre-landslide movements. In particular, the presence of older failure structures positively influences the frequency and intensity of movements (Geertsema et al. 2006). These findings support general assumptions of high landslide hazards in regions with ancient slope failures (Smith 2001).

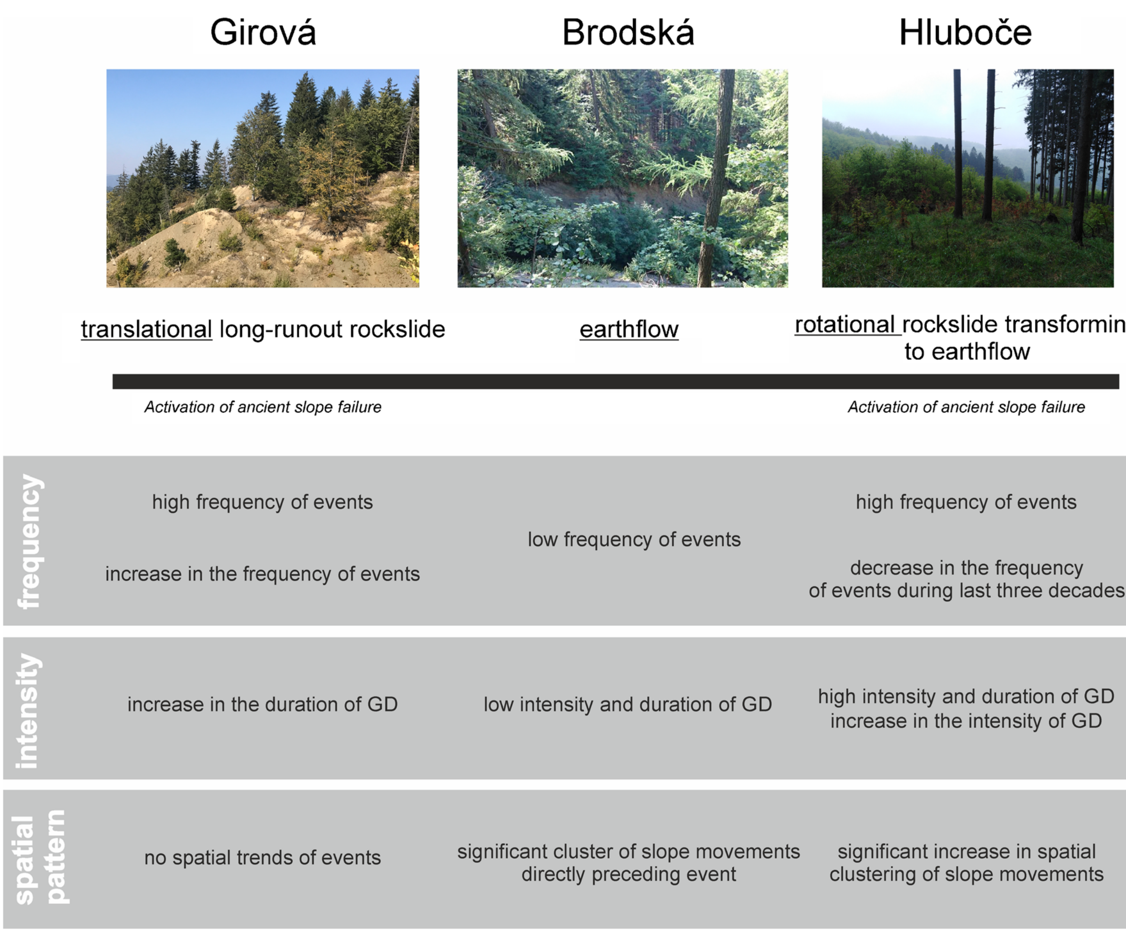

Fig. 10 The overview and scheme of detected properties of pre-landslide slope movements for all studied catastrophic landslides

Conclusions

This study uses data from 300 tree ring series of trees growing in the source zones of three different catastrophic landslides in the Outer Western Carpathians with the aim of describing various aspects of pre-landslide slope movements. In general, the frequency, intensity and spatial distribution of slope movements were analysed.

Dendrogeomorphic methods seem to be a relevant approach for the detection and characterization of pre-landslide slope movements due to the high sensitivity of trees to deformation of landslide surfaces. The translational catastrophic Girová rockslide in 2010 was preceded by an increase in the frequency of intensive movements but without any spatial clustering. The catastrophic Brodská earth flow in 1997 was preceded by a very low frequency of events with low intensity. These events were clustered only for several years before the landslide. Finally, the rotational catastrophic Hluboče rockslide in 2006 was preceded by the significant growth in intensity of gradually spatially concentrated movements. However, their frequency gradually decreased.

The character of the affected slope (with or without the presence of ancient slope failures) and the landslide movement mechanism seem to be significant factors influencing the properties of pre-landslide movements. This study is pioneering the application of tree rings. Thus, the presented dendrogeomorphic approach should be tested on the next catastrophic landslide to reach more robust conclusions and this knowledge should be used in landslide hazard assessments.

Acknowledgements

The language was reviewed by American Journal Experts. Andrea Fabiánová, Lucie Kurovská, Tereza Němcová and Radek Tichavský are warmly acknowledged for their help with field sampling.

Funding information

The Czech Science Foundation project 19-01866S and the Specific Research Project of University of Hradec Králové Nr. 2115/2018 supported this study.

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