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Regional, tree-ring based chronology of landslides in the Outer Western Carpathians

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ABSTRACT

Landslides are a type of mass wasting and denote any downslope movement of soil and rock under the influence of gravity; as such they can represent a dangerous natural hazard process, especially in case that they affect inhabited areas or transport infrastructure. Because the occurrence of landslides is typically favoured by terrain and lithological conditions, the process is frequently concentrated in relatively small, isolated regions exhibiting suitable initial conditions of terrain instability. Extensive regional assessments of landslide activity have been used in the past to uncover common triggers and process patterns, mostly in the aftermath of large, regional disasters. By contrast, however, regional reconstructions of past landslide activity have not been realized with dendrogeomorphic techniques, and with the aim to date past landslide histories over extended time periods and with annual dating precision. This study therefore aims at disentangling landslide dynamics at the regional scale (covering ca. 600 km^2) by using growth-ring records of trees that grow on active landslides. The studied area of the Hostýnsko-vsetínská hornatina Mts. (Central Europe) is well known for its high landslide activity, but has so far been lacking a detailed chronology of past events. To this end, we dated past activity on 26 landslide bodies using tree-ring series from 1322 disturbed trees to reconstruct 327 landslide reactivations during the last century.

The reconstructed landslide database allowed correlations between landslide types and their frequencies or occurrence, as well as inferences between selected morphometric parameters with landslide frequency and magnitude. We also observe periods of increased landslide activity (1940s, 1960s, 1980s, and 1990s) and events of regional importance (e.g., 1961, 1985, and 1997), as well as a significant decrease in landsliding during the last two decades.

1. Introduction

Landslides are a widespread and often hazardous gravitational process and causes human injury, loss of life and/or economic devastation in many areas worldwide (Huabin et al., 2005; van Westen et al., 2006; Pánek, 2015). When occurring, they may cause substantial financial losses both at the local and regional scales, in the order of billions US $ annually (Sassa and Canuti, 2009). Landslides can occur as discrete, individual events or in the form of landslide calamities affecting larger regions (Pánek et al., 2011; Tsuchida et al., 2015; Raška et al., 2016). Landslides occur preferentially in regions with specific geological weaknesses, such as rigid rocks overlaying plastic rocks, in terrains dominated by flysch, or from unconsolidated volcanic sediments (Barbano et al., 2014; Migoń et al., 2017; Pánek et al., 2018), and provided that slope morphometry allows slope movement. The actual triggering of landslides is often favoured by high-magnitude, short duration, or low-magnitude, long duration precipitation events (Guzzetti et al., 2007; Gariano and Guzzetti, 2016), the rapid melting of snow (often enhanced by rain-on-snow events; Morán-Tejeda et al., 2016; Beniston and Stoffel, 2016); or by earthquakes (Nakamura et al., 2014; Has and Nozaki, 2014). The combination of triggers and site-inherent landslide pre-conditions, various types of landslides can occur (Cruden and Varnes, 1996; Dikau et al., 1996). As various types of landslides generally depend on different triggering patterns (e.g., deep-seated slope deformation vs. shallow debris slides), their chronology and/or magnitude-frequency (M-F) relationship will be inherently different, even for landslide processes occurring within the same region. As such, an improved knowledge and the reconstruction of past landslide chronologies is quite crucial for an improved understanding of processes at the local scale and their management. Any retrospective reconstruction of past

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events will thereby improve evaluation of landslide risk in terms of land-use and/or landscape management planning (Alexander, 1989; Bonnard and Corominas, 2005), but can also be employed for the prospective modelling of future landslide occurrences (Lopez Saez et al., 2013b; Barlow et al., 2016). As the actual release of landslides is often controlled by meteorological or climatic factors, any improvement in their knowledge in terms of past process chronologies will be key for an improved understanding of expected future climate changes (Stoffel and Huggel, 2012; Lopez Saez et al., 2013a; Stoffel et al., 2014).

Various techniques have been used in the past to date landslides in absolute terms (Lang et al., 1999), but only rarely have these approaches yielded yearly dating precision, which is critically needed if one wants to compare event chronologies within a region. Dendrogeomorphic methods, i.e. the use of growth-ring records from trees affected by geomorphic processes (Alestalo, 1971; Stoffel et al., 2010), such as landslides, can offer high-resolution dating, and have thus often been considered as the most precise dating approach for the construction of landslide histories in forested areas of the temperate climate zone. Indeed, dendrogeomorphic reconstructions of past landslides have been shown to provide dating results with up to seasonal precision (Stoffel, 2008; Lopez Saez et al., 2012a) and that chronologies can cover up to several centuries (Šilhán et al., 2012).

The basic principle of tree-ring based process reconstructions has been defined by Alestalo (1971) and Shroder (1978). In their seminal papers, the authors state that landslide movement will affect trees growing on its surface in various way, e.g. by tilting their stems or by disrupting their roots. Trees will react to these external disturbances by specific changes in growth, and by producing specific anatomical features in their growth-ring records. Reaction wood is such a growth response to stem tilting, and abrupt growth decreases would occur after root damage. The absolute dating of these growth disturbances (GD) will, once the growth patterns are analysed for a population of trees growing on the same landslide body, be summarized to form the basis for the dating of individual landslide events (Corona et al., 2014).

The use of tree-ring records for landslide dating has a considerably long history and was applied to various case-study sites in various regions worldwide, e.g. in North America (Fleming and Johnson, 1994; Carrara and O'Neill, 2003; Cockburn et al., 2016), European Alps (Astrade et al., 1998; Lopez Saez et al., 2012a, 2012b, 2013a, 2013b, 2017; Savi et al., 2013), Italian Apennines (Fantucci and Sorriso-Valvo, 1999; Stefanini, 2004) Carpathians (Šilhán, 2012; Šilhán et al., 2013, 2014, 2016; Migoń et al., 2014), Pyrenees (Corominas and Moya, 1999) or the Ardennes (Van Den Eeckhaut et al., 2009).

A vast majority of past work on landslides has been focused on individual cases or sites. By contrast, more regional reconstructions including multiple landslides have remained exceptional so far (Corominas and Moya, 1999; Lopez Saez et al., 2013a).

We argue here that both the activity and origin of individual landslides is influenced by site-specific conditions (e.g., lithology, topography, or "anamnesis" of the site), in addition to individual triggering events (e.g., meteorology, climatology, hydrology), whereas a more extensive, regional assessment based on several landslides would yield more extensive information on landslide variability across the region and without the common limitations inherent to small-scale case studies. We base this assumption on the fact that tree-ring reconstructions have indeed provided extensive, regional records for other mass wasting processes and have thereby allowed key insights into process activity, drivers and dynamics. Regional dendrogeomorphic studies have focused primarily on debris flows (Pelfini and Santilli, 2008; Bollschweiler and Stoffel, 2010; Procter et al., 2011; Bollschweiler-Schneuwly and Stoffel, 2012; Schraml et al., 2015; Šilhán et al., 2015; Šilhán and Tichavský, 2016) or floods (Rodriguez-Morata et al., 2015; Ballesteros Cánovas et al., 2015, 2017; Šilhán, 2015), for which the presence or absence of events is intimately related to rainfall events.

Based on the above considerations, this study therefore seeks to (i) create an extensive regional dendrogeomorphic reconstruction of past landslide movements, (ii) determine possible differences in process behaviour between different sites and as a result of different landslides types, and (iii) evaluate the possible effect of landslide morphometry on landslide frequency and magnitude. The study region we selected is situated within one of the most active landslide region of Central Europe – the Hostýnsko-vsetínská hornatina Mts.

2. Study area

The Hostýnsko-vsetínská hornatina Mts. were chosen for process analysis due to their long and rich history of landslide activity. Within this region, the study area selected for the tree-ring based regional reconstruction of past landslide activity was centred around the coordinates 49.4° N and 18.0° E (Fig. 1). Not only are the Hostýnsko-vsetínská hornatina Mts. well known for their dense occurrence of landslides (in the several hundreds), but also for the different types of landslide processes occurring at the site (Kirchner and Krejčí, 1998; Krejčí et al., 2002). In fact, the density of landslides in the region is considered unique for Central Europe (Klimeš, 2007).

Within this study, the total area investigated covers ca. 600 km^2 (ca. 40 × 15 km). The site is characterized by highlands and mountains with the highest peak reaching 1024 m a.s.l. (the Vysoká Mt.), mean elevations of ca. 550 m a.s.l., and slopes reaching inclinations of up to 20°. The vast majority of the region belongs to the Magura Nappe. This fold-belt system with radial faults was thrusted during the Paleogene and Early Neogene, and is composed of flysch structures with alternating bands of claystones, shales, sandstones, and conglomerates of Mesozoic and Tertiary age (Baroň et al., 2004). In general terms, flysch bedrock is weak, deeply weathered (Pánek et al., 2010), and contains significant proportions of expanded clay minerals, in particular smectite (Baroň et al., 2003). The geological and tectonic structures present at the site represent an important predisposing factor for landslide occurrence and also influence the type of landslide forming at different localities. The range of slope deformations in the study area includes deep-seated slope deformations, deep block landslides, complex landslides, flow-like landslides, earthflows, shallow landslides, and debris slides.

In the Hostýnsko-vsetínská hornatina Mts., mean annual precipitation totals range from 700 to 800 mm in the western part to 1000–1200 mm in the eastern part, of which roughly 400 mm are recorded in summer. Extreme precipitation events occur repeatedly in the area, and can exceed 100 mm per day. The mean number of days with snow cover ranges from 60 to 80 days at the foots of mountains and 120–140 days on their summits. Mean annual temperatures range from 7 to 8 °C in low-elevation valley floors and 5–6 °C on summits (Tolasz et al., 2007).

The investigated area has been used intensively for pasture in the past, but following rural exodus starting in the 1950s, forests started to become established on the slopes. The newly grown forest is dominated mostly by Norway spruce (*Picea abies* (L.) Karst.) and European beech (*Fagus sylvatica* L.), and accompanied by individual silver fir (*Abies alba* Mill.), sycamore maple (*Acer pseudoplatanus* L.), European larch (*Larix decidua* Mill.) or silver birch (*Betula pendula* L.) trees.

The sites investigated have been known for decades for their landslide activity. Archival records contain information about several past landslides, records, however, were limited mostly, as in other regions (Mayer et al., 2010), to localities in which mass movement processes interfered with human settlements (Špůrek, 1974). Many landslides occurred in remote areas lacking human settlements. Whereas the lack of villages can possibly be explained by the fact that locals were aware of past process activity, it also means that – in the absence of damage to infrastructure – information on past events may not have been recorded. Exceptions to this rule are past calamities as the one in 1919 that affected the western portion of our study area (Záruba, 1922). Other documented events include the several hundred slope deformations recorded in the Outer Western Carpathians after extreme

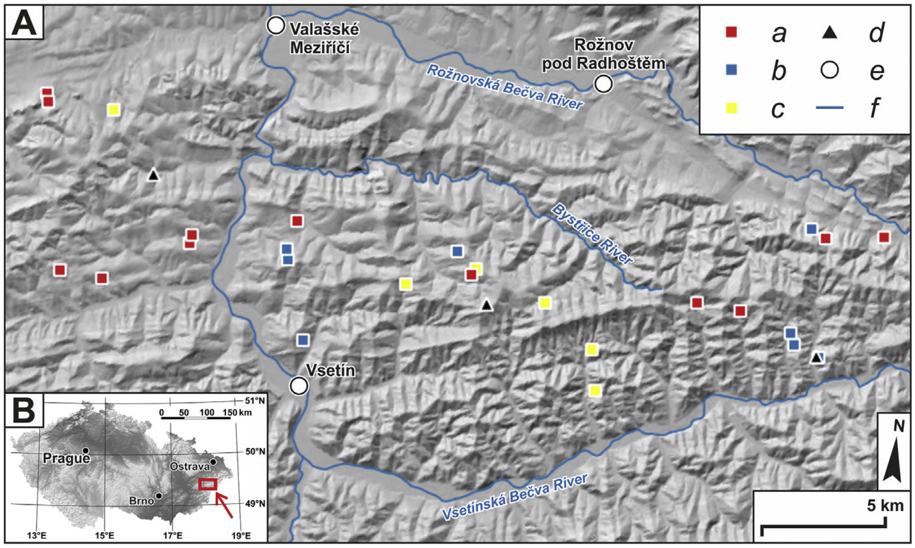

Fig. 1. Localization of the study area. A –Situation of the close surroundings of the study area, B – localisation within Czech Republic (*a* – complex landslides, *b* – flow-like landslides, *c* – shallow landslides, *d* – location of trees sampled for reference chronologies, *e* – towns, *f* – streams) (data source: State Administration of Land Surveying and Cadastre; T.G. Masaryk Water Research Institute, p. r. i.).

precipitation events in July 1997. The latter landslide calamity also triggered intense and systematic field mapping of slope deformations in the area (Rybář et al., 2000), which was pushed further after the landslide calamity of spring 2006 when a rain-on-snow event in late March favoured the fast melting of an unusually thick snow cover (Bíl and Müller, 2008).

3. Methods

This study uses growth anomalies in trees to date past landslide activity in space and in time (Corona et al., 2014; Stoffel and Corona, 2014). Therefore, sites had to be identified where landslides occurred in the past and damaged trees, without however, destroying vegetation

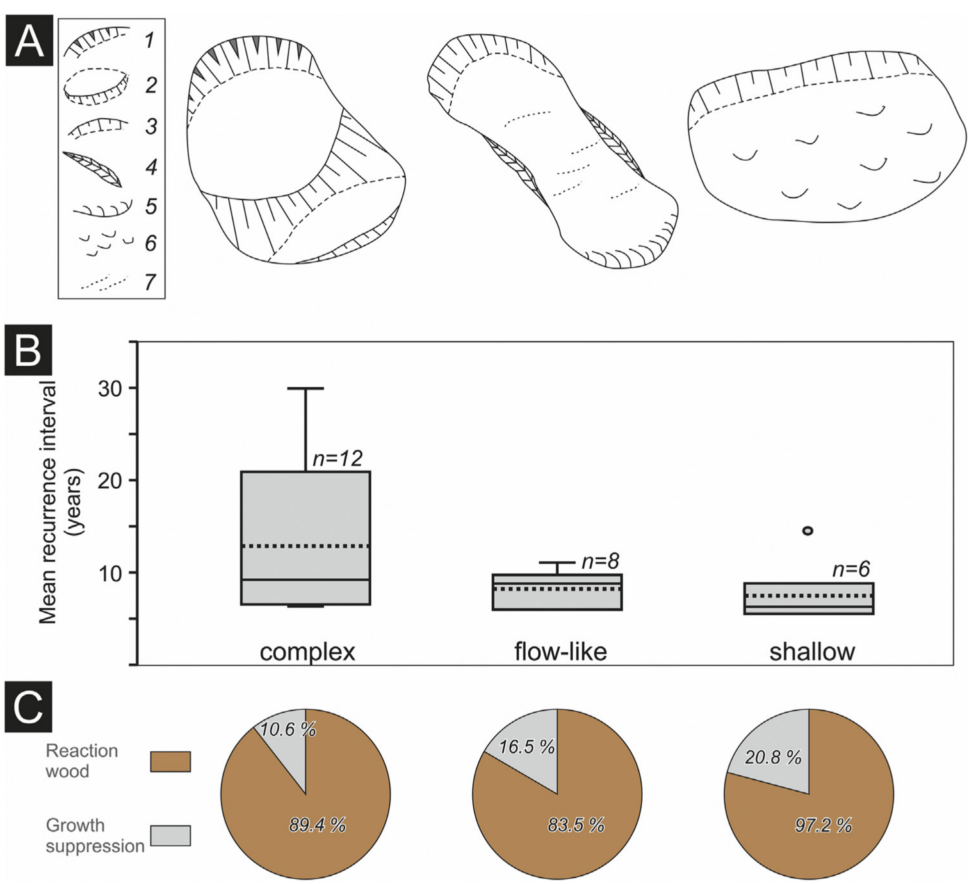

Fig. 2. Landslide types and their basic aspects. A –morphological character of complex, flow-like and shallow landslides (1 – rocky head scarp, 2 – landslide block, 3 – less distinct main scarp, 4 – lateral levees, 5 – frontal lobe, 6 – undulated surface, 7 – transversal cracks), B – mean recurrence intervals of each landslide type, C –proportion of growth disturbances induced by the different landslide types.

on the site completely (Stoffel et al., 2013; Šilhán and Stoffel, 2015). As such, not all landslides in the Hostýnsko-vsetínská hornatina Mts. are suitable for dendrogeomorphic survey, and a set of criteria had to be defined to analyse the most suitable locations. The selected landslides had to: (i) have a forested landslide surface (based on orthophoto interpretation), and (ii) show visible activity of landslides (determined based on field surveys and the detection of open tension cracks, active lobes, and tilted tree stems). On the basis of the abovementioned criteria, we selected 26 landslide locations for further analyses. At each landslide, we started analysis with geomorphic mapping using LiDAR data, and then identified the position of all those trees showing the effects of landsliding on their growth (e.g. tilted stems). In a subsequent step, all landslides were described using the morphological criteria defined by Cruden and Varnes (1996): complex landslides, flow-like landslides (earthflows), and shallow landslides (Fig. 2A).

3.1. Dendrogeomorphic approaches in the field

All trees with visible external growth defects induced by landslides (Stoffel and Bollschweiler, 2008, 2009) were selected for sampling. Each tree was sampled with a Pressler increment borer (40 × 0.5 cm) at the height of maximal stem bending. At least two increment cores were extracted from each tree. One core was extracted from the upper side of the tilted stem and another one from the opposite side. In some cases, two additional cores were extracted perpendicular to the slope direction. Moreover, three reference chronologies were compiled from 60 undisturbed trees (120 increment cores) to document tree growth in the absence of geomorphic disturbance. These reference chronologies were then used to distinguish noise (climate, insect signals) from signal (process activity) in the trees sampled on the landslide bodies. The decision to sample three sites was because the sites selected in this study cover different parts of the Hostýnsko-vsetínská hornatina Mts. (Fig. 1) for which local, micro-climatic differences can affect tree growth in slightly different ways.

3.2. Dendrogeomorphic approaches in the laboratory

Samples were processed following standard dendrogeomorphic techniques, i.e. gluing increment cores onto woody supports, air drying of samples, sanding with increasingly finer sand papers, tree-ring counting, and measurement of tree-ring widths under a binocular microscope connected to a TimeTable and PAST4 software (VIAS, 2005; Stoffel and Bollschweiler, 2008). The reference chronologies were built with Arstan software (Cook, 1983) using a standard double detrending procedure (with a negative exponential function, or linear regression, in the first step and a cubic spline function in the second step).

All samples from the disturbed trees were cross-dated with the reference chronologies to identify and correct possible missing or false tree rings, and to distinguish climate-related growth changes from landslide-induced growth disturbances (GDs). In this study, and with the aim to identify GDs induced by landslides, we looked for two types of anomalies in the macro-anatomy of samples (under the binocular) and in the increment curves: (i) the onset of reaction wood (compression wood in our case because of the exclusive sampling of conifers) as a response to tree stem tilting; characterized by brownish-yellowish-reddish colour of tree rings due to the presence of denser latewood cells with thicker and rounded cell walls (Westing, 1965); and (ii) abrupt growth suppression as a response to damage of tree root system by subsurface slope movements (Lopez Saez et al., 2012b, 2013b). Abrupt growth suppression was determined according to the criteria defined by Schweingruber (1996) and considered only in those cases where tree-ring width dropped by at least 70% in comparison to the mean width of the four previous tree rings.

All GD were summarized in a database and translated into annual chronologies of growth anomalies recorded at each of the study sites. Determination of landslide events was based on the standard event-response index (I_t) as proposed by Shroder (1978):

$$It = \sum R_t / \sum N_t \times 100\%, \quad (1)$$

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*. Two I_t thresholds were used to determining landslide events and to exclude noise from the final chronology of landsliding: past events were considered probable in case that $I_t = 5$–10%, and certain in case that $I_t \geq 10\%$. Past work has shown that an I_t threshold of 5% should be optimal for sample sizes of 30–50 trees (Corona et al., 2014). In addition to the I_t value, at least three trees from a site had to show GD simultaneously. Moreover, we limited the length of each landslide chronology to the period for which a minimum of 10 trees was available for analysis. The recurrence interval of landslide reactivations was then calculated as the quotient of the length of the landslide chronology and the number of reconstructed landslide events. Dated landslide events were compiled in a regional landslide chronology in a first step and then into chronologies for each the of different landslide types considered in this study.

The morphometric parameters of each landslide were then used for comparison with the recurrence intervals; these data were derived from data contained in the LiDAR-based Digital Elevation Model (DEM). Among the morphometric parameters possibly influencing landslide activity, we selected: (i) landslide length/width ratio, (ii) sub-basin area (i.e. the runoff contributing area of landslide), (iii) mean elevation, (iv) local relief, (v) mean slope, and (v) area.

4. Results

4.1. Landslide characteristics

Twenty-six landslides were selected across the study region for morphometric analysis and dendrogeomorphic dating of past process activity (Fig. 1). In terms of basic morphological groups, most landslides (12; 46.2%) can be defined as complex landslides with distinct source zones. These sites often show rocky scarps, minor scarps, near-scarp depressions, upslope facing rotated blocks, alternation of sub-horizontal, and very steep surfaces. Flow-like landslides were observed in eight cases (30.8%). This type of landslides is characterized by their elongated shape, relatively distinct source zone, transverse tension cracks, lateral levees, and plastic front lobe. The third category, shallow landslides, was present in six cases (23%). In general, this type of landslides expressed a rather areal shape (comparable width and length dimensions) with a much less distinct source zone, undulated surfaces, tension cracks, and occasionally also lobate structures (Fig. 2 A, B).

The average area of the 26 landslides investigated was ca. 48,000 m^2 (stdev: 40,944.3 m^2). Landslides had a mean length of 334 m (stdev: 167.5 m), a mean width of 192 m (stdev: 125.8 m), and a mean length-to-width (L/W) ratio of 2.3 (stdev: 1.6). Mean slope angles of the landslide bodies was 15.6° (stdev: 3.8°), and mean elevation of landslides was 572.8 m a.s.l. (stdev: 106.2 m a.s.l.). On average, the mean runoff contributing area of landslides was 29,211 m^2 (stdev: 27,375.1 m^2). All details about landslides morphometry are provided in Table 1.

4.2. Dendrogeomorphic data

Dendrogeomorphic analysis of all landslides was performed using 2942 increment cores from 1322 trees (1244 *P. abies*, 53 *L. decidua*, and 25 *A. alba*), resulting in 50.8 trees per landslide on average (stdev: 24.4 trees). The smallest number of trees sampled was 20, and the largest number of trees analysed on one single landslide body was 155. The mean age of sampled trees was 71.7 years (stdev: 21.5).

In total, we identified 1262 GDs induced by past landslide movement, resulting in 48.5 GDs on average per individual landslide (stdev: 26.8 GDs). Reaction wood (1054 GD; 83.5%) was by far the most

Table 1
Overview of basic morphometric parameters of studied landslides.

Landslides	Length (m)	Width (m)	L/W	Subbasin area (m^2)	Mean elevation	Mean slope (°)	Area (m^2)
Kobylská	287	146	2.0	4850	702.2	19.8	33,819
Kývňačka	168	90	1.9	9975	706.0	18.2	11,326
Bečva	280	36	7.8	71,825	578.3	17.2	7181
Vlčice II	485	152	3.2	18,300	517.8	14.6	50,107
Cáb III	340	105	3.2	47,825	626.1	16.0	24,884
Vlčice I	300	134	2.2	12,075	493.8	15.4	24,430
Cáb I	292	181	1.6	26,875	723.0	10.0	39,058
Jezerné	344	68	5.1	8800	601.7	22.4	18,512
Loučka II	448	500	0.9	10,750	471.2	11.9	127,149
Hluboký	164	80	2.1	22,725	661.8	23.8	11,256
Podolí	265	306	0.9	24,150	443.0	13.6	54,442
Pržno II	245	421	0.6	113,625	396.7	12.5	86,135
Uvezené	821	228	3.6	31,550	506.7	12.4	168,755
Kateřinice	309	143	2.2	21,475	457.5	14.1	33,403
Pržno I	506	414	1.2	19,575	435.1	13.6	93,731
Růžd'ka	575	201	2.9	46,800	420.0	12.0	92,597
Lušová I	266	60	4.4	4775	603.7	22.0	10,990
Bzové II	280	144	1.9	2450	640.6	18.5	28,881
Cáb II	370	175	2.1	19,350	717.9	7.9	52,071
Bzové I	224	84	2.7	16,150	621.5	15.5	15,814
Soláň	430	243	1.8	23,675	722.8	18.6	61,610
Loučka I	230	181	1.3	16,375	486.9	12.9	27,810
Jasénka	650	247	2.6	74,500	454.6	15.3	100,686
Lušová II	166	106	1.6	1175	598.4	16.8	12,070
Dušná	123	427	0.3	75,375	651.6	14.2	44,682
Lubenky	112	125	0.9	34,475	653.1	15.7	13,200
Mean (stdev)	333.8 (167.5)	192.2 (125.8)	2.3 (1.6)	29,210 (27375)	572.8 (106.2)	15.6 (3.8)	47,869 (40944)
Maximal	650	500	5.1	113,625	723	23.8	168,755
Minimal	112	36	0.3	1175	396.7	7.9	7181

frequent signal detected in the trees affected by landslides; abrupt growth suppression was, by contrast, only found 208 times (16.5%). Details regarding tree numbers and tree ages, as well as on the number and structure of GDs for each of the landslides are presented in Table 2.

Distinct differences in the number and proportion of GDs occur between the different categories of landslide types. In the case of the complex landslides, the proportion of reaction wood was largest with 89.4% (against 10.6% of growth suppression). The predominance of reaction wood decreases slightly in the case of flow-like landslides (83.5/16.5%), and drops further in the case of shallow landslides (79.2/20.8%; Fig. 2D). The slight increase of growth suppression in the latter types of landslides may be related to their depth, and the less frequent destruction of root structure in trees. In all three types, however, differences in the ratios between the two types of GDs remain insignificant.

Table 2
Overview of sampled trees, growth responses, and chronological aspects of studied landslides.

Landslide	Sampled trees	Mean age	Maximal age	Minimal age	Total GD	Reaction wood	Growth suppression	Chronology length (min. 10 trees)	Events	Recurrence
Kobylská	49	79.4	130	34	38	36	2	120	4	30.0
Kývňačka	32	104.1	144	36	40	34	6	118	12	9.8
Bečva	20	98.9	126	49	34	20	14	110	13	8.5
Vlčice II	42	99.5	135	62	44	40	4	109	13	8.4
Cáb III	53	100.6	110	33	11	11	0	106	17	6.2
Vlčice I	53	81.6	108	35	83	69	14	102	17	6.0
Cáb I	155	101	115	70	120	73	47	102	8	12.8
Jezerné	47	88.5	113	38	23	16	7	100	9	11.1
Loučka II	47	89.5	108	67	57	42	15	98	15	6.5
Hluboký	35	84.1	90	55	13	8	5	89	4	22.3
Podolí	44	78.0	115	40	61	47	14	88	16	5.5
Pržno II	37	78.1	119	30	58	52	6	86	13	6.6
Uvezené	56	65.3	102	15	24	18	6	84	4	21.0
Kateřinice	36	76.7	105	38	52	50	2	80	7	11.4
Pržno I	52	67.3	103	44	54	49	5	74	8	9.3
Růžd'ka	48	70.6	122	46	56	46	10	72	11	6.5
Lušová I	50	64.9	88	46	42	40	2	69	10	6.9
Bzové II	74	62.2	72	55	61	53	8	66	7	9.4
Cáb II	30	58.0	88	43	11	11	0	58	4	14.5
Bzové I	60	53.0	67	43	57	54	3	56	6	9.3
Soláň	50	53.0	57	42	45	41	4	55	8	6.9
Loučka I	36	61.4	106	46	15	13	2	54	4	13.5
Jasenka	52	47.0	77	36	65	50	15	48	8	6.0
Lušová II	48	42.0	56	31	42	36	6	45	8	5.6
Dušná	43	34.3	57	28	46	37	9	38	6	6.3
Lubenky	73	25.3	37	19	110	108	2	32	5	6.4

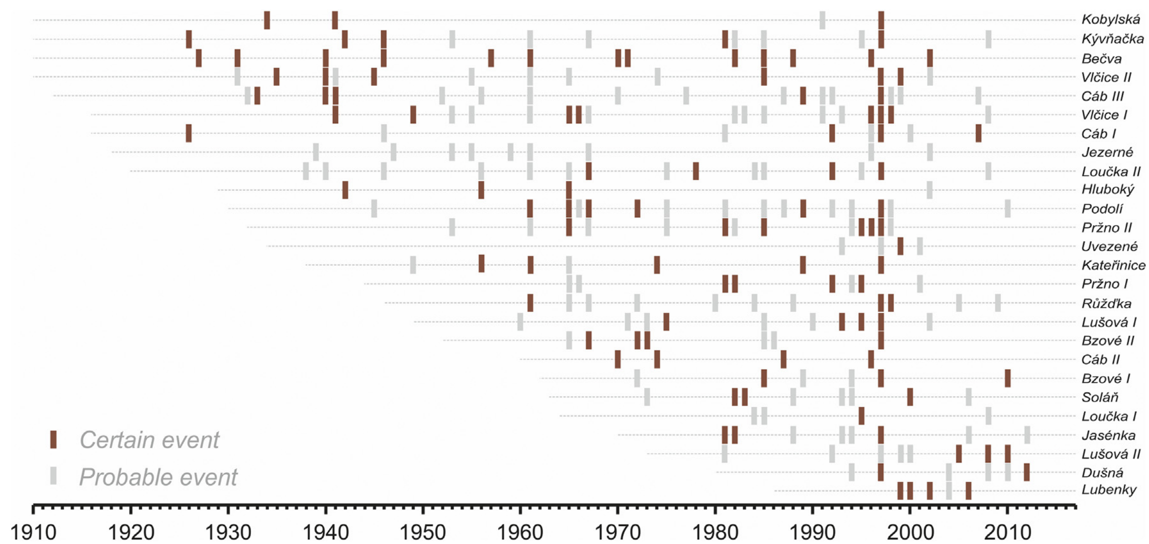

Fig. 3. Annual chronology of dated landslide events with distinction of probable and certain events. For details see text.

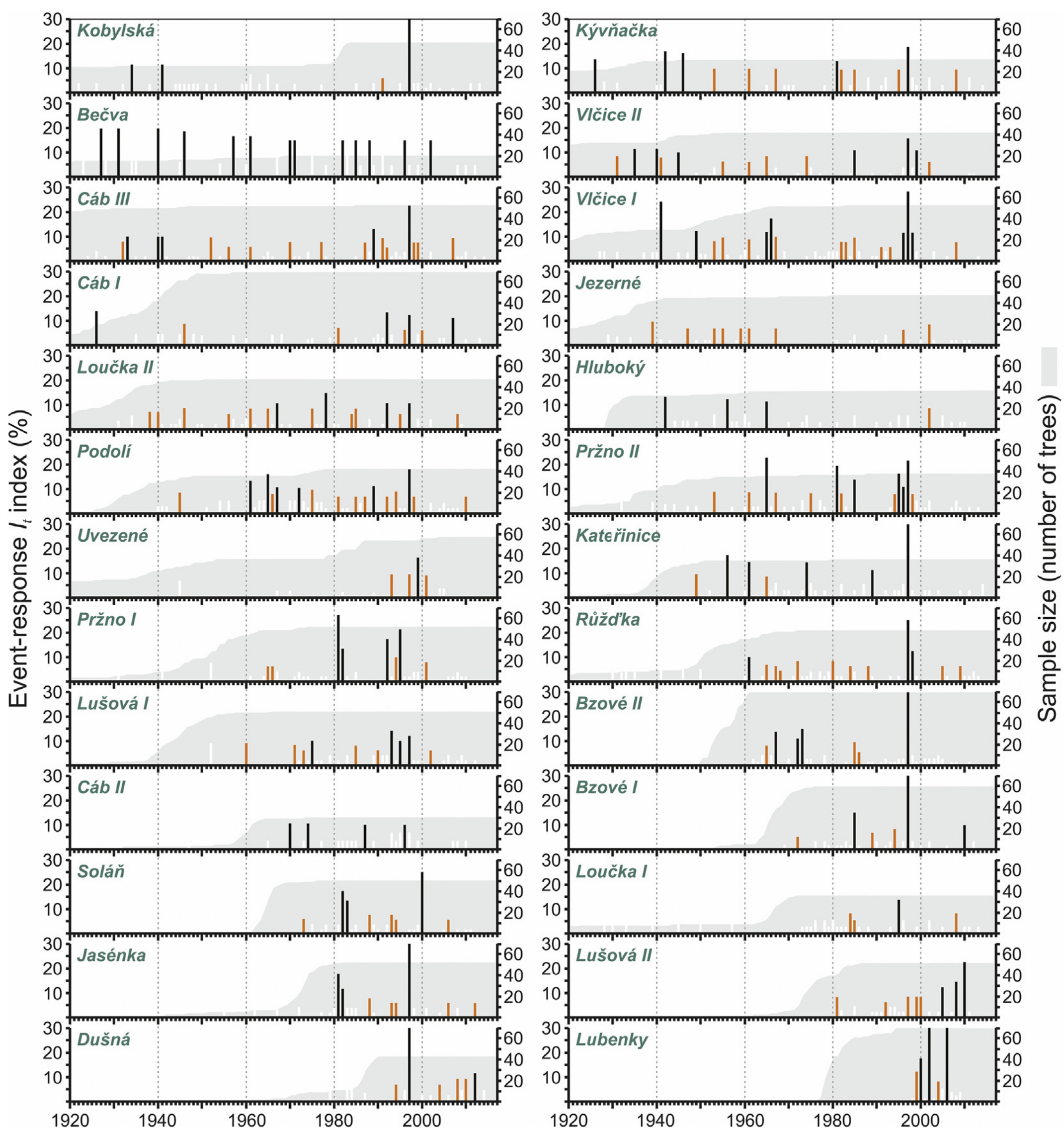

Fig. 4. I_t values and sample size evolution for all landslides (orange column – probable event; black column – certain event).

4.3. Landslide chronologies

The length of each individual landslide chronology was limited to the period for which at least 10 trees sampled were available for analysis (defined subjectively), resulting in a mean chronology length of 79.2 yrs. (stdev: 25.6 yrs); with the longest chronology covering120 yrs. and the shortest 32 yrs. In total, 237 landslide events fulfilled all dating thresholds across the 26 landslides, resulting in an average of 9.1 events per landslide (stdev: 4.6 events) with a maximum of 17 and a minimum of four events (Table 2). The ratio between certain and probable events was rather balanced with 106 (44.7%) and 131 events (55.3%) (Figs. 3, 4). The mean recurrence interval of landslide movements was 10.3 years for all landslide bodies (stdev: 6.0 years; maximum 30 years; minimum 5.5 years).

Interestingly, recurrence intervals of landslides differ distinctly between different landslide types (Fig. 2C). This means, flow-like and shallow landslides express much higher activity with mean recurrence intervals of 8.3 years (stdev: 2 yrs) and 7.5 years (stdev: 3.4 yrs), respectively, in comparison with complex landslides where mean recurrence intervals are at 12.9 yrs. (stdev: 7.6 yrs).

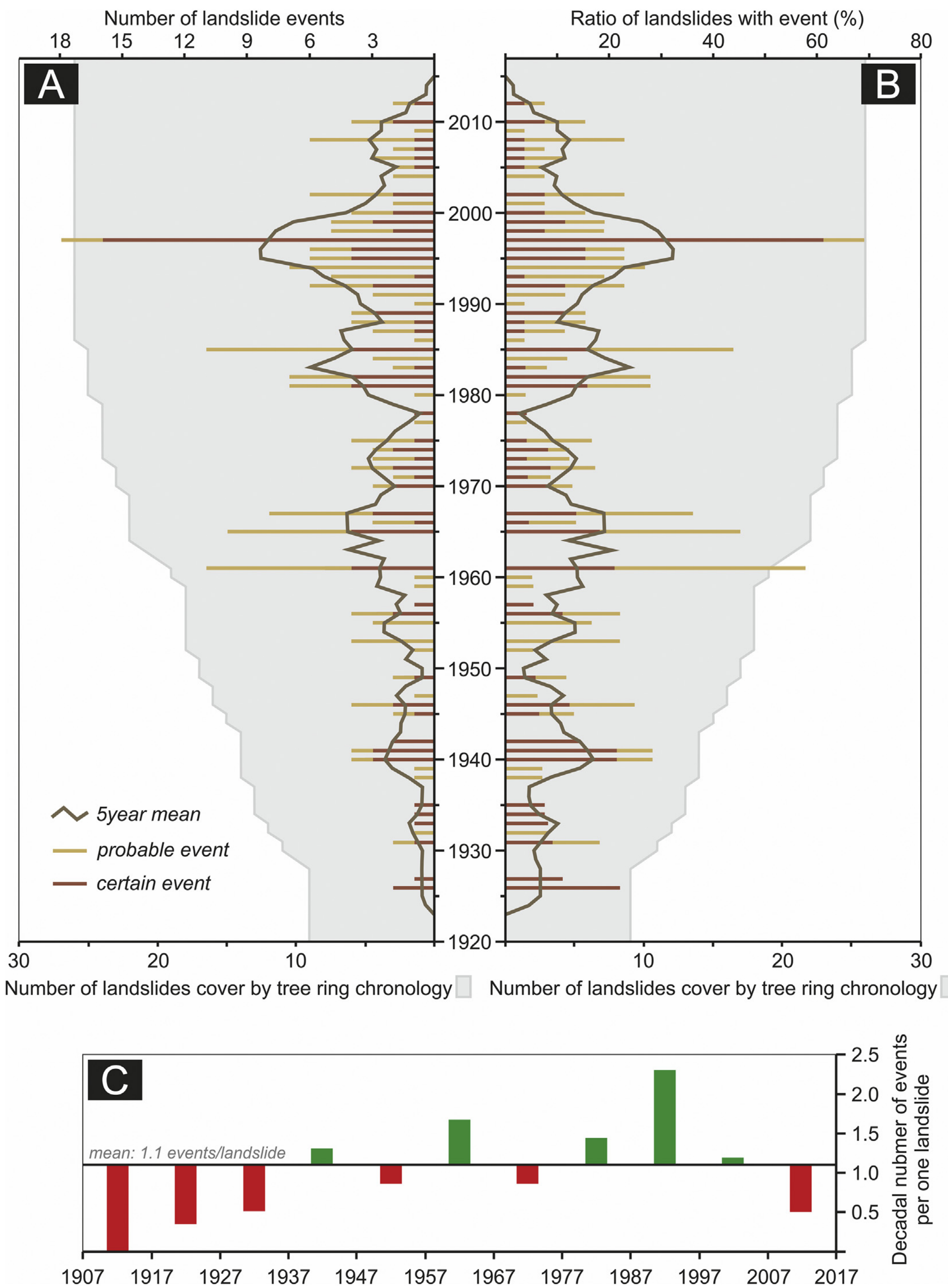

Fig. 5. Regional chronologies of landslide events. A – chronological numbers of certain and probable landslide events, B – chronological proportion of landslides showing an event, C – decadal frequency of landslide events.

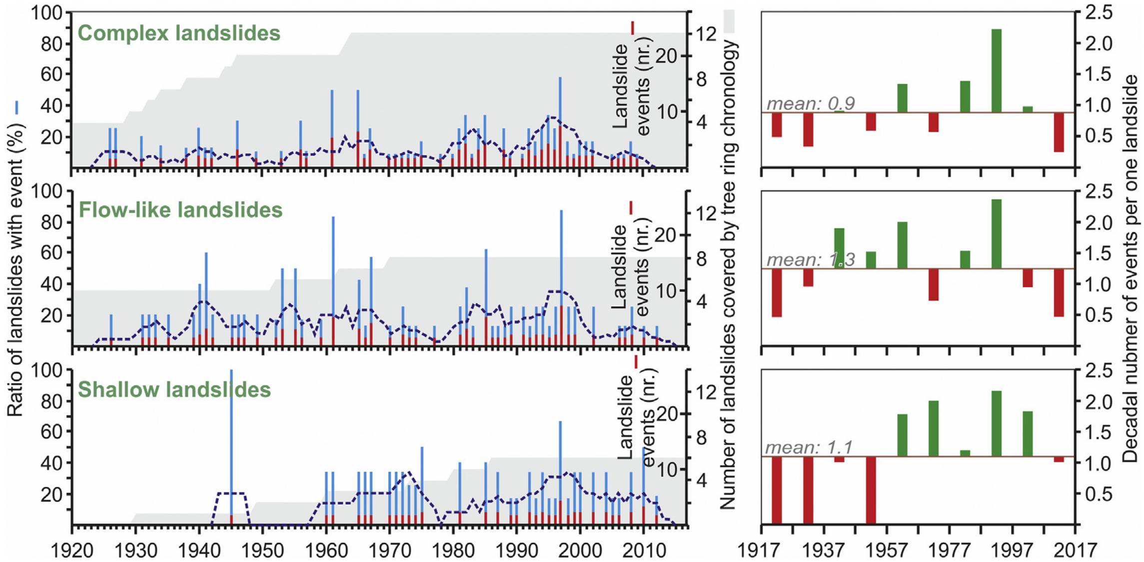

Fig. 6. Individual annual (number of landslide events, and ratio of landslides with events) and decadal (presented as deviations from mean frequency) chronologies for the three landslide types investigated.

In this study, the oldest landslide event was dated to 1926 CE. In total, the 237 landslides occurred in 66 different years between 1926 and today (Fig. 5). Whereas some events years are characterized by very limited activity at one or just a few sites, this study also documents years with widespread landsliding. In that sense, the year with the most widespread landslide activity (i.e. landslide reactivations) was 1997 when more than two thirds (69%) of all landslides investigated showed clear evidence of movement. Other years with significant landslide activity were recorded in 1961, 1965, 1967, and 1985, when more than one-third of the landslide bodies were affected by process activity. On the other hand, during 17 (of the 66) years with landslide activity, only one site each showed signs of instability, whereas all other sites were not affected by any soil movement (Fig. 5A). The landslide reconstruction across all 26 sites does not exhibit any significant changes in process activity over time (Fig. 5B), but shows slight increases in landslide frequency during the 1940s, 1960s, 1980s, and more particularly during the 1990s. By contrast, and since the culmination in landslide activity in 1997, our data suggests a significant decrease in activity up to the present (Fig. 5B, C). The slightly fluctuating patterns of activity during most of the time period covered by this reconstruction, and the culmination of activity in 1990s followed by significant activity decrease, is in fact visible both at the sites with complex and flow-like landslides (Fig. 6), and even at decadal time scales. In general terms, however, flow-like landslides seem to be more active as compared to complex landslides. By contrast, shallow landslides expressed a more balanced activity over the period covered by the analysis and less peaks in landsliding, but the culmination in 1997 is clearly visible shallow landsliding as well (Fig. 6).

4.4. Other aspects of landslide activity

In a subsequent step, we used (i) recurrence intervals of landslide activations as a proxy for landslide activity and (ii) mean I_t index values as a proxy for the mean importance of reactivation, and then compared these proxies with selected morphometric parameters of landslides. Interestingly, none of the morphometric parameters used in this study

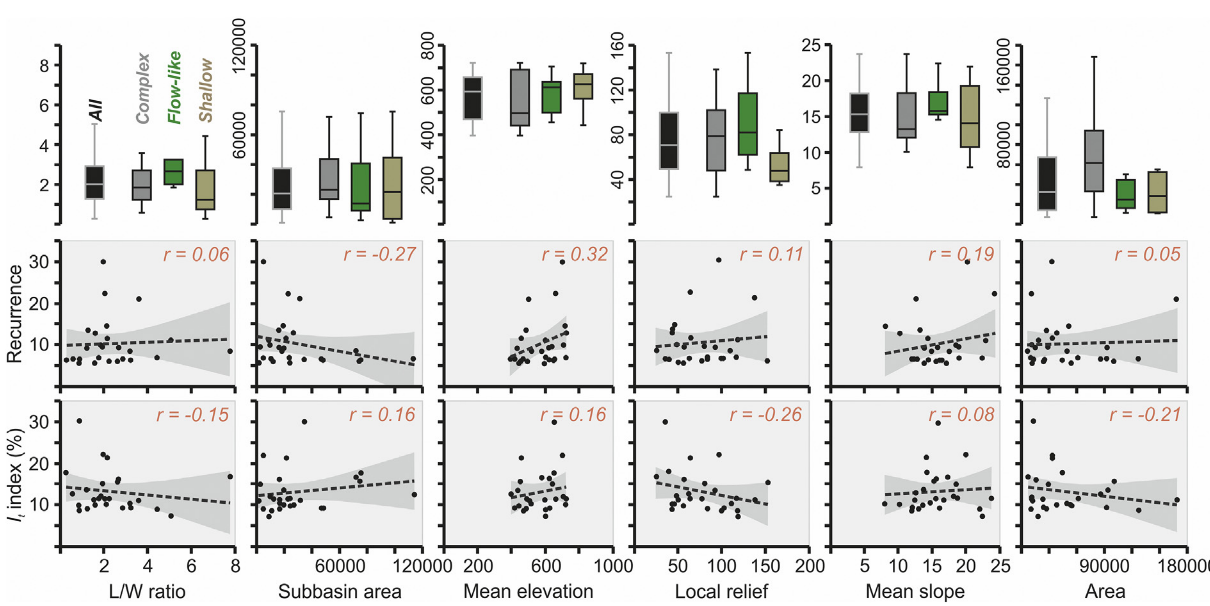

Fig. 7. Basic morphometric parameters of each landslide type and their relation with landslide recurrence intervals and event-response I_t index.

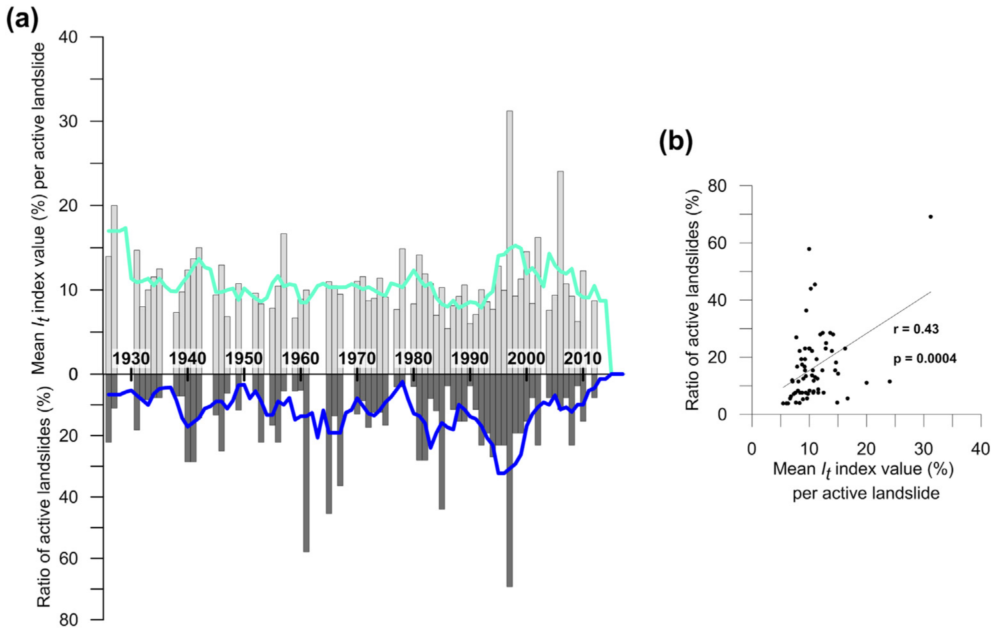

Fig. 8. Relationship between the ratio of active landslide in each year and the mean I_t index during these events.

expressed statistically significant dependencies recurrence intervals or the I_t index (Fig. 7). Nevertheless, possible, yet insignificant relationships were found between some of the parameters: Recurrence intervals, for instance, correlate positively with the mean elevation of landslides ($r = 0.32$), and negatively with mean sub-basin area ($r = -0.27$). The I_t index expressed negative correlation with the local relief of landslides (i.e. the elevation range of landslide area) and landslide area ($r = -0.26$, and $r = -0.21$, respectively).

In a further step, we compared the mean I_t index of all landslide events in individual years with the ratio of all active landslides (i.e. ratio of the regional extent of events vs. the proxy magnitude of events). In general terms, a statistically significant dependence exists between these two variables ($r = 0.43$; p value $= 0.0004$) (Fig. 8).

5. Discussion

The regional chronology of past landslide movements in the Hostýnsko-vsetínská hornatina Mts. was based on tree-ring records from 26 landslides and contains information on 237 individual landslide events derived from information contained in 1322 disturbed trees between1926 and today. As such, the study presented here is unique, both in terms of its spatial extent and in terms of the size of the dataset used for analysis.

5.1. Tree-ring based regional chronology of landslides

Indeed, tree-ring based reconstructions of geomorphic process histories have been based mainly on case studies restricted to one single site, and only rarely considered process activity at regional scales. Exceptions to this rule are a handful of debris-flow histories, plus some very scarce studies on floods (as indicated in the Introduction) or rockfalls (Moya et al., 2010; Šilhán et al., 2011). By contrast, regional chronologies of landslide processes have remained exceptional and or limited to a very small number of sites (Corominas and Moya, 1999; Lopez Saez et al., 2013a). This paper therefore represents a real exception to the rule as it exceeds the number of sites used in past studies and irrespective of the process under investigation.

We argue here that regional chronologies can more easily capture the influence of changes in environmental conditions influencing process triggering and behaviour than would studies limited to individual sites (Fig. 4).

Despite the obvious advantages of multi-site, regional assessments, the general specificities and limitations encountered in regional tree-ring based landslide chronologies are not fundamentally different from those inherent to individual case studies. The main limiting factor in both cases is the age of trees as it determines the length of individual chronologies. In a similar way, the minimum number of trees analysed per study site will be influenced by local conditions and does not reduce because of the larger number of landslide sites analysed. We concur with Corona et al. (2014) that roughly 50 trees (for an area of 32 ha) should be enough to derive a balanced, valid dendrogeomorphic chronology of past landslide movements without any significant losses of information, even with an I_t threshold of 5%. In case that the number of trees fluctuates distinctly between individual landslides, the I_t threshold should be adjusted to each landslide individually to allow for a clear distinction between signal and noise (e.g. Stoffel et al., 2013). The next potential limitation inherent to case studies and the work presented here is the subsiding of any landslide movement during the weeks or months (sometimes even years) after the main reactivation phase (or after two and more reactivation phases during the same year), which can lead to persistent, and sometimes even late, reactions and therefore in a faulty attribution of tree-ring signals to the year after the main landslide activity. By way of example, it is possible that after the July 1997 reactivation phase, landslide movements subsided into autumn 1997 (Krejčí et al., 2002), and could have caused what we usually refer to a possible delay or "inertia" of tree growth responses to landslide movements (Šilhán, 2017). By using a sufficiently large number of trees for analysis, risk of misdating an event can, however, be reduced substantially.

5.2. Landslide dynamics in the study area

All landslides analysed in this study have been attributed to one of the main morphological categories, namely complex, flow-like, and shallow landslides. Interestingly, the proportion of landslide types in our study corresponds reasonably well with that of the observational study (ca 46/31/23%) of Krejčí et al. (2002). In that regard, our landslide dataset can be regarded as representative for the wider study region. We also realized that the relative proportion of GDs dated in trees growing on individual landslide types is representative of the landslide mechanisms occurring in each of the different landslide types (Šilhán et al., 2016). In that sense, the very prominent occurrence of reaction wood in trees growing on complex landslides can be confirmed (Šilhán et al., 2013), and is characteristic of widespread slope deformation and prevailing stem tilting. In contrast, a slightly higher proportion of abrupt growth suppression could be found in the case of shallow landslides, which may reflect more frequent damage to the tree root system as a result of the much shallower slip surface (Lopez Saez et al., 2012b).

It also seems that differences in mean recurrence intervals of landslide reactivations reflect the different conditions needed to effectively trigger each of the landslide types. In general, the smallest frequency of reactivations was observed among the complex landslides (Fig. 2C) where slip surface usually occur at depths exceeding several tens of meters. Although the sandstone and claystone bedrock is deeply weathered in the area (and up to depths of 20 m; Pánek et al., 2010), the infiltration of surface water remains rather limited because of significant slope inclination (Krejčí et al., 2002). By contrast, flow-like and shallow landslides were reactivated more frequently (Fig. 2C), as they originate in the upper layers of weathered rocks and therefore are able to be triggered even by short-term precipitation events. In this regard, our findings are in agreement with Krejčí et al. (2002) who supposed a strong independency of shallow landslides to geological structure in the Hostýnsko-vsetínská hornatina Mts.

In addition, this study shows that landslide frequency is related positively to sub-basin area and negatively to elevation. It therefore seems that both the surface and subsurface water inflow have a noticeably influence on the critical saturation and water pore pressure in landslide bodies in our study region. Our study thus agrees with the observations of Kirchner and Krejčí (1998) who documented a predominance of reactivations in the middle and lower elevations during the 1997 landslide calamity.

At the regional scale, a strong, positive correlation emerges between the extent (expressed here as the proportion of active landslides in a single year as seen in tree-ring record) and the magnitude (obtained with the event-response I_t index) of landslides shown in Fig. 8, thereby pointing to some control of landslide triggers on the abundance and size of events. As such, precipitation type, duration and intensity are likely to exert major control on process activity at the study site. The 55-mm precipitation, single-day threshold defined by Obdržálková (1992) seems reasonable at first sight and for widespread landslide reactivations, whereas more isolated landslides are more likely initiated by localised, short-duration rainstorms (Tichavský et al., 2017), without delivering enough water to activate larger portions of landslide bodies. The widespread landsliding in 1961, 1985, or 1997 were probably triggered by long-term advective rainfalls (as demonstrated in the case of the 1997 calamity; Kirchner and Krejčí, 1998).

5.3. Contribution to regional knowledge of past landslide activity

Until now, a regional picture of landsliding and a documentation of landslide activity in the Hostýnsko-vsetínská hornatina Mts. has been missing, and was limited to very small set of archival records (Špůrek, 1974) and basically no data from sparsely populated areas (Raška et al., 2015). Pánek et al. (2013) developed a somewhat longer time series of landslide activity in the area using radiometric (AMS) dating. This paper and the chronologies presented herein complement the above datasets and contribute substantially to the general understanding of mass wasting in the area, both in terms of landslide frequency (reactivations) and precision for the last century. Interestingly, eyewitnesses in the village of Dušná reported landslide reactivations in 1948, 1952, and 1986. We identified activity in the landslides to which the local residents referred to with moderate to minor signs in the tree-ring records, thereby underlining the value and significance of site studies and regional chronologies.

6. Conclusions

This study presents the first extensive, regional-scale (covering ca 600 km^2) tree-ring based reconstruction of landslide movements, and illustrates possibilities and limitations inherent to dendrogeomorphic reconstructions. The work was realized in the Hostýnsko-vsetínská hornatina Mts. (Czechia) where landslide activity is quite high, but where a complete overview or regional chronology of landsliding has been missing until now. The reactivation of landslides at 26 localities yielded data on 237 events over the last century.

The study also showed that the construction of regional landslide chronologies can provide a much more complete overview of process activity than individual case studies, and even more so than archival records. In this study, we also provide information on landslide behaviour in the study area and are able to distinguish phases with enhanced (1940s, 1960s, 1980s, and 1990s) from periods with more limited (1970s, 2000s, and 2010s) landslide activity. Moreover, those landslide events with a large spatial extent (calamites) – and known from the archives – could be identified as well (1961, 1985, and 1997). Analysis of the extensive dataset containing information on 26 landslide bodies also enabled distinction of landslides by morphological type and to identify different reactions and frequencies among different categories of landslides.

Regional dendrogeomorphic reconstructions of past landslide behaviour are a strong and powerful tool in landslide analysis, and can thus assist decision making in terms of better informed hazard assessments and for the determination of areas at risk. In the future, research should include relationships between climatic triggers and landslide activity in areas like the one illustrated here, so as to account for the impacts of climate change on mass wasting in mountain environments.

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