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DENDROGEOMORPHOLOGICAL ANALYSIS OF THE EVOLUTION OF SLOPE PROCESSES ON FLYSCH ROCKS (VSETÍNSKÉ VRCHY MTS; CZECH REPUBLIC)

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Abstract: Slope movement and gully erosion represent important slope-modelling processes. Since the processes occur frequently in Carpathian flysh belt, a detailed study of such phenomena is desirable. In a selected locality within Vsetínské vrchy Mts. we have investigated a landslide area via 73 cross sections from *Picea abies* and *Larix decidua* and a gully network via 21 cross sections from exposed roots. The analysis was carried out on the basis of tree-ring eccentricity, reaction wood formation and anatomic changes on root cells. We reconstructed a 15-year-long series of landslide movement and a 40-year-long series of erosion events. Only slight dependence was proved between reaction wood formation and tree-ring eccentricity. The years 1997, 2002 and 2006 were evaluated as the years of the most pronounced landslide activity. Dendrogeomorphology revealed 12 erosion events. Steep slopes of the gullies were dominated by upward erosion, whereas less steep concave parts showed upward erosion alternating with downward erosion. A majority of erosion and landslide events originated due to short-term extreme precipitation totals (incl. more than 100 mm/24 hours).

Keywords: dendrogeomorphology, landslide, gully erosion, flysch rocks, Vsetínské vrchy Mts.

1. INTRODUCTION

Landslides are highly dangerous slope processes that are presently under intensive investigation (Dikau et al., 1996). They stand for the most frequent type of slope processes in Czech flysch Carpathians (Baroň et al., 2004; Hradecký & Pánek, 2008). Landslides can cause not only damage to property, but also casualties. Erosion processes accelerate degradation of farm land causing economic damage. In order to prevent these dangerous processes, it is necessary to identify the conditions in which they occur. The most common method used to identify the origin of slope processes is the evidence and evaluation of triggering mechanisms of already existing slope deformations (Buma, 2000). The relation between the origin of a slope process and its triggering climatic cause is dependent on the character of the process. Gully erosion, debris flows and shallow landslides originate in flysch Carpathians most commonly in conditions of very intensive short-term precipitations (Šilhán & Pánek, 2010). On the contrary, deeper landslides or deep-seated movements are preceded by a few weeks' or months' above-average precipitation totals (Corominas & Moya, 1999; Stefanini, 2004; Pánek et al., 2011).

The record of landslides is, however, very often incomplete; it sometimes covers an insufficient time series (Lopez Saez et al., 2012). These processes therefore need to be dated using the methods of absolute dating. An effective analysis of the interaction of slope processes and their triggering factors is dependent on the most accurate possible determination of the time of the process origin. At present, the most accurate methods of the dating of geomorphological processes which take place in forested areas are dendrogeomorphological approaches (Stoffel & Bollschweiler, 2008).

A methodical set has been elaborated for the reconstruction of debris flows (Bollschweiler & Stoffel, 2010) and rockfall (Stoffel & Perret, 2006). Similarly, tree-ring analysis in the research of gully erosion disposes of a well elaborated fundament (Vandekerckhove et al., 2001; Malik, 2008; Gärtner, 2007). The reconstruction of landslide movements, however, lacks a definite methodology, which is why different authors apply different approaches. Steffanini (2004) and Fantucci & Sorriso-Valvo (1999) make use of increment anomalies (growth suppression/release) in the dating of landslide movements. Braam et al., (1987), Van Den Eeckhaut et al., (2009) and Pánek et al., (2011) use the analysis of eccentric tree growth. Ilinca & Gheuca (2011), Shroder (1978), Lopez Saez et al., (2012) and Carrara & O'Neill (2003) have concentrated on the analysis of reaction wood, the formation of which is caused by the tilting of a tree stem trying to move back to its original vertical direction. A general assumption is that there is a direct proportion between reaction wood formation and tree-ring eccentricity. Nevertheless, this assumption has not thoroughly been examined yet.

The aim of this article is to i) reconstruct both temporal and spatial activity of landslides along with the evolution of gullies in flysch Carpathians using selected dendrogeomorphological methods, ii) verify and evaluate direct reaction of trees to stem tilting occurring due to landslides and iii) evaluate the influence of selected climatic characteristics on the acceleration of both types of processes.

2. STUDY AREA

For the purposes of dendrogeomorphological analysis we have selected an area in the upper course of Tísňava stream (49°22'46" N, 18°7'28" E) in the Vsetínské vrchy Mts (Fig. 1A). It is an area within the Magura Nappe built by flysch rocks dominated by claystones and sandstones of Mesozoic and Tertiary ages. Flysch bedrock is commonly only slightly or medium weathered and along with other factors (steep slopes, high precipitation totals, high content of smectite) it represents a positive condition for the emergence of various types of slope deformations (Baroň et al., 2004). Average annual precipitation totals (1930–2009) measured at the Horní Bečva meteorological station (565 m a.s.l.; 49°25'53"N, 18°18'05" E) about 10 km far are 230.9 mm.

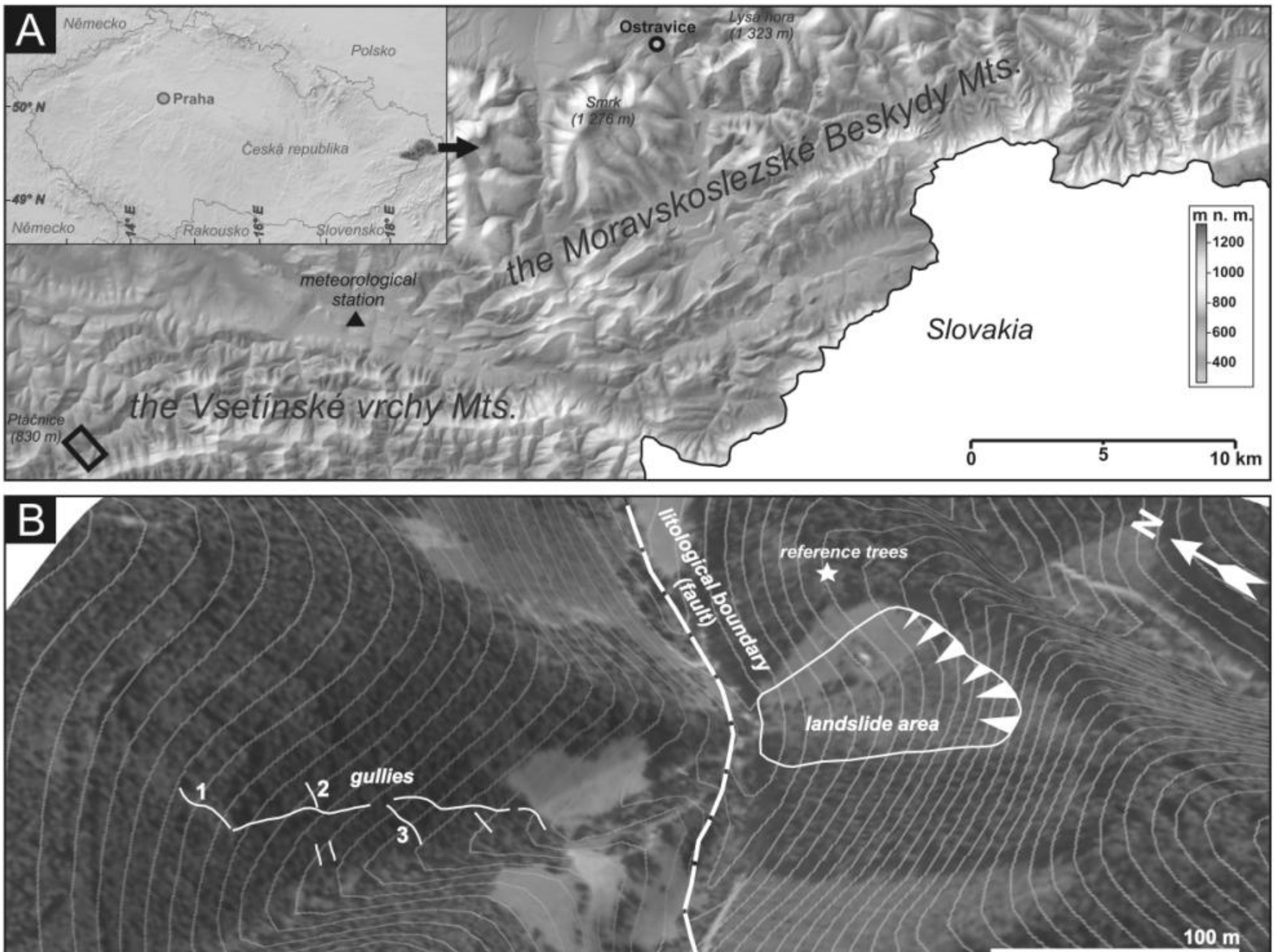

Figure 1. A – Position of the studied locality (black rectangle) in the Czech Republic and Vsetínské vrchy Mts, B – Detailed view of the landslide area, position of the studied gullies and places of reference trees sampling.

I analyzed two closely neighbouring localities of different geological structure, orientation and morphological development (Fig. 1B). The valley bottom between both the localities is cut through by a fault boundary of two distinct lithological units. The first locality lies on the NW-oriented slope built by slightly SW-inclined claystones of Lhota Formation. This area is characterized by elements of landslide activity (mobilized blocks, depressions on slopes, pressure folds) at an altitude of 630–690 m a.s.l. Signs of landslide activity are obvious in all parts of the landslide in the form of deformed (especially tilted and knee-bent) tree stems. The landslide is thickly covered by young trees (max. 30-year-old), artificially planted after primary vegetation extraction. The other locality lies on the opposite slope of S orientation. This area is built by slightly N-inclined bench-like sandstones of the Soláň Formation. Unlike the previous area, this one is characterized by dominant development of deep gullies on slopes. Majority of the gullies, which are as deep as 5 meters, have stabilized slopes. Some of them show an actively deepening valley with exposed tree roots which stick out. The surrounding forest contains old trees, some of which can be more than 100 years old.

Wider surroundings of the studied localities are characterized by frequent occurrence of various types of slope deformations that originate particularly in extreme precipitation events (Baroň et al., 2004). A dominant wood plant of both the localities is Norway spruce (*Picea abies* L. Karst.) accompanied by European larch (*Larix decidua* Mill.) and rarely by European beech (*Fagus sylvatica* L.).

3. METHODS

3.1. Geomorphological mapping

The first necessary step of the research involved detailed geomorphological mapping at a scale of 1:100. A record was made of basic morphological features of the landslide-affected area (head scarp, minor scarps, moist depressions, lobes and gullies) as well as of the gully network development. Since the mapping failed to make use of GPS due to thick vegetation, laser rangefinder and compass were used instead.

3.2. Field approaches

Samples designed for dendrogeomorphological analysis were purely cross-sections. In the gullies, samples were taken from exposed and/or damaged roots growing across the gullies. Each sample was taken halfway of the gully width where the initial and most profound deepening was supposed. At the same time, distance was recorded between the sample and the upper margin of the gully. Within the landslide-affected area, the samples were taken at a height of maximum knee-like bending of tree, whereas in the gullies, the samples were taken from all possible roots. Trees growing on the landslide were carefully selected for the analysis in order to cover evenly as large area as possible. The position of each tree was recorded in a map. In addition to the above-mentioned samples, 20 samples (10 *Picea abies* and 10 *Larix decidua*) were taken from trees growing outside the area affected by the studied geomorphological processes for the purpose of reference chronology.

3.3. Laboratory approaches

All samples were subsequently processed and analyzed in compliance with standard methodology described by e.g. Stoffel & Bollschweiler (2008). Individual steps included sample drying, sample surface polishing, tree-ring counting and ring width measuring by means of TimeTable measuring device and PAST4 software (Vienna Institute of Archaeological Science, 2005). Tree-ring width was measured on three axes of disk (the longest, opposite the longest and perpendicular to the longest). Increment curves were crossdated with the reference chronology in order to identify false or missing tree-rings.

3.4. Reconstruction of erosion and landslide events

The intensity of gully lengthening was analyzed based on the dating of changes in the tree-ring anatomy of roots caused as a result of root exposure. If at least a part of the tree root becomes exposed quickly, a fifty-percent decrease is observed in the size of root cells in the following years (Malik, 2008). Exposed roots may even suffer damage to which they subsequently react by scar and callous tissue formation at the margin of the damage (Fig. 2A). Gully erosion rate (GER) was calculated for each part of gullies between two samples and the whole gully itself as well: GER = distance between neighbouring samples/time between the exposure of neighbouring samples.

Analysis of the landslide movements carried out from tree stem disks concentrated on two aspects. The most distinctive reaction of coniferous trees towards tilting due to landslide-generated bedrock destabilization was the formation of compression wood at the lower side of the tree stem. This asymmetric growth resulted in knee-like bending of the stem (Stoffel & Bollschweiler, 2008). Reaction wood (dark, wide rings) was identified on the stem cross-sections (Fig. 2B). The activity of landslides was reconstructed on the basis of reaction wood and expressed by means of *It* ‘event-response index’, calculated after Shroder (1978):

$$I_t = \frac{\left(\sum R_t\right)}{\left(\sum SD_t\right)} \cdot 100\% \text{ , (1)}$$

where R_t is the number of trees revealing reaction wood as a response to landslide movement in year t and SD_t (Sample Depth) is a number of sampled trees alive in year t. Additionally, we calculated E_i tree-ring eccentricity (Fig. 2C, D) after Braam et al., (1987):

$$E_i = \frac{RA_i - RC_i}{RA_i + RC_i} \text{ , (2)}$$

where RA_i is the width of tree-rings at the lower side of the stem and RC_i is the width of tree-rings perpendicular to the previous ones. Identified eccentricity was weighed according to its value: $Ei > 0.5$ – weight 2, $Ei = (0.25\text{-}0.5)$ – weight 1. Weighted eccentricity was expressed in percentage from all trees analyzed in the year *i*.

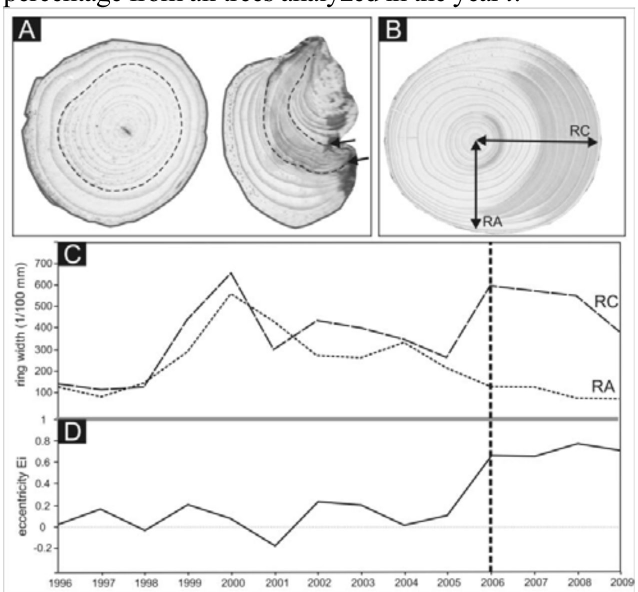

Figure 2. Indicia leading to the determination of landslide and erosion events. A – Time development of tree-ring eccentricity with a jump increase in the year of tree tilting. B – Tree-ring increment curves measured on two perpendicular sides on a tilted tree cross-section. C – Cross-section from a tilted tree with apparent dark reaction (compression) wood. D – Cross-sections from an exposed and damaged root due to erosion event (closed dashed line – boundary of the reaction to exposure, black arrows – position of the root damage).

4. RESULTS

4.1. Morphology of the studied localities

The landslide area originated in rocks dominated by soft claystones over sandstones and conglomerates. The highest positions where slope movements have occured are in the upper part of the slope where a few less distinct tension cracks have evolved. Downslope, below this zone, there is a large area of a subsided and most likely rotated block accompanied by another block in the southern part. The lowest part of the landslide area, bounded by the Tísňava stream, is dominated by plastic deformations. In some places, the stream has eroded the forefront of the landslide. For the purpose of a thorough spatial analysis of the landslide movement evolution, the landslide was into 4 morphologically distinct sectors (I – IV) in which individual trees where sampled (Fig. 3). The highest-situated sector, the largest of all the sectors, represents an area of slightly inclined surface on the highest-situated rotated landslide block. The second sector of a rather small area lies on the forefront of the above-mentioned block in the central part of the slope. Connected to the second one, the third sector occupies slightly undulating parts of the slope with numerous moist depressions. The fourth sector occupies the very forefront of the landslide, namely the positions of plastic deformations with pressure folds and cutting gullies.

Table 1. Morphometric characteristics of landslide area and gullies.

	Landslide	Gully 1	Gully 2	Gully 3
Area (ha)	0,68	x	x	x
Orientation	NW	S	S	S
Mean slope (°)	30	7	12	16
Length (m)	100	80	15	30
Max. width (m)	90	1	1,2	1,9
Altitude range (m a.s.l.)	630-690	675-690	673,5-675	650-660
Vertical distance (m)	60	13	1,5	10
Max. gully depth (m)	x	0,8	1	1

For the analysis, three connected gully segments were selected on the opposite slope (Fig. 1B, 3C). These are maximum 1-m-shallow, actively cutting and elongating gullies (Table 1). The first and longest segment of an inclination of 7° is almost 80 m long. At its end, it is connected to the second, very fresh 15 m long segment of 12° inclination. A flat alluvial fan of fine-grained material coming from the gullies has evolved below the contact of these two segments. The third gully segment, which is 30 m long, starts under this fan and is characterized by the highest longitudinal inclination of all the segments (16°). The total transversal profile of the landslide area along with the slope affected by gully erosion is given in figure 3A.

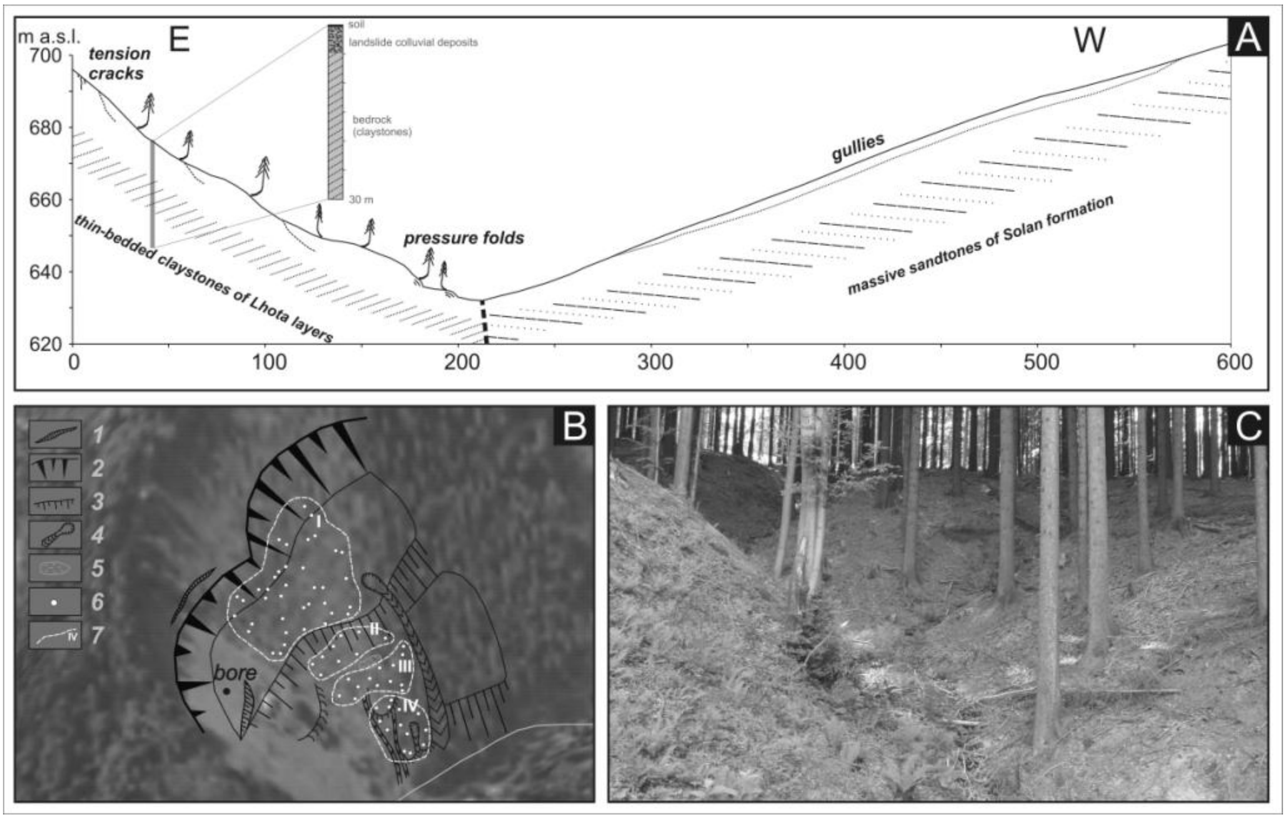

Figure 3. A – Longitudinal profile of the landslide area and gullies with a marked position of hydrogeological borehole. B – Detailed geomorphological map of the landslide area (1 – tension cracks, 2 – main scarp, 3 – distinct level within the slope, 4 – gully, 5 – moist depression, 6 – sampled tree position, 7 – boundary of partial sectors). C – character of the studied gullies (active deepening takes place at the bottoms).

4.2. Dendrogeomorphological record of landslide movement

The samples amounted to a total of 73 cross-sections from coniferous species (59 *P. abies* and 14 *L. decidua*), the oldest of which was 28 years old and the youngest one 5 years old. Average age of the sampled trees was 16.7 years (STDEV = 3.2 years). Most trees (38) grow in sector I, whereas the fewest trees (9) in sector II. The representation of individual tree species within all the sectors is presented in table 2.

Table 2. Number and type of sampled trees in individual sectors of the landslide area.

Sector	*Picea abies*	*Larix decidua*	Total
I	31	7	38
II	7	2	9
III	9	4	13
IV	12	1	13
Total	59	14	73

Initial growth of compression wood was identified in 127 cases. The oldest compression wood, which comes from the year 1997, was observed on 10 trees. Years with the most frequent occurrence of compression wood are 2002 (*It* = 56 %) and 2006 (*It* = 63 %). Other years with a significant *It* (up to 20 %) are 1997, 1999 and 2000. On the other hand, no occurrence of compression wood was found out for the years 1995, 1996 and 2003. Temporal occurrence of compression wood of trees in individual sectors is given in figure 4. Sectors I and II show a very similar development. In both cases, the most active years are 2002 and 2006 (*It* exceeds 50 %). Sector III is characterized by the lowest activity as its *It* exceeds 20 % only in the year 2006 (23 %). On the contrary, three important years related to sector IV involve 1997 (*It* > 90 %), 2000 and 2006.

Although different results were brought by the analysis of tree-ring eccentricity, there are also common features (Fig. 5). At least minimal tree-ring eccentricity was found out for all the studied years. However, there was a gradual increase in eccentricity starting in 1997 and culminating in 2006 and 2007. A similar development holds true for sector I. As for sectors II, III and IV, higher eccentricity values occur also in the first years of the reconstructed time series (1995, 1996 and 1997). Trees of sector III give the lowest eccentricity values, while a rather gradual decrease in values can be observed.

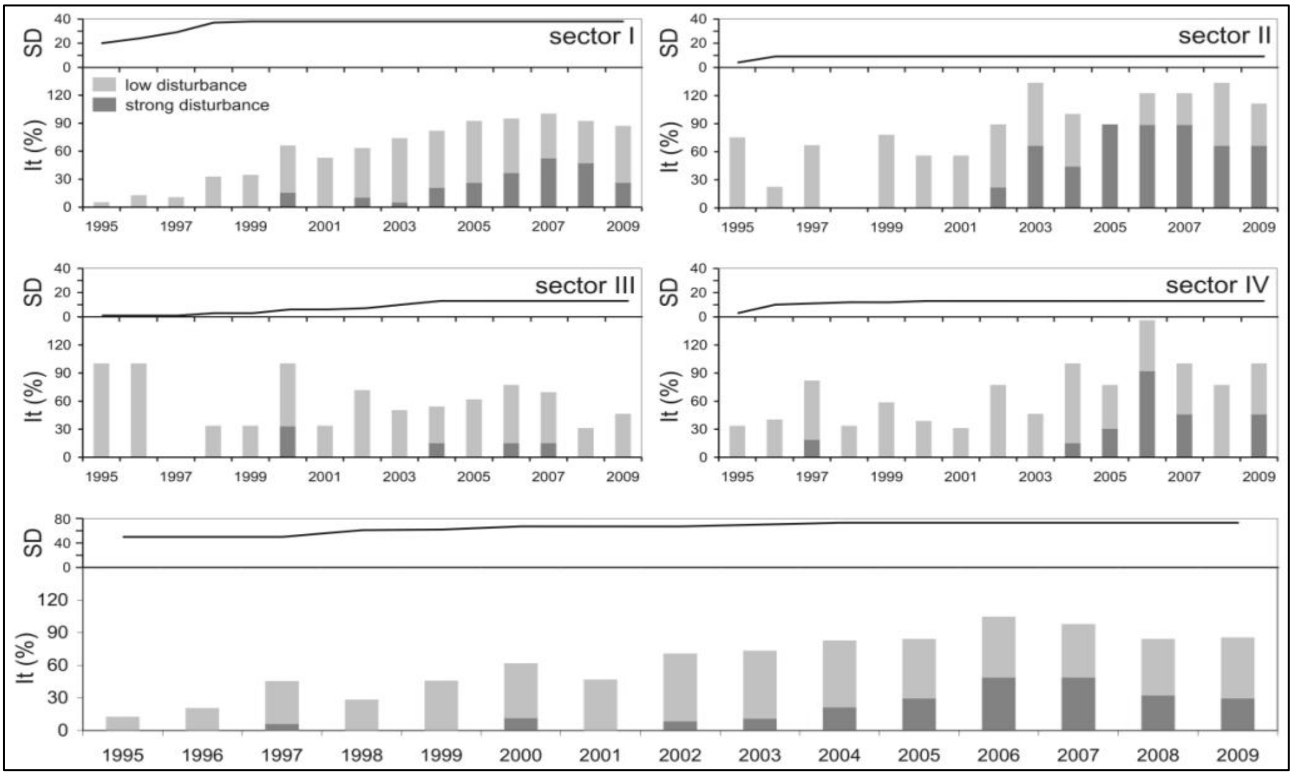

Figure 4. Development of *It* index in individual sectors of the landslide area and the landslide area as a whole (lower diagram).

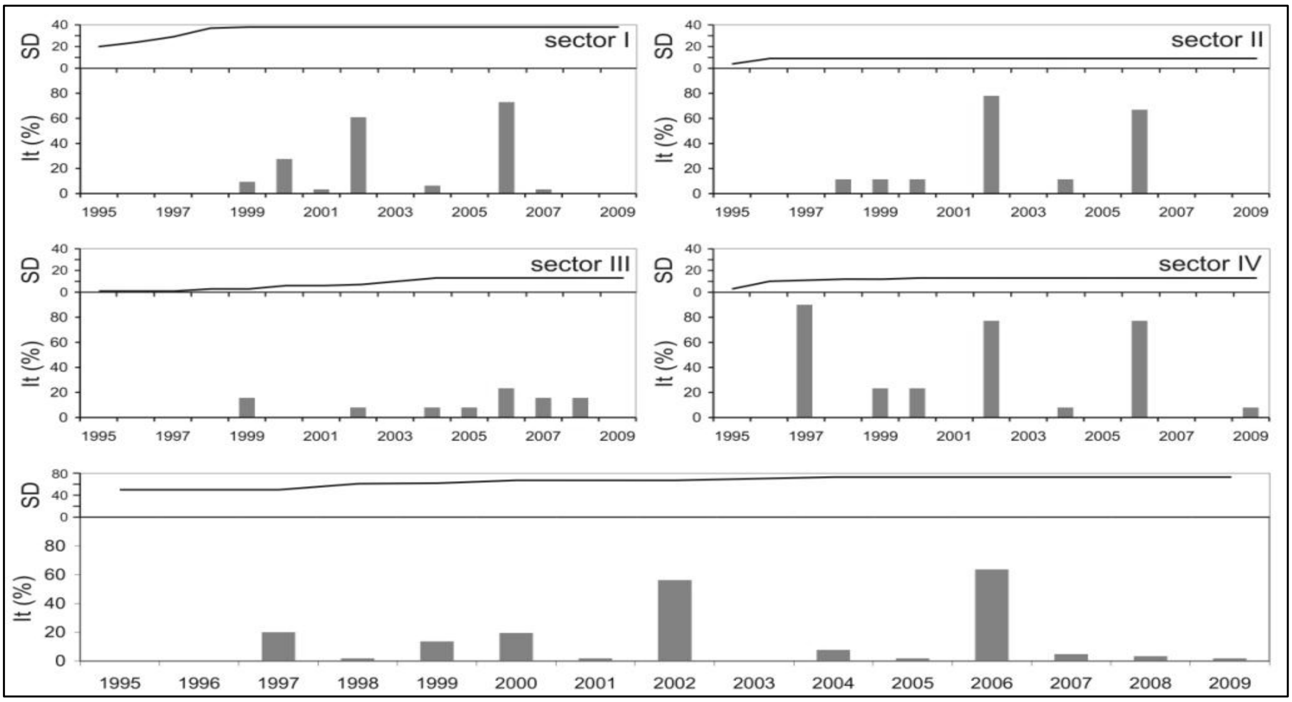

Figure 5. Sum of growth disturbances (GD) expressing eccentricity values (strong disturbance = 2, Ei>0.5, low disturbance =1, Ei=0.25–0.5) in individual sectors of the landslide area and in the landslide area as a whole (lower diagram).

4.3. Dendrogeomorphological record of erosion events in gullies

The analysis was based on a total of 21 root samples that had been taken from all the three segments of gullies, namely 10 samples from the first segment, 2 samples from the second segment and 9 samples from the third segment of the gullies (Fig. 6). The longest distance between two samples was 19 m, the shortest distance was 1 m and the average distance was 4.9 m. Average age of the sampled trees made 39.8 years (STDEV: 16.4

years). The oldest root contained 74 rings, while the youngest root 19 rings. If average oldest samples came from the third segment (48.1 years), average youngest samples were from the first segment (36.4 years). The oldest recorded erosion event came from the year 1972 and the youngest one from 2006. The samples helped to identify a total of 32 growth disturbances, on the basis of which 12 years were determined during which the gullies extended in depth and length. There were 21 cases of root exposure and 11 cases of root damage followed by scar formation.

The age of roots in the first segment ranged from 19 to 50 years. The oldest reconstructed event occurred in 1982, whereas the youngest in 2006. Average gully erosion rate (GER) reached 3.19 m/year (minimal 0.12 m/yr and maximal 19 m/yr). With regard to the second segment, in which we have only managed to identify two events (1997 and 2006), GER was 0.16 m/year. The age of roots in the third segment ranged between 30 and 74 years. The oldest recorded event occurred in 1972, whereas the youngest one in 1999. Average GER of the whole segment amounted to 0.78 m/year (minimal 0.15 m/yr and maximal 1.33 m/yr). All details related to the samples and dated events in gullies are presented in table 3.

5. DISCUSSION

The shaping of flysch Carpathian landforms is strongly affected by various types of slope processes. In the selected locality within the Vsetínské vrchy Mts, landslide movements and gully erosion on adjoining slopes were analyzed using cross-sections from 73 *P. abies* and *L. decidua* and 21 cross-sections from *P. abies* roots. Taking into account the possibilities of the analysis of tree-ring series, cross-section disks are generally considered to be more convenient than cores drilled by an increment borer because they provide a view of rings along the entire tree stem circumference (Van Den Eeckhaut et al., 2009). 73 cross-sections taken from tilted trees thus represent a valuable set for quality analysis of landslide movements.

The analysis of tree-ring series from trees occupying the landslide area made use of two common methods of assessment. Clear-cut evidence of tree tilting and its effort for compensation is the formation of wide rings of reaction wood (compression wood in case of conifers; Lopez Saez et al., 2012). Its formation on one side of the tree stem is compensated by growth suppression on the opposite side of the stem.

Table 3. Position and year of exposure of the roots and gully erosion rate in the studied gully segments.

Gully	Sample ID	Distance from gully beginning (m)	Distance from previous sample (m)	Distance from gully floor (cm)	Age of root	Date of root exposure	Date of root wounding	Gully erosion rate (m/year)
I	1	18		40	31	2006	-	
	2	26	8	48	37	1997	-	0,88
	3	28	2	30	56	1997	-	1,11
	4	33	5	30	47	1997	2006, 2000	1,67
	5	42	9	10	40	1996	-	19,00
	6	55	13	5	19	1997	-	3,00
	7	62	7	5	23	2006	-	0,70
	8	65	3	9	50	1982	1982, 2002	0,12
	9	69	4	14	23	2003	-	0,19
	10	77	8	30	38	1999	1999	2,00
II	11			30	19	2003	-	
	12		1	40	21	1997	-	0,16
III	13	1		30	70	1988	1988	
	14	3	3	42	44	1991	-	1,00
	15	5	2	51	66	1988	1988	0,66
	16	9	4	2	33	1991	1999	1,33
	17	12	3	30	74	1972	1972, 1994	0,15
	18	17	5	12	48	1999	1999	0,18
	19	21	4	21	30	1996	-	1,33
	20	26	5	37	36	1988	-	0,62
	21	29	3	42	32	1988	-	1,00

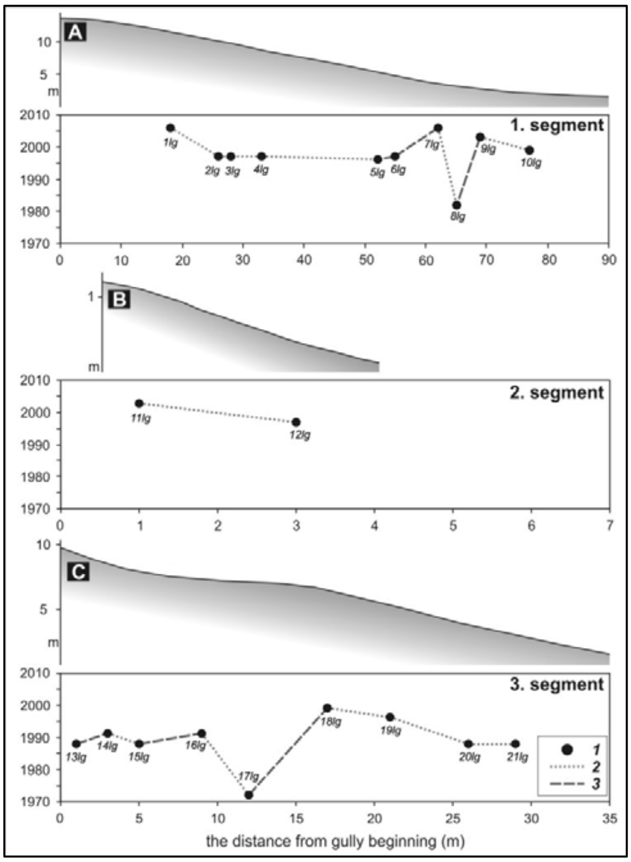

Figure 6. Results of the dating of erosion events in individual segments of gullies and their longitudinal profiles (1 – dated root sample and its ID, 2 – upward erosion section, 3 –downward erosion section).

The result of this asymmetric growth is tree-ring eccentricity. However, computed correlations between the eccentricity value and the width of rings containing reaction wood (Table 4) show that this relation is not fully clear. Significant positive correlations are only observed in case of trees from sectors III and IV. In reality, dominant display of reaction wood is not tree ring widening but anatomical changes of wood cells that strengthen their walls (Braam et al., 1987). The formation of reaction wood is therefore not always related to tree-ring eccentricity. Moreover, in our case the landslide onset is only related to the first tree-ring containing reaction wood but the eccentricity often manifests itself also during several consecutive years. The analysis of tree-ring eccentricity may thus disregard a signal that has been left in tree-ring series by landslide movements. Main attention should primarily be paid to the first tree-rings that contain reaction wood. The analysis of eccentricity brings additional information for the outline of the evolution of landslide movements in long time horizons.

Table 4. Correlation (r) between tree-ring eccentricity (Ei) and tree-ring width involving reaction wood.

	Sector I	Sector II	Sector III	Sector IV	Average value
r	0,27	0,17	**0,54**	**0,52**	0,37
n	38	9	13	13	73

The occurrence of reaction wood shows that well-marked acceleration of some parts of the landslide body took place in three individual years (1997, 2002 and 2006). A similar record from sectors I and II is a result of compact behaviour of this part of the landslide area. On the contrary, sector III appears to be the most stable part of the landslide. This fact is supported by the sector's morphology, which is, unlike the two previous sectors, characterized by a gentler gradient. Sector IV represents the most active part of the landslide as the *It* reaches the highest values (over 80 %). This is most likely caused by not only great steepness of this sector due to erosion activity of the stream but also the character of plastic deformations in this part of the landslide area. Contemporary landslide activity is only limited to locally accelerated creep movements near the surface. This finding is supported by the analysis of a core sample coming from a hydrogeological borehole drilled in the upper part of the landslide that revealed the presence of max. 4-m-thick slope colluvial sediments on underlying clay stratum.

Ring eccentricity gradually increased and then decreased after culminating in 2006. Accordingly, the activity of slope movements increased gradually, but since the last acceleration in 2006 it has been ceasing. Similar evolution of landslides in flysch rocks has been recorded by Pánek et al., (2011) and Klimeš et al., (2009). Attention needs to be paid to the evolution of landslides characterized by locally reactivated long-run creep movement since potential catastrophic acceleration of a deeper landslide is not excluded (Petley & Allison, 1997; Geertsema et al., 2006; Hancox, 2008; Bigot-Cormier et al., 2005).

Similarly to the landslide activity, gully erosion is a relatively widespread process on flysch rocks (Stankoviansky, 2003). However, unlike landslides, the information on its evolution in Carpathian flysh belt is relatively scarce (Šilhán & Stacke, 2011). Three gullies analyzed in this study thus represent the first attempt at dendrogeomorphological reconstruction of the development of a gully system in Carpathian flysh belt. The upper 50 m of the first gully segment evolved due to upward erosion between 1996 and 2006.

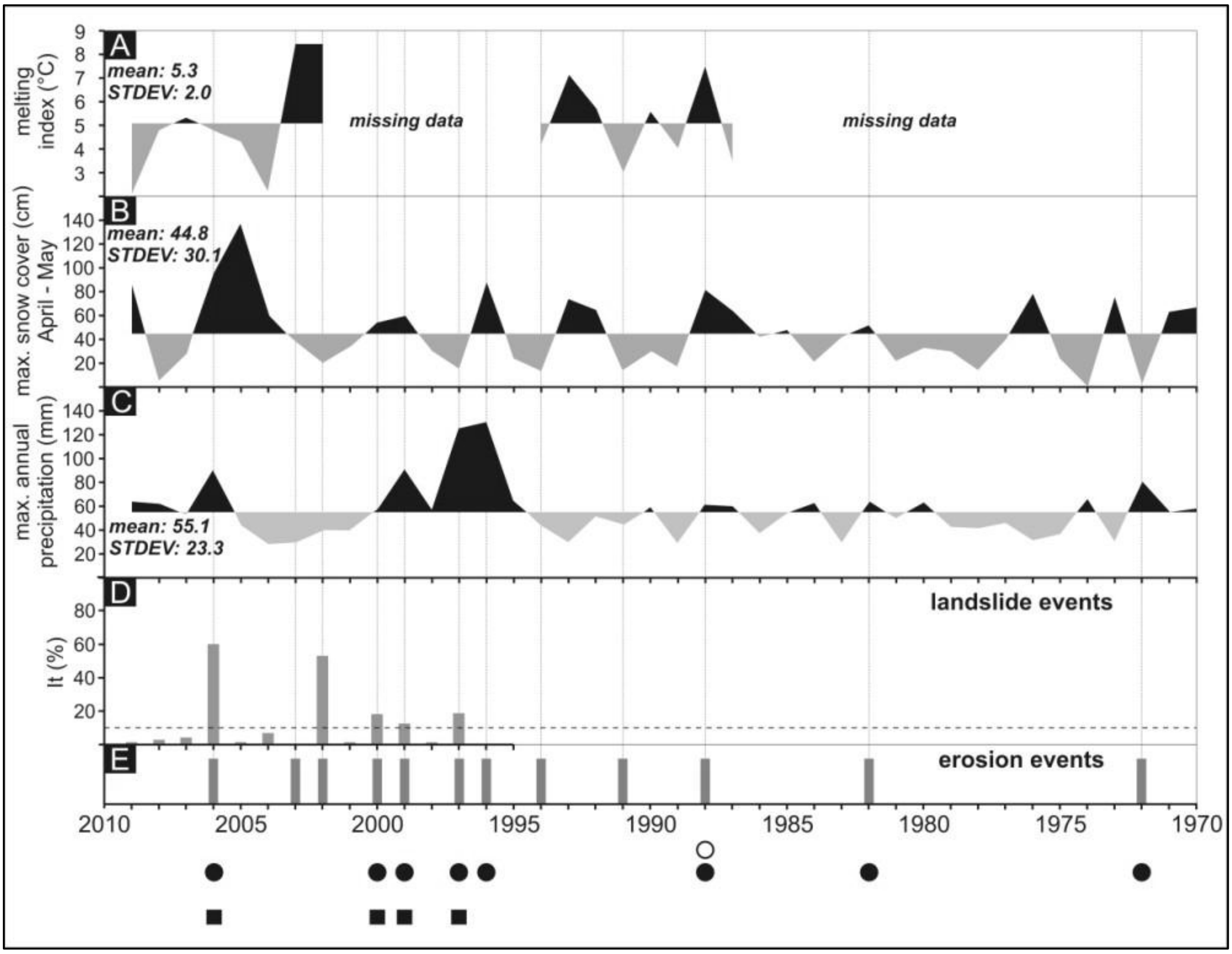

Figure 7. Comparison of the occurrence of dated processes (landslide events – D, erosion events – E) using selected meteorological indices. A – melting index (difference between average temperatures in April and May, Zielonka et al., 2008) B – maximum snow cover thickness in April and May, C – maximum daily precipitation total per year (black spots – erosion event years with above-average daily precipitation; white spots – erosion event years with above-average melting index combined with snow cover occurrence; black square – landslide event years with above-average daily precipitation).

Its lower part witnessed the alternation of the sections of upward erosion and the sections of downward erosion. The second gully segment fully developed due to upward erosion. Similarly, the lower part of the third segment originated due to upward erosion.

Its upper part then shows the sections of upward erosion alternating with the sections of downward erosion. This reconstruction reveals that upward erosion is typical of steeper parts of gullies with a concave longitudinal profile. On the other hand, less steep parts of gullies with a convex profile become affected by both upward and downward erosion. Moreover, the development of concave parts is faster and without greater idle time. Similar dependence of gully's longitudinal profile and the direction of erosion have also been found out by Malik (2008), yet on loess substratum.

GER within all the gullies is very changeable. Average value of all the gullies – 1.95 m/year – is surprisingly high in comparison with other erosion prone regions of the world, e.g. loess plateau in China 0.01–0.20 m/year (Wu & Hong, 2005), Catalonia 0.02–0.08 m/year (Martinez-Casasnovas, 2003) or Southeast Spain 0.1 m/year (Vandekerckhove et al., 2001). High average value is caused by extreme GER in the central part of the first gully segment (19 m/year). Without this anomaly, the average GER is 0.89 m/year, which is a comparable value to GER in Southern Poland 0.63 m/year (Malik, 2008). Extreme elongation of the gully took place in 1997 when the highest 24-hour precipitation total was recorded in the history of the nearest meteorological station of Rožnov pod Radhoštěm.

Numerous findings on triggering factors of slope processes in Carpathian flysh belt (Bíl &

Müller, 2008; Šilhán & Pánek, 2010; Pánek et al., 2011; Baroň et al., 2004; Klimeš et al., 2009) made it possible to analyze short-term extreme precipitation totals and fast spring snow melt (expressed by maximal snow cover height in April and the difference in average temperatures in April and May; Zielonka et al., 2008) (Fig. 7). The results show that 8 out of 12 identified erosion events occurred in the year of an extreme precipitation event. This triggering factor is closely connected to landslide movements in 4 out of 5 events with $It \geq$ 10 %. On the other hand, fast spring snow melt only caused the erosion event of 1988.

6. CONCLUSION

In a selected locality of the Czech Carpathian flysh belt, landslide movements were dated using cross-sections from 73 tilted trees along and erosion events in gullies using 21 cross-sections from exposed roots. The reconstruction concerned a 15-year time series of landslide activity and a 40-year time series of erosion events.

The study compared the method of landslide movement assessment on the basis of tree-ring eccentricity and the method observing initial occurrence of reaction wood. Obtained results show that these two parameters cannot clearly be placed into a mutual relationship. It is events that induce the formation of reaction wood that are considered to be a more important indicator of landslide activity. Within the studied landslide locality, five events of this type were identified during which at least 10 % of trees became tilted. Four out of five of these events were most likely caused by a short-term precipitation event. Spatial distribution of tilted trees and analysis of a borehole made into the landslide body helped to identify the character of movements and define them as surface creep movements locally accelerated at extreme precipitation events.

Development of the gully network was very fast in conditions of an average GER of 1.95 m/year. The character of erosion depends on the longitudinal gully profile. If upward erosion prevailed in steep concave sections, less steep convex sections were dominated by alternating upward and downward erosions. Similarly to landslide movements, major triggering factor in the case of gullies was extreme short-term precipitation. There was only one case in which the gully erosion was induced by fast spring snow melt. The occurrence of both processes was thus related to the same type of meteorological event. Still, the very type of the process was predisposed by local morphometry and different geological substratum.

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