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DENDROCHRONOLOGICAL RECORD OF COUPLING BETWEEN LANDSLIDES AND ERODING STREAM CHANNEL (WESTERN OUTER CARPATHIANS, CZECH REPUBLIC)

Abstract. Dendrochronological datings of landslide activity on slopes and of fluvial erosion in adjacent channel were performed. Landsliding was dated from the tree-ring eccentricity. Erosion was dated using the wood anatomy of roots. The obtained results on the temporal occurrence of these geomorphic processes were compared and then confronted with the precipitation record. Analysis of the temporal relations between landsliding, erosion and rainfall has revealed that two types of repeating sequences occur in studied sites: (1) rainfall → landsliding → channel erosion, (2) rainfall → channel erosion → landsliding. In the first type landsliding triggered by rainfall delivers colluvium onto the valley floor and causes its narrowing, which in turn triggers increased channel erosion. In the second type channel erosion triggered by rainfall disturbs the slope equilibrium and causes landsliding. Coupling between landsliding and channel erosion was proved using dendrochronology but also its influence on the relief of the study sites was observed. Channel shifting, forced sinuosity and increased erosion of the slopes opposite the active landslides occurred. The results suggest that the repeating of the described sequences over longer periods of time can lead to a general widening of the valley floor at the expense of slopes and to a gradual change of the valley cross profile from narrow, V-shaped into a wide flat-bottomed one.

Key words: landsliding, fluvial erosion, slope-channel coupling, dendrochronology, the Moravsko-slezské Beskydy Mts.

INTRODUCTION

Slope-channel coupling is often considered as a fundamental aspect of the functioning of geomorphic systems (Harvey 2002). Landslide-induced displacement of debris from hillslopes to the drainage system has an episodic nature and is usually started by excessive rainfall and snowmelt (e.g. Froehlich, Starkel 1995; Johnson et al. 2008), earthquakes (e.g. Korup 2005; Fort et al. 2010) but also by stream erosion undermining slopes (e.g. Azañón et al. 2005; Fort et al. 2010; Lévy et al. 2012). In mountain areas, hillslopes and channels may form potentially strongly coupled systems where the transmission of energy and matter between landscape units is not disturbed by buffers, e.g. floodplain features (Brunsden 1993; Harvey 2001). Colluvium may be delivered directly from adjacent hillslopes during landsliding events and from the channel banks due to river erosion (e.g. Nakamura et al. 2000; Hassan et al. 2005). Sediment supplied from slopes and stored within the channel is the main factor determining channel form and pattern downstream of the hillslope sediment delivery zones (Owczarek 2008). Excessive lateral sediment input is responsible for the overloading of river channels resulting in aggradation, reduction of channel cross-profile area, and lateral instability leading to channel avulsions (Korup 2004).

Recording the occurrence of slope-channel coupling is difficult, because it is difficult to determine the precise temporal and spatial relations between events of colluvium delivery from a landslide slope and fluvial erosion within a valley floor. However, by using dendrochronological methods we can date mass-movement events (by dating tree-ring eccentricity) and channel erosion (by dating root exposure and wounding) to compare the time of their occurrence within one valley cross-profile (Fig. 4). The aims of the study were: to determine the temporal relations between the occurrence of landsliding on slopes and erosion in stream channels, to define the mutual relation between slope and channel processes and its importance in shaping the relief of the studied mid-mountain area.

STUDY AREA

THE MORAVSKOSLEZSKÉ BESKYDY MTS.

The study was conducted in the south-eastern part of the Moravskoslezské Beskydy (the Western Outer Carpathians, Fig. 1). The bedrock is composed of flysch rocks of the Silesian Nappe and Magura Nappe (Menčík et al. 1983). The relief of the Moravskoslezské Beskydy is determined by geological structure, shaped by slope (e.g. Klimeš et al. 2009; Pánek et al. 2011, 2013; Šilhán et al. 2013) and fluvial (e.g. Galia, Hrádecký 2011; 2012; Galia et al. 2012) processes. Landsliding is especially promoted by alternating occurrence of sandstone and mudstone beds in flysch rocks together with the occurrence of a thick mantle of regolith and slope deposits (Halicki 1955; Czudek 1973; Czudek, Demek 1976; Starkel 1995). In the Moravskoslezské Beskydy high precipitation totals are recorded (avg. annual precipitation: >1400 mm, Štekl et al. 2001). Heavy rainfalls and spring melts cause abrupt floods on rivers and streams (Štekl et al. 2001). Vegetation cover in the area is strongly transformed by human activity. Natural forests were replaced with forest plantations of Norway spruce (*Picea abies* Karst.; Matuszkiewicz 1993).

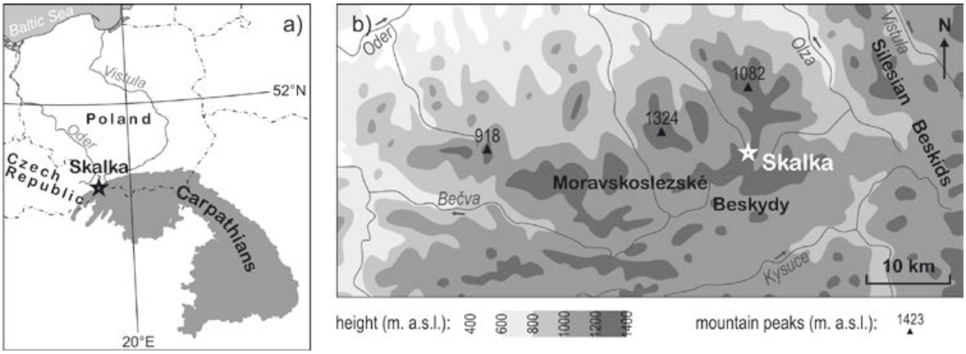

Fig. 1. Location of the study area, Skalka catchment: a) within the Carpathian Mountains and in the Czech Republic, b) in the Moravskoslezské Beskydy Mts.

RELIEF OF THE STUDY AREA

The study sites (c. 750 m a.s.l.) are located in the catchment of the Skalka stream (tributary of the Morávka river, the Oder basin), on NE slopes of the Kozí hřbet (981,5 m a.s.l., Figs. 1b, 2). Bedrock of the Skalka catchment is mainly composed of thin- and medium-bedded shales and sandstones (the upper Godula beds). In the uppermost part of the catchment outcrops of sandstones and arcosic conglomerates (the Istebna beds) occur (Fig. 2, Interactive Geological Maps... 2003). Catchment surface is partially covered by alluvium and slope deposits, including landslide colluvium (Interactive Geological Maps... 2003). The catchment is strongly dissected by asymmetric drainage network (Fig. 2.).

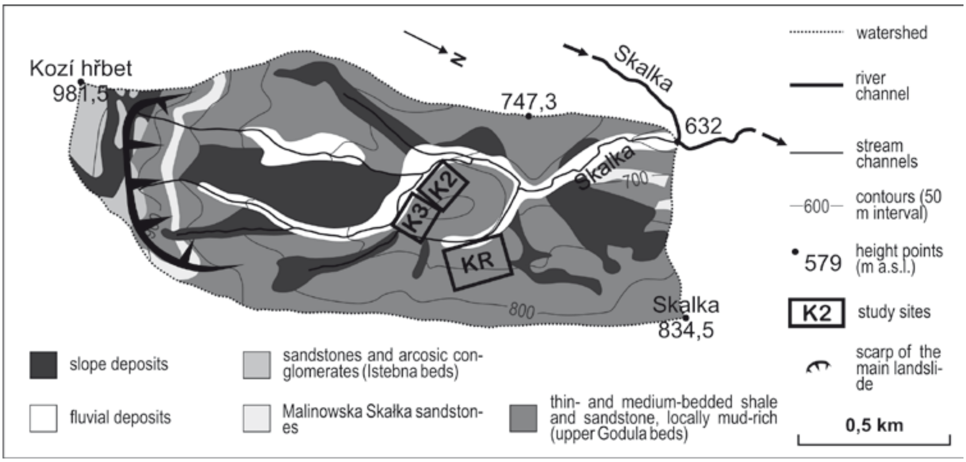

Fig. 2. Relief and bedrock of the Skalka catchment with the location of study (K2, K3) and reference (KR) sites

In the valley head of the Skalka stream a large landslide is located. The height of the main scarp (Fig. 2) is up to 75 m and scarp inclination reaches 75–80°. Surface of the landslide body below has lower inclination (avg. 30°). Landslide body is dissected by numerous erosional channels and gullies with V-shaped cross-sections, high gradients, uneven long profiles and various depth (from <1 m in the upper part of landslide to 4–5 m in the lower part).

The lowest part of the landslide body forms a large colluvium mound (200 m wide, 120 m long, 60 m high) with small secondary landslide forms with slope trenches, cracks, secondary scarps, landslide tongues descending into stream channel (Fig. 3) and step-like cross profiles (Fig. 4). Two of them (Figs. 2, 3) were the subject of this study. K2 and K3 study sites where we collected samples for dendrochronological dating comprise landslide slopes, adjacent sections of valley floors, channels and opposite slopes. On slopes opposite to the studied landslides shallow landslides and landslips (Fig. 11) also occur.

MATERIALS AND METHODS

DATING LANDSLIDE ACTIVITY ON SLOPES

On secondary landslides at sites K2 and K3 (Figs. 3, 4) we collected dendrochronological samples (cores, e.g. Fig. 5 c) from stems of Norway spruce (*Picea abies* Karst.). Two cores were taken from each stem (on up- and downslope sides of stems). We sampled all trees growing within studied landslides (K2: 21, K3: 19 trees). At site K2 samples were taken mainly in the central and lower

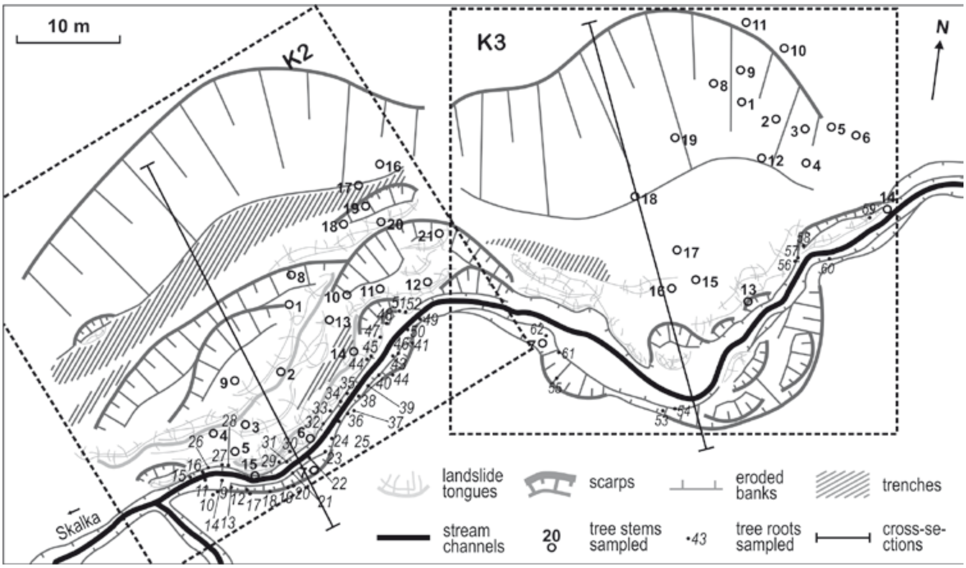

Fig. 3. Relief of the K2 and K3 study sites with the location of sampled trees, tree roots and slope cross-sections (Figure 4)

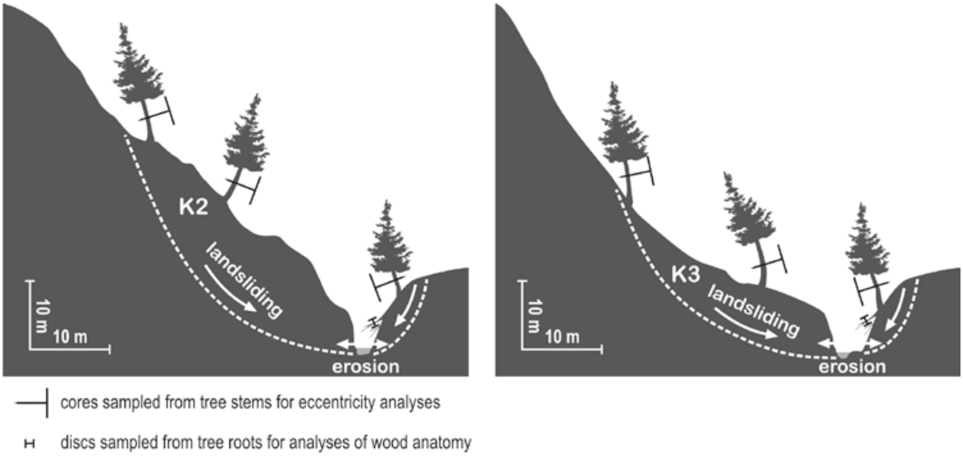

Fig. 4. Cross-sections of landslide slopes and stream channels at K2 and K3 study sites with a scheme of the conducted dendrochronological sampling

part of the landslide body, also in the NW part of the landslide: in the upper part of the landslide tongue and on slope trench. At site K3, samples were taken from the eastern part of the main scarp and from the middle and lower part of landslide body. On both sites we also sampled trees growing on opposite slopes, on landslip scars (Figs. 3, 4).

Cores were polished using sand paper and tree-ring widths were measured (LinTAB 6 equipment, TSAPWin Professional 4.65, with 0.01 mm accuracy) for up- and downslope sides of stems. Using the method of eccentricity index of tree rings (W i s t u b a, M a l i k 2011; M a l i k, W i s t u b a 2012; W i s t u b a et al. 2013) we determined the occurrence and timing of landsliding on the studied slopes (causing trees to tilt and develop eccentricity). Dating was conducted using reference thresholds calculated from 12 trees sampled on a stable reference slope (KR) located outside the main landslide and devoid of landslide relief.

Dating procedure involved measurements of tree-ring widths on both sides of tree stems (downslope: D [mm], upslope: U [mm], year (annual tree ring): x) which were next recalculated into eccentricity of tree rings (E [mm]) and eccentricity index of tree rings (Ei [%]) with the use of the following formulae:

$$Ex\ [mm] = Ux - Dx; \quad [1]$$

when Ex [mm] > 0: upslope eccentricity; $Eix\ [\%] = (Ex/Dx) \times 100\% > 0;$ [2a]

when Ex [mm] = 0: lack of eccentricity; $Eix\ [\%] = Ex\ [mm] = 0;$ [2b]

when Ex [mm] < 0: downslope eccentricity; $Eix\ [\%] = (Ex/Ux) \times 100\% < 0;$ [2c]

Eccentricity index was calculated for each annual ring in the collected samples. The moments of slope movement are recorded on the eccentricity index graphs of single samples (e.g. Fig. 5 e) as abrupt, year-after-year changes of the course of the curve. The changes were analysed using the yearly variation of eccentricity index (vEix [%]) calculated as follows:

$$vEix\ [\%] = Eix - Eix\text{-}1; \quad [3]$$

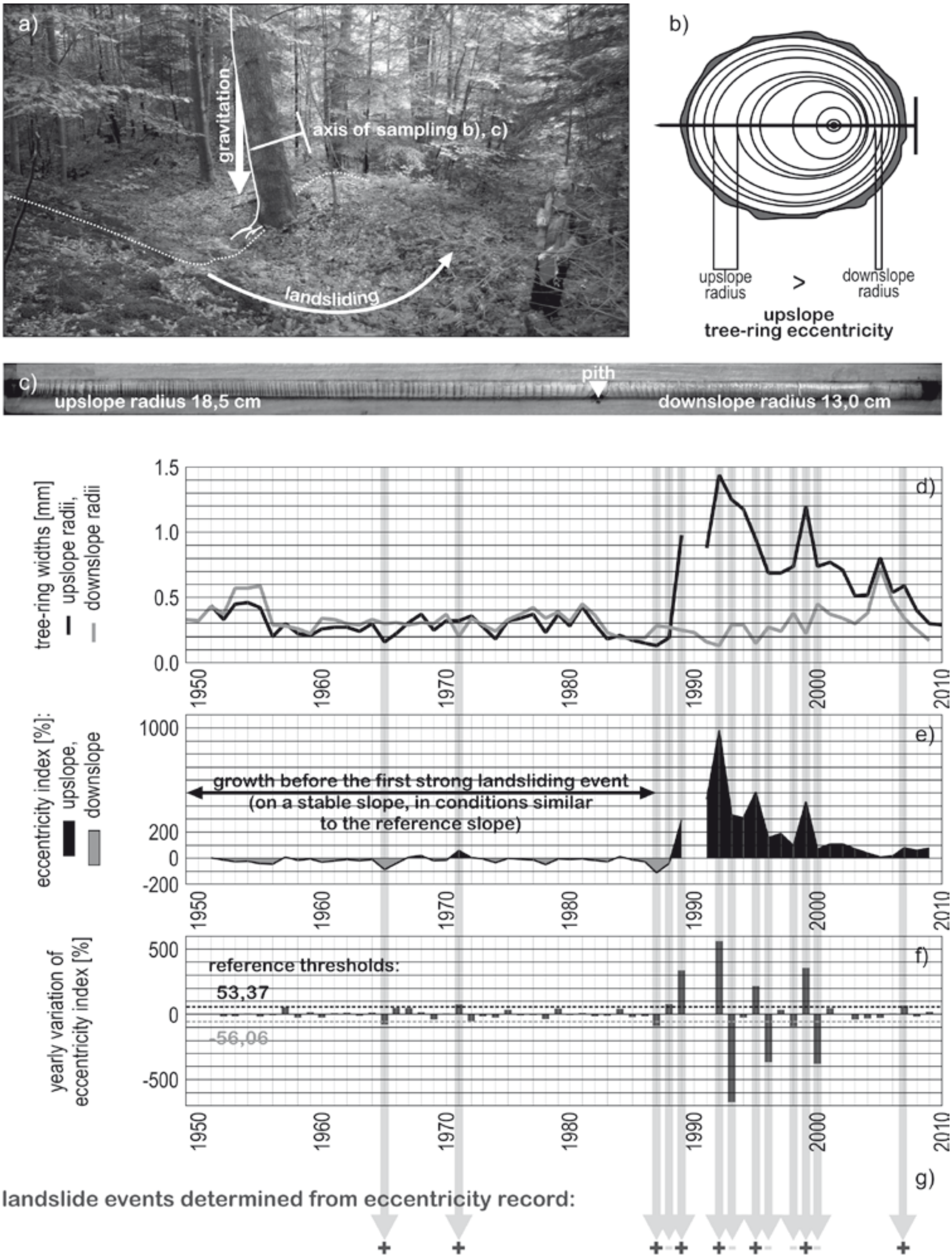

Fig. 5. a) Tree tilted upslope by mass movements on a landslide slope. b) Cross-section of a stem of a tree tilted upslope. c) An example of a core sampled from a tree tilted upslope with a clear upslope stem eccentricity. d) Tree-ring widths measured on up- and downslope sides of a stem tilted upslope. e) Values of eccentricity index calculated from tree-ring widths. f) Values of yearly variation of eccentricity index compared with reference thresholds. g) Landslide events dated using d-f graphs

Bar graphs of the yearly variation of the index were created for individual samples (Fig. 5 f). Results from the reference slope were used for dating landslide events. Among reference data arithmetical means and standard deviations were calculated separately for the set of increases (yearly variation vEi >0), and decreases (vEi <0). The values of means plus deviations are used as reference thresholds (Fig. 5 f) for determining the most distinct, abrupt changes of eccentricity index value at the study sites. After considering the directions of changes (only increases into positive values and decreases into negative values can be included), these thresholds were used for dating the most probable time of landslide activation on the studied slopes (Fig. 5 g). Cases of year-after-year decreases of index values within positive value range or increases within negative value range were interpreted as tree recovery, and return into balance after periods of destabilization by the mass movements.

DATING EROSION IN STREAM CHANNELS

On stream banks within study sites K2 and K3 (Figs. 3, 4) we collected samples (discs, Figs. 6 b) from roots of Norway spruce (*Picea abies* Karst.) exposed in

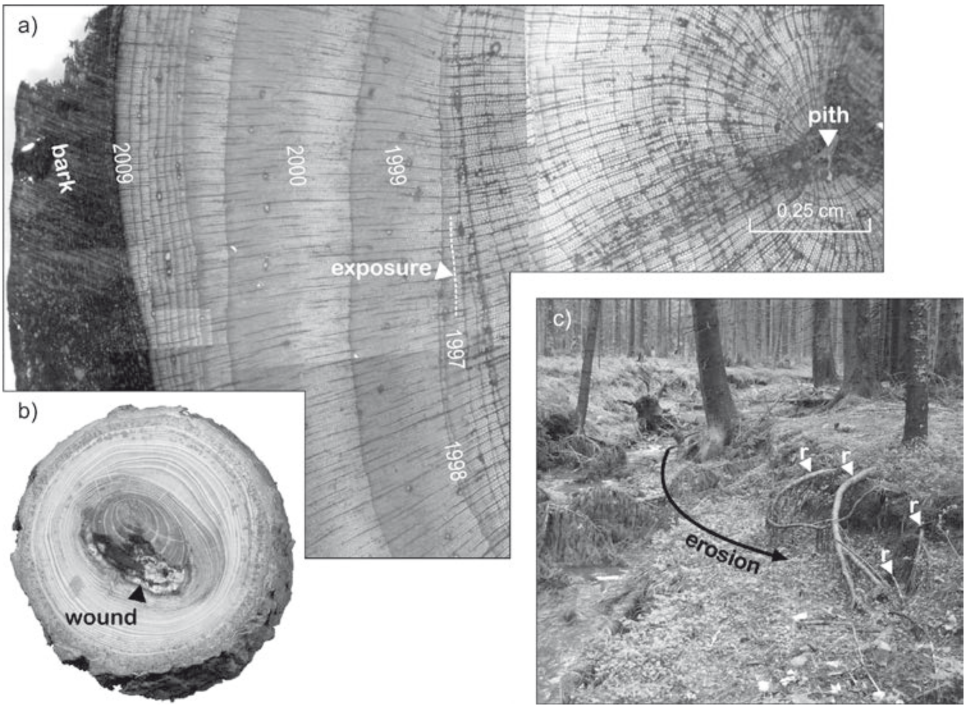

Fig. 6. a) Thin section of a root exposed by fluvial erosion during flood in July 1997. b) Disc sampled from a spruce root with a scar (healed wound) on a cross-section. c) Spruce roots exposed by erosion in a stream bank

erosional dissection of the Skalka stream. We sampled all roots available at the study sites (K2: 44, K3: 10 roots). At site K2 roots are evenly distributed at the toe of the studied landslide and on the opposite bank of the Skalka stream. Samples were collected at different elevation above the channel (up to 4 m above the valley floor, (Fig. 11). At K3 sites samples were taken low on the valley bottom and stream banks, both at the landslide toe and on the opposite bank.

In the collected samples we determined dates of root exposure from the soil cover and dates of root wounding by coarse material during floods. The dating of erosion was carried out according to the procedure described by I. Malik (2006) and H. Gärtner (2007). Discs were polished using sand paper and then examined under a stereomicroscope in search for a sudden decrease of cell size and sudden appearance of late wood in tree rings following exposure.

ANALYSIS OF PRECIPITATION AS A TRIGGERING FACTOR AND ANALYSIS OF COUPLING BETWEEN LANDSLIDING AND EROSION

To determine the conditions in which landsliding and erosion took place, dendrochronological datings were compared with monthly precipitation totals recorded at the station of Lysá hora (located at 1324 m a.s.l., 11 km from the study sites, Fig. 1) in the period 1947–2011. We considered May to September precipitation that exceeded average values and thus could have been a trigger for erosion and landsliding. We have also included data published by J. Štekl et al. (2001) on extreme daily rainfall totals recorded in the Skalka catchment.

Temporal relations of landsliding, erosion and rainfall were presented as time sequences. The sequences were determined by identifying a heavy precipitation event and analysing the occurrence of landsliding and erosion in the following years in search for any regularities.

RESULTS

DENDROCHRONOLOGICAL RECORD OF LANDSLIDING IN K2 AND K3 SITES

The oldest landsliding event at site K2 occurred in 1954 (Fig. 7). The obtained datings show that the most intensive landsliding occurred in: 1977, 1980-82 (max. 1981), 1993 and1997-98. The proportion of trees showing reaction to landsliding at site K2 did not exceed 10% in single years and reached a maximum of 40% in 1981. The oldest landsliding event at site K3 occurred in 1940 (Fig. 7). Dating results suggest that K3 landslide was the most active in 1940, 1943, 1948, 1980–81 (max. 1981), 1985–86 (max. 1985), 1994–96 (max. 1996), 2009. During the most of the period 1940–2009 the share of trees showing reaction to landsliding in single years did not exceed 10%, reaching 33.33% in 1996.

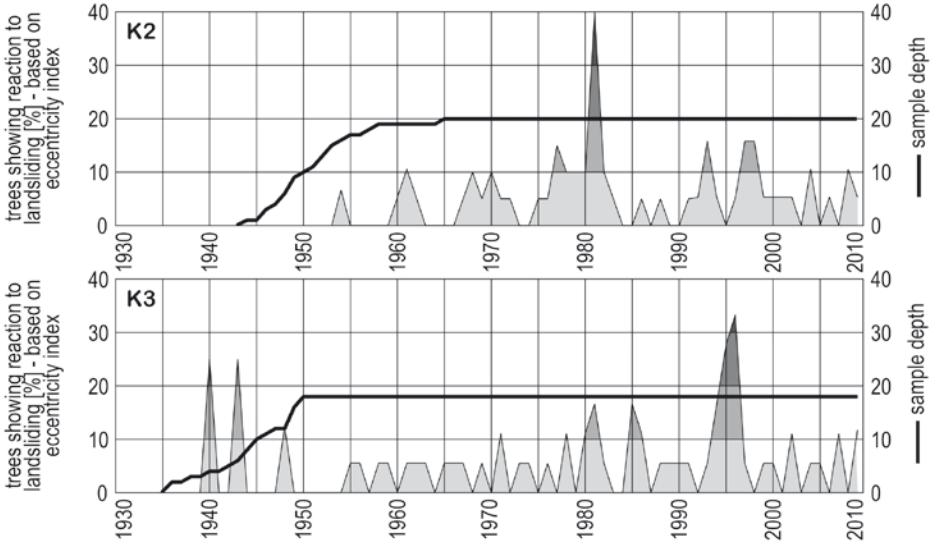

Fig. 7. Per cent of trees showing reaction to mass movements on K2 and K3 slopes compared to the sampled population

Landslide events determined on both landslide slopes do not fully coincide. The exception is the 1981 event, clearly recorded on K2 slope and less strongly represented on K3 slope. On both studied landslides reaction of trees to landsliding clusters in short periods (most dendrochronological events occurred in 1980–82 – K2, 1994–96 – K3, Figs. 7, 8). We have also detected weaker events of mass movement on both slopes to which markedly fewer trees reacted (K2: 1977, 1993, 1997–98, K3: 1980–81, 1985–86, Figs. 7, 8). Dated landslide events are separated with longer periods (up to decades-long) for which we recorded only single symptoms of landslide activity (e.g. 1983–1992 on K2 site, Fig. 8).

DENDROCHRONOLOGICAL RECORD OF EROSION AT SITES K2 AND K3

In the Skalka channel, at site K2, the oldest event of root exposure/wounding was dated to 1949. Significant erosion events were found in (Fig. 8): 1973, 1975, 1977, 1979 (the strongest one), 1986, 1989, 1991, 1997 and 1999. At site K3 the oldest event of erosion was dated to 1949, and significant events occurred in 1977, 1986, 1989 and 1995 (Fig. 8).

Only the events in 1977, 1986 and 1989 occurred in both studied sections of the Skalka channel (Fig. 8). The dendrochronological events of root exposure and wounding are dispersed in time (especially at K2 site). Apart from the above-mentioned years with well-documented erosion events we also found evidence of root exposure/wounding in other periods. In the case of site K2 dendrochronological events of erosion occurred each year in the periods 1977–1994,

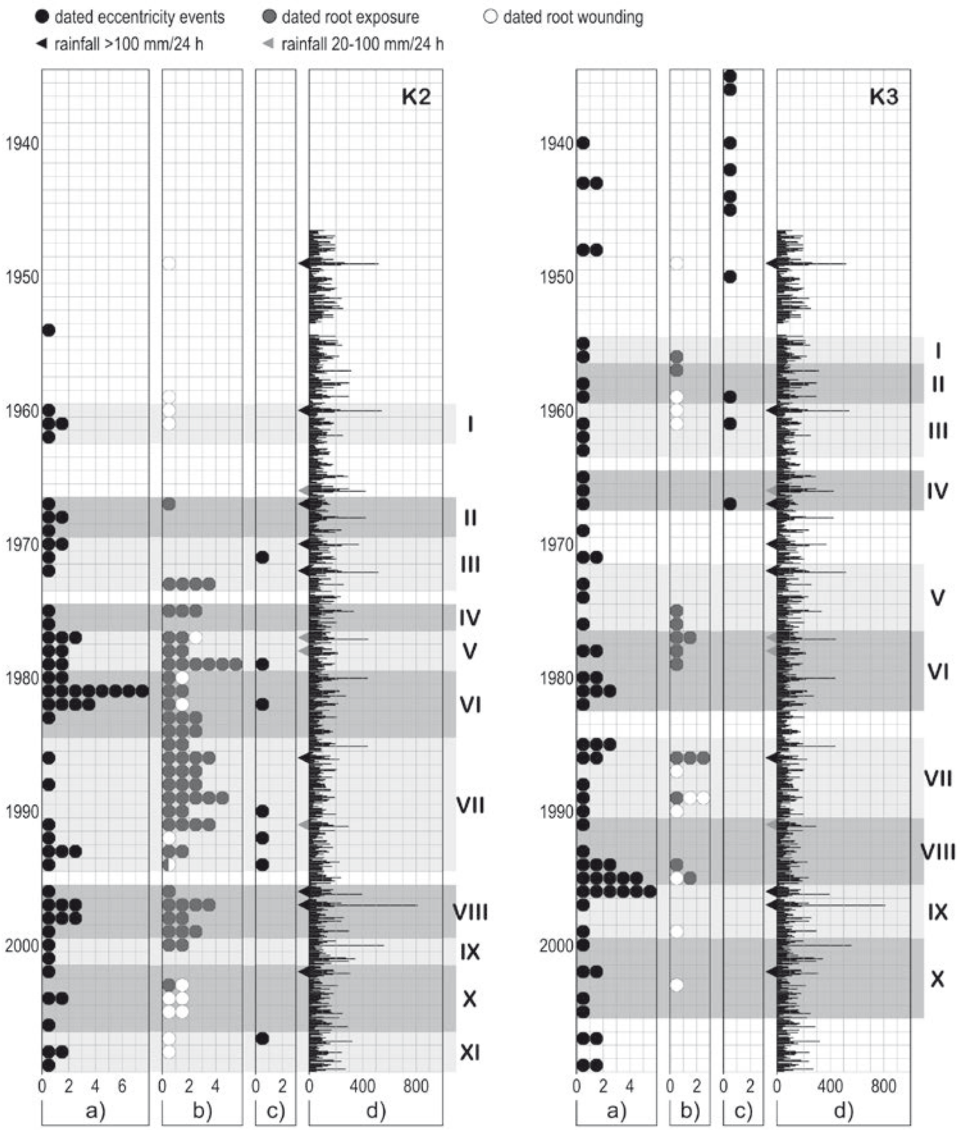

Fig. 8. Results of dendrochronological dating at sites K2 and K3: events of eccentricity development due to ground instability on landslides (a) and on opposite slopes (c), events of root exposure and wounding due to erosion (b) compared with precipitation record on Mt. Lysá hora – monthly precipitation totals, extreme daily precipitation totals (d). I–XI, I–X: sequences determined from rainfall events, landsliding and erosion

1996–2000 and 2003–2005. Also in the case of site K3 we were able to determine the periods during which at least one root was exposed or wounded due to fluvial erosion each year (1956–61, 1975–79).

DISCUSSION

INTERPRETATION OF LANDSLIDE AND EROSION ACTIVITY BASED ON THEIR TEMPORAL VARIABILITY AT STUDY SITES

The obtained results suggest that using dendrochronological methods allowed to determine the most significant events of landsliding on the study slopes K2 and K3; as well as some secondary events with fewer trees showing reaction to ground instability. Presence of periods with single eccentricity events dated each year suggests that gradual and continuous ground movements occur on the studied slopes year after year.

Besides years with significant erosion we also detected numerous years with single events of root exposure or wounding. High dispersion of dendrochronological events recording erosion in the studied sections of the Skalka channel implies nearly continuous low- to medium-intensity erosion, similarly as in the case of landsliding.

The minor events of landsliding and erosion, which occur every year at the study sites, can be triggered by e.g.: snow melt, precipitation of average intensity or, indirectly, by coupling of landslides and eroding stream channel. E. Gil and A. Kotarba (1977) found that if undermined by streams, shallow landslides on valley sides can be permanently active.

Landsliding and erosion events were dated at the study sites located very close to each other, in the same catchment with identical hydrological and meteorological conditions (identical amounts of precipitation, nearly identical catchments supplying channels with water). This eliminates the impact of spatial variability of precipitation as a control on the intensity of landsliding and, in particular, erosion. Despite this fact, the datings of landsliding and erosion obtained at both sites overlap only partially. This suggests significant local variability in the occurrence of landsliding and erosion, which may be influenced by a factor other than the spatial distribution of precipitation.

PRECIPITATION CONDITIONS AFFECTING LANDSLIDING AND EROSION AT THE STUDY SITES

Comparison between dendrochronological datings and precipitation record shows that events of landsliding and erosion at the two studied sites were triggered by rainfall of diverse type and intensity e.g. (Fig. 8):

- landsliding in 1977 (K2), 1997 (K2) and 1985 (K3) was triggered by long-term, heavy rainfall (precipitation significantly exceeding average monthly totals),
- landsliding in 1996 (K3) was triggered by torrential, short-lasting rainfall,
- erosion in 1977 (K2, K3) and 1997 (K2) was triggered by long-term, heavy rainfall (precipitation significantly exceedingaverage monthly totals),
- erosion in 1986 (K2, K3) and1991 (K2) was triggered by torrential, short-lasting rainfalls.

Most of the dated events of erosion and landsliding match the occurrence of extreme rainfall (Fig. 8). M. Długosz and P. Gębica (2008) as well as E. Gorczyca and K. Krzemień (2008) also link the development of landslides on valley sides in the Carpathians with heavy rainfall. However, we also found that some events of landsliding or erosion (with strong dendrochronological record) do not coincide with the occurrence of extreme monthly or daily precipitation. The 1979 erosion event, evidenced with the strongest dendrochronological record, does not coincide with extreme precipitation. Dendrochronologically dated landsliding events in 1982, 1993, 1994 and 2009 do not match extreme rainfall either. These events were recorded one year (2009) or two-three years (1982, 1993, 1994) after heavy rainfall events.

Due to the high precision of dendrochronological dating of the landslide activity and erosion, it is possible that geomorphic processes at the sites K2 and K3 also depend on factors other than the occurrence of extreme rainfall. The level of the long-term saturation of the soil and bedrock can be very important controls on landsliding which occur in the years with average rainfall. Yet, significant temporal dispersion of landsliding and erosion, and the fact that they are active almost permanently also suggest that at the studied sites special conditions occur in which these geomorphic processes can also be triggered by average precipitation.

THE CYCLICAL OCCURRENCE OF RAINFALL, LANDSLIDING AND EROSION AT THE STUDY SITES

We considered the coupling of landslide activity and erosion as an additional factor triggering the processes during periods with average precipitation and resulting in a significant local variability in the intensity of the processes at the study sites. Apart from:

- dispersion of dendrochronological events of landsliding and erosion in time,
- asynchronous occurrence of landsliding and erosion in adjacent sites,
- divergent occurrence of landsliding and erosion in comparison with rainfall record,

we also found that landsliding and erosion occur in repeating cycles and probably are interdependent. The sequences of succession of landsliding and channel erosion that begin with rainfall events (Figs. 8, 10) can be divided into two main types: (1) rainfall → landsliding on the slope → erosion in the channel at the foot of the slope → secondary landsliding and erosion (Figs. 9, 10), (2) rainfall → erosion at the foot of the slope → landsliding on the slope → secondary erosion and landsliding (Figs. 9, 10).

The first type-sequence situations occur when a rainfall event triggers landsliding on a slope, causing delivery of colluvium onto the valley floor (Fig. 9). The lateral delivery of slope material forces narrowing of the valley floor increasing

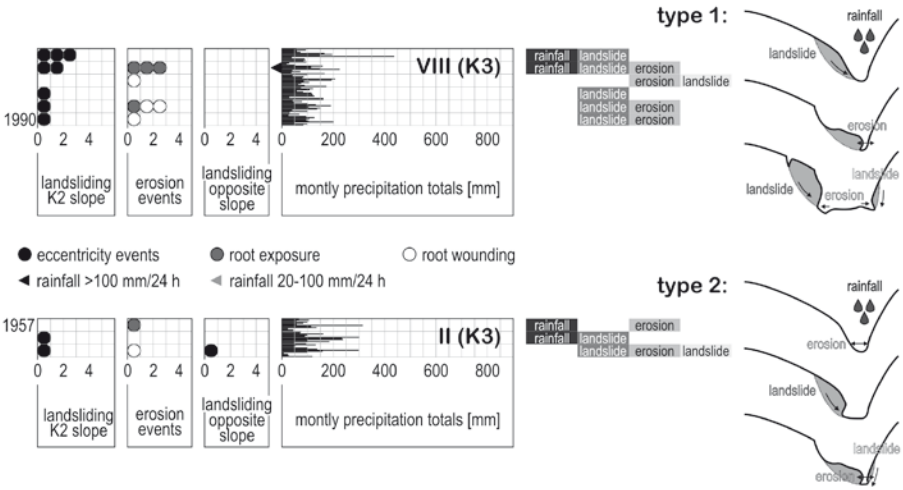

Fig. 9. Sequence VIII, site K3 is an example of the first type of sequence (rainfall → landsliding → erosion) and sequence II, site K3 is an example of the second type of sequence (rainfall → erosion → landsliding)

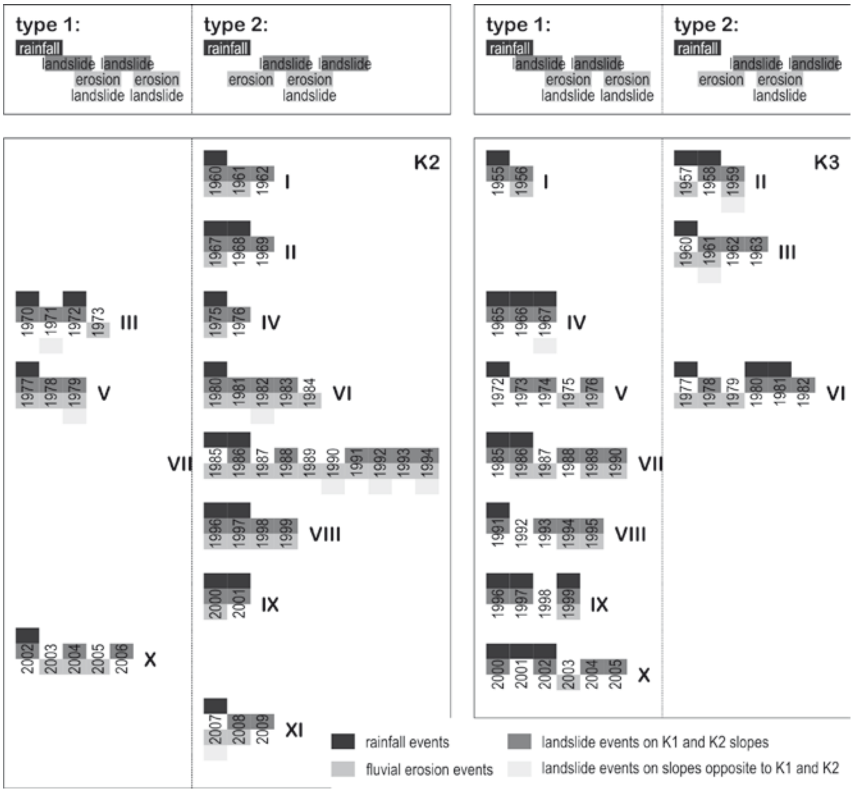

Fig. 10. Sequences of the occurrence of rainfall, landsliding and erosion at the study sites as determined by dendrochronological dating

the potential for erosion at the foot of the slopes. Erosion caused by colluvium delivery can occur in the following years typified with average precipitation. Sequences of the second type begin with rainfall which triggers strong erosion in the channels at the foot of slopes (Fig. 9). Erosion within the valley floor causes disturbance of the slope equilibrium (by undermining its foot) and landsliding.

In both cases, apart from the triggering rainfall, erosion and landsliding often are not accompanied by further extreme precipitation. We found evidence for the occurrence of alternating secondary erosion and/or landsliding in the years following the onset of a sequence, and also typified by average precipitation. This would explain the high intensity of the processes (e.g. secondary erosion in 1979, sequence V, K2; Figs. 8, 10). The alternation of landsliding and erosion in the years without extreme rainfall indicates a mutual coupling of the processes. Once a sequence has been initiated by rainfall, the resulting erosion and landsliding can trigger and strengthen one another independently of precipitation.

We also recorded mass movements on slopes opposite to the studied landslides. As a part of the outlined sequences, these movements usually are triggered by secondary erosion caused by the delivery of colluvium onto valley floors (Fig. 10). It seems that lateral delivery of slope material causes channel shifting towards the opposite slope which is then particularly exposed to erosion.

Individual sequences of coupled landsliding-erosion (Figs. 8, 10) were determined on the basis of different number of dendrochronological datings. In consequence, each sequence has a different significance and they cannot be treated as equal. Yet, this does not change their geomorphic interpretation and an established pattern of slope-channel coupling.

THE IMPACT OF LANDSLIDING-EROSION COUPLING ON RELIEF OF THE STUDY SITES

At the K2 and K3 study sites where we dendrochronologically recorded the coupling between landsliding and erosion, we also observed distinctive features in the relief. These are both the manifestations and the results of coupling between landsliding and erosion.

Lateral delivery of colluvium from the slopes onto the valley floors may locally push and cause shifting of the stream channels (Fig. 3) in the direction of the slopes opposite to the landslides. As a result of lateral shifting of the channel, the opposite slopes are locally eroded and undermined by erosion. Similar cases of increased footslope erosion due to the delivery of colluvium into river channels were described in highmountains by e.g. O. Korup (2004; 2005) in the Southern Alps. It seems that, at the study sites, erosion induced by the delivery of colluvium can affect the originally stable slopes opposite to the studied landslides. At sites K2 and K3 erosional disturbance of the equilibrium of the opposite slopes caused development of shallow landslips (Fig. 11).

Fig. 11. Slope opposite to K2 landslide eroded by the Skalka channel pushed away due to colluvium delivery onto valley floor. A scar of a landslip developed due to secondary slope undermining with exposed roots

In the zones of colluvium delivery onto valley floors, sinuosity of the streams is increased (Fig. 3) due to channel shifting caused by landslide toes (landslides are located on convex banks). Changes in the channel pattern and sinuosity in connection with lateral delivery of landslide colluvium onto valley floors were described in detail by O. Korup (2004).

The results of this study suggest that the relief at the study sites is shaped in the following stages (Fig. 12): (a) precipitation causes erosion and landsliding on K2, K3 slopes and (b) delivery of colluvium into the Skalka channel. Colluvium delivery causes narrowing of the valley floor and increased erosion of the footslope. Stream channel is shifted in the direction of the opposite slope and becomes sinuous. Balance of the slopes opposite to the studied landslides is disturbed resulting in mass movement. (c) As the material delivered onto the valley floor is prone to erosion, it is thus easily removed downstream and erosion spreads to the foot of the original landslide slope. (d) Secondary event of landsliding occurs. Colluvium is delivered onto the valley floor, which once again causes increased erosion.

Dendrochronological results of this study indicate that such cycle can repeat several times in a century. As a consequence, described slope-channel interaction can cause a general increase in the activity of landsliding and erosion, transfer of slope material onto valley floors, total denudation and transfer of material within and outside of the studied catchment.

The described cycle consists in alternate narrowing and widening of valley cross profiles within short timescales (Fig. 12). Narrowing occurs through the delivery of colluvium that fills up valley floors (Figs. 12 b, d), while widening occurs through the removal of colluvium by stream erosion (Fig. 12 c). Because erosion affects not only the body of colluvium, but also the valley slopes (initially the slope opposite to the landside – Fig. 12 b, afterwards also the landslide slope itself – Fig. 12 c), the valley floor can also widen in relation to the state before the initial landsliding event. Also the removal of slope material by the landslides themselves adds to the widening process. Over longer timescales this repeating of the sequences of slope-channel coupling may lead to a general widening of the valley floors at the expense of slopes and gradual change of valley cross profiles from narrow V-shaped to wide and flat-bottomed.

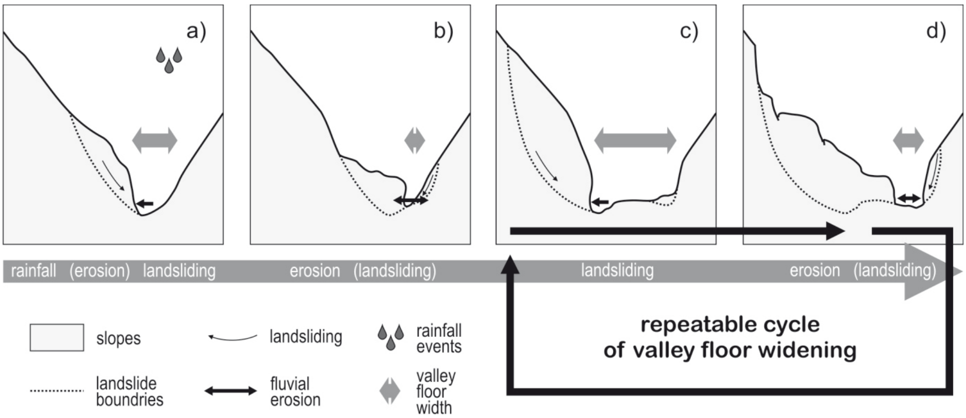

Fig. 12. Consecutive stages (a–d) of cyclic valley floor narrowing and widening as a consequence of landsliding-erosion coupling

In southern Spain J. M. Azañón et al. (2005) described the evolution of a canyon somewhat similar to that discussed for the studied sections of the Skalka catchment. According to their scheme, degradation of the canyon floor causes undermining of its slopes and induces rock slumps. The cyclic character of the landslide-erosion interaction leading to an increase in valley width was described by S. Lévy et al. (2012) in eastern Canada, where rotational slides on valley sides were caused by bottom erosion and lateral migration of the river channel. These authors demonstrated that erosion and landsliding are strongly coupled in a way similar to that presented in this paper. S. Lévy et al. (2012) also found that the interaction of landslides and erosion leads to the widening of a valley floor and the change of its cross profile from V-shaped to flat-bottomed – which corresponds to the observations in the Skalka catchment.

In principle, the phenomenon described in the Skalka catchment is similar to a cyclical process of bank retreat along composite banks described by K. Fryirs and G. J. Brierly (2013).

CONCLUSIONS

1) Dendrochronological datings conducted in this study show that landsliding and erosion at sites K2 and K3 have low to medium intensity and rather high frequency.

2) Some of the dated landsliding and erosion events do not coincide with the occurrence of heavy rainfall events. Landsliding and erosion at study sites K2 and K3 do not depend solely on the occurrence of extreme rainfall and may also occur in periods with average precipitation.

3) Detailed analysis of the temporal relations between dated landsliding, erosion events and recorded precipitation indicates that landsliding and erosion at the Skalka study site are coupled and occur in repeating cycles. We have determined two general types of coupling sequences:

- the first type: rainfall → landsliding on the slope → erosion at the foot of the slope → secondary landsliding and erosion,
- the second type: rainfall → erosion at the foot of the slope → landsliding on the slope → secondary erosion and landsliding.

Regardless of the geomorphic process which is initially triggered by rainfall (landsliding or erosion), a sequence of mutual slope-channel interaction is induced.

4) In short periods coupling between landsliding and erosion causes alternate narrowing and widening of the valley cross-section. It seems that over longer periods, the described interaction can lead to a general widening of the valley floor and the retreat of the slopes above.

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