DENDROGEOMORPHOLOGY OF SPATIO-TEMPORAL ACTIVITY OF ROCKFALL IN THE FLYSCH CARPATHIANS: A CASE STUDY ON THE WESTERN SLOPE OF MT. SMRK, MORAVSKOSLEZSKÉ BESKYDY MTS. (CZECH REPUBLIC)

Karel ŠILHÁN

Abstract

Research on rockfall activity by dendrogeomorphological methods is a completely new approach to the study of such phenomena in the Czech Republic. The most recent findings concerning a study of rockfalls in the Moravskoslezské Beskydy Mts. are presented in this paper. The methods used included making an inventory of rockfall visual displays and the dating of scars by core drilling. The influence of rock wall character and tree location within a talus cone on the spatial variability of rockfall activity, was established. A curve of rockfall historic activity was created.

Shrnutí

Dendrogeomorfologie prostorově-časové aktivity skalního řícení ve flyšových Karpatech (příkladová studie na západním svahu Smrku; Moravskoslezské Beskydy, Česká republika)

Výzkum aktivity skalního řícení dendrogeomorfologickými metodami je na našem území prakticky zcela nová problematika. Tato studie se tak pokouší přinést nové poznatky ze studia tohoto svahového procesu v Moravskoslezských Beskydech. Byla použita metoda inventarizace vizuálních projevů skalního řícení, a metoda datování jizev z vrtných jader. Byl prokázán vliv charakteru skalní stěny a rozmístění stromů na osypu na prostorovou variabilitu aktivity skalního řícení a byla vytvořena i křivka historické aktivity skalního řícení.

Key words: *rockfall, dendrogeomorphology, spatio-temporal analysis, Moravskoslezské Beskydy Mts., Mt. Smrk, Czech Republic*

1. Introduction

Rockfall represents a type of highly hazardous slope process (Halley, 1984). Despite numerous studies dealing with this problem (Duarte and Marquínez, 2002; Braune et al., 2005; Lan et al., 2007), there is still a large unexplored territory in the Czech Republic. Particularly, the issues of spatio-temporal aspects of rockfall stand for a field of research of high potential. Moreover, the knowledge of these aspects is a very useful tool in the proposal of measures in personal security and protection of property in affected areas.

Dendrogeomorphic methods have recently turned into a highly effective tool in the research of spatial and historic rockfall activity. These methods have primarily been used in the analysis of a few Alpine localities characterized by different physical geographic conditions (Stoffel and Perret, 2006) and they brought high-quality results in all cases. Dendrogeomorphic methods can nowadays be used also to analyze a few-hundred-year-old rockfall (Stoffel et al., 2005a). Nowadays, the rockfall research contributes to the expansion of the application scope of these methods (Stoffel, 2006a) as they have successfully been used in the research of debris flows (Strunk, 1997; Bollschweiler et al., 2007), landslides (Corominas and Moya, 1999; Stefanini, 2004) or floods (Hrádek and Malik, 2007; Zielonka et al., 2008) for many years.

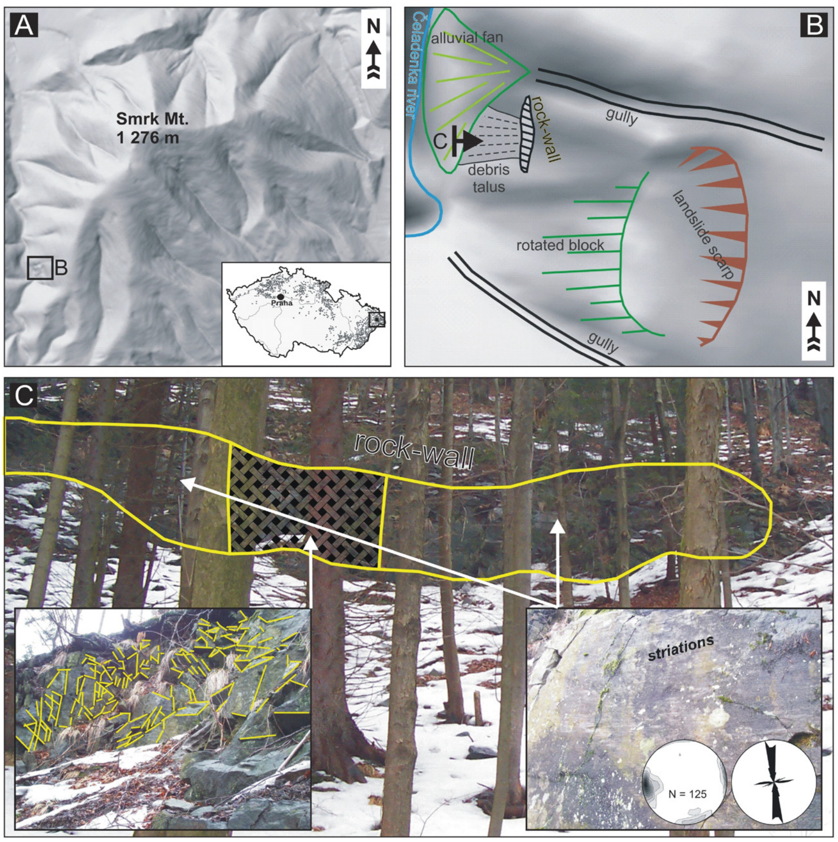
The methods used involve the inventory and dating of scars left on the tree stems by falling rock fragments. However, the spatial display of rockfall differs considerably from other geomorphological processes (e.g. debris flows) as the released moving fragments may damage a few trees on their way or they may not hit any tree at all (Stoffel and Perret, 2006). It is practically impossible to determine which of the scars were caused by one single fragment and they thus represent results of one particular event. Moreover, a single tree could have been impacted more than once in a year in which a few scars originated but the identification of individual scars from the increment cores is very difficult. All stem scars that originated within one year are considered a result of a single rockfall event in this study. Consequently, rockfall values are considered to be minimum values (Stoffel and Perret, 2006; Schneuwly and Stoffel, 2008).

The first attempt to analyse rockfall by means of dendrogeomorphic methods in the Czech Republic was presented by Raška (2007). Nevertheless, our paper focusing on a complete rockfall analysis both from the spatial and temporal points of view represents a pioneer study in the field of Czech geomorphology. Its objectives are as follows

a) to verify possibilities for the application of dendrogeomorphic methods in the rockfall research in the Flysch Carpathians,
b) to analyze spatial aspects of rockfall in a selected locality and (iii) to create a frequency series of historic rockfall activity.

2. Locality

The locality of the northern slope of Mt. Smrk (1 276 m) in the Moravian-Silesian Beskids Mts. (Fig. 1a) was chosen as a case study. It is in the vicinity of the valley floor of the Čeladenka River, which creates a narrow, deep-incised valley with very steep slopes (up to 35 °) between Mt. Smrk and Mt. Kněhyně (1 257 m). The area is built of flysch layers slightly (10–15 °) inclined in the SE direction (Menčík et al., 1983). The locality is situated on the right bank of the Čeladenka River at an elevation of 600–650 m. The rockfall source zone is a ~40 m wide and up to seven meters high rock-wall oriented to W (~270 °) direction and characterized by protruding thick sandstone rocks of the middle member of Godula Formation. The surface of the sandstone rocks shows horizontal striations. The sandstone rocks in the central part of the rock-wall are intensively jointed and sporadically almost disintegrated. The crack analysis showed a prevailing crack orientation almost parallel to the orientation of the rock-wall (Fig. 1c). By contrast, marginal (N and S) parts of the outcrop are formed by a nearly vertical rock-wall with numerous striations (Fig. 1c). The outcrop thus represents an exposed part of a fault zone. A ~40 m long talus cone containing material released from the rock-wall, consisting primarily of fragments



Figs. 1A–C: A – Position of the studied locality in the Moravskoslezské Beskydy Mts., Czech Republic. B – Geomorphic map of the studied locality with a marked direction of the C image. C– View at the rock-wall from the foot of the talus cone. A detailed photo of two significantly different parts of the rock-wall and a tectonogram of fissures.

of 25–30 cm, has developed under the wall. In its NW part the talus cone is partly overlaid by an alluvial fan. Its surface has been colonized by a full-grown forest where *Acer pseudoplatanus* prevails over *Picea abies* and *Fagus sylvatica*. This geomorphological situation is found on the forefront of a ~200 m long and slightly rotated block of Godulian sandstones (Fig. 1b).

3. Methods

A few common dendrogeomorphic methods were chosen for the purpose of this study. The first step involved a detailed geodetic localization of individual analyzed trees. The system of geodetic coordinates was used for the spatial interpolation of investigated rockfall parameters and in order to create a DEM of the studied locality. The interpolation method of Kriging in Surfer 8 was applied using a step of one meter.

Further steps involved an inventory of the number of visible tree scars, their elevation above sea level and orientation towards the rock-wall. As no other geomorphic processes were observed in the locality that might have been the cause of the tree scars (debris flows, snow-slides), we suppose that all identified scars were caused by falling rock-wall fragments.

Increment cores were extracted in order to determine the age of both visible and completely overgrown scars. The sampling was based on a well-proven methodology used in the Alpine environment (Stoffel et al., 2005a; Stoffel and Perret, 2006). It involved four increment cores oriented in agreement with the slope gradient, contrary to the slope gradient and facing each other on the stem sides of individual trees (Stoffel et al., 2005a). Sampling height was the medium height of all visible scars, i.e. ~80 cm. The increment cores were subsequently processed in a laboratory by using a standard methodology according to Bräker (2002). They were air-dried, stabilized in wooden channels, flattened and polished. The tree rings were counted and measured using the VIAS TimeTable measuring device. In order to eliminate the influence of climate on the width of tree rings a comparative referential curve was created based on data related to 30 trees growing in the proximity of the analyzed locality, the growth of which was neither affected by rockfall, nor by other geomorphic processes.

The identification of the incidence of scars was based on the direct visual inspection of increment tree-ring curves and on the surface of flattened cores (Fig. 2a) (Schweingruber, 1996). The attention was focused on a sudden narrowing of tree-ring widths as a consequence of

a) the appearance of a scar,
b) the tree chop-off (Fig. 2b) or
c) the decreased competition due to the death of a neighbouring tree (Fig. 2e) or tree inclination accompanied by the occurrence of reaction wood. The observation included the presence of callous tissue at the scar margin that helps the tree to join up the scar (Fig. 2d). A significant scar indicator is the occurrence of Traumatic Resin Ducts (TRD) in tree rings (Fig. 2c) in years following the impact (Stoffel, 2006b; Bollschweiler et al., 2008b). Not

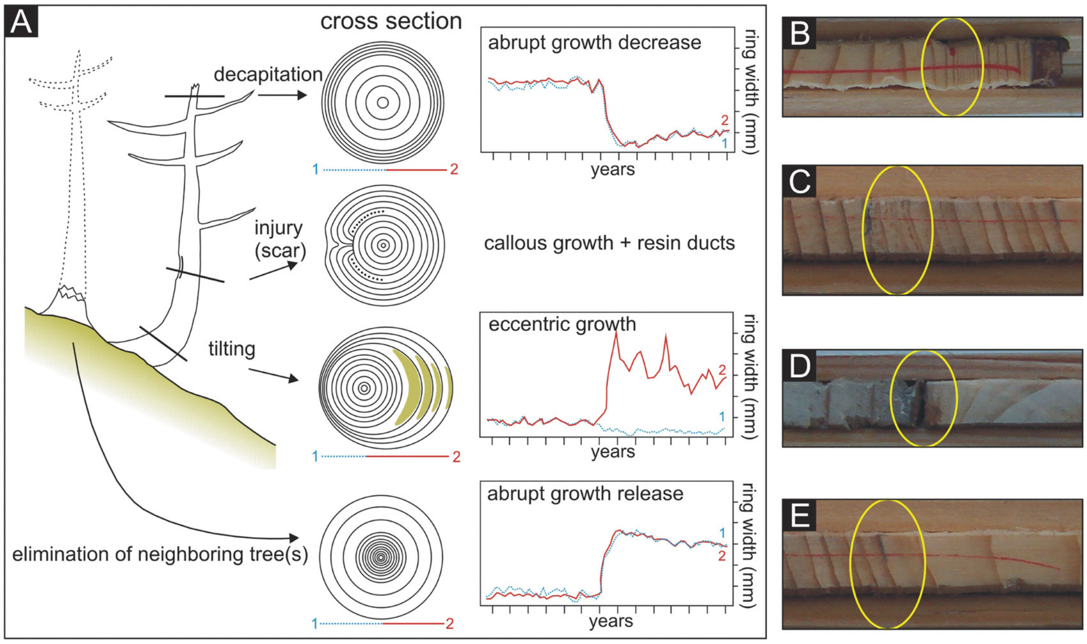


Fig. 2: Increment tree-ring deformations used in the identification and dating of scars (adapted after Stoffel et al., 2005a). A – Scars on trees and their reflection in the tree-rings. B–E – The display of scars in processed increment cores (explained in the text).

all TRDs can, however, be considered as the scar evidence. The dating involved rather large TRDs that formed continuous sequences and appeared in a few consecutive years (Stoffel et al., 2005a; Schneuwly et al., 2009a; Schneuwly et al., 2009b).

Chronology of the rockfall activity was expressed by means of the 'rockfall rate' indicator defined as a number of dated scars per one meter of diameters of all trees sampled in a given year (Stoffel et al., 2005a) and its formula is:

$$\mathbf{RR_y = \sum S_y / \sum D_y},$$

where RR_y is 'rockfall rate' in the given year, S_y represents scars dated in the same year and D_y represents all tree surfaces in the given year.

The 'rockfall rate' values for individual trees needed in the spatial analysis were calculated as follows:

$$\mathbf{RR_t = \sum S_t/(r_t \cdot A_t)},$$

where RR_t is 'rockfall rate' of the tree, rt is the tree radius, A_t is the tree age and S_t is the number of dated tree scars.

4. Results

Inventory of visible tree surface damage

A total of 57 trees growing on the talus cone surface were visually analyzed. The dominating species was *Acer pseudoplatanus* (39 trees), followed by *Picea abies* (12 trees) and *Fagus sylvatica* (6 trees). The number of visible scars reached 431 with an average of 7.6 events per tree. The average height of scars above the land surface was 82.6 cm, whereas the highest scar was observed 300 cm above the ground level. The average scar length was 11.9 cm. On average, the longest scars were observed on *Picea abies* (18.8 cm), while the shortest ones on *Fagus sylvatica* (6.8 cm). The results are given in Tab. 1.

Spatial aspects of visible scars

The spatial distribution of visible scars shows that a majority of scars were found on stems in the proximity of the rock wall (Fig. 3a). Numerous scars on the tree stems were also situated in the central part of the talus cone, in the upper part of which was the density of trees very sparse. Another tree cluster showing a high number of scars (11–14) was also observed in the lower part of the talus cone. On the other hand, the fewest scars occurred on the lateral peripheries of the talus cone as well as on the trees growing at lower fringes of denser tree clusters. The average scar height on stems was highest in the proximity of the northern fringe of the rock-wall and along lateral fringes of the talus cone. The lowest average height was measured in the proximity of the central and southern parts of the rock wall and in the central part of the talus cone (Fig. 3b). The maximum scar height occurring on the stems corresponded with this spatial distribution (Fig. 3c).

The scar orientation on stems towards the rock-wall position showed a dominant position of scars in the direction that was nearly vertical to the rock-wall (Fig. 3d). A minimum of scars occurred on the sides of trees or on their rear sides.

Tree sampling

Increment cores were taken from 42 trees owing to wood rot and a very small diameter of some tree stems. However, a total number of sampled increment cores was 168. The average age of sampled trees was 45.3 years, whereas the oldest tree was 57 years old and the youngest one 25 years old (Tab. 2). The average stem width was 26.9 cm. The mean annual increment value was highest in Picea abies (0.78 cm/year), while the lowest value was measured in Fagus sylvatica (0.37 cm/year). The average value then made 0.58 cm/year.

Scar dating

Most scars were identified in boreholes inspecting the results of the sudden narrowing of tree rings (37.9%). Sudden growth releases revealed a comparable amount of scars (23.5%), as well as the presence of callus tissue (25.7%). The fewest scars were identified by means of Traumatic Resin Ducts (TRD) (12.9%). The total number of dated events reached 181 (Tab. 3). With regard to the fact that some scars were identified using secondary indicators

Number of scars	Scars per 1 m of diameter	Average length of scar (cm)	Average height of scar (cm)	Maximal height of scar (cm)
69	5.7	18.8	90.0	300
299	7.6	11.4	83.5	210
63	10.5	6.8	72.8	200
431	7.6	11.9	82.7	300

Tab. 1: Results of the inventarization of visible tree scars

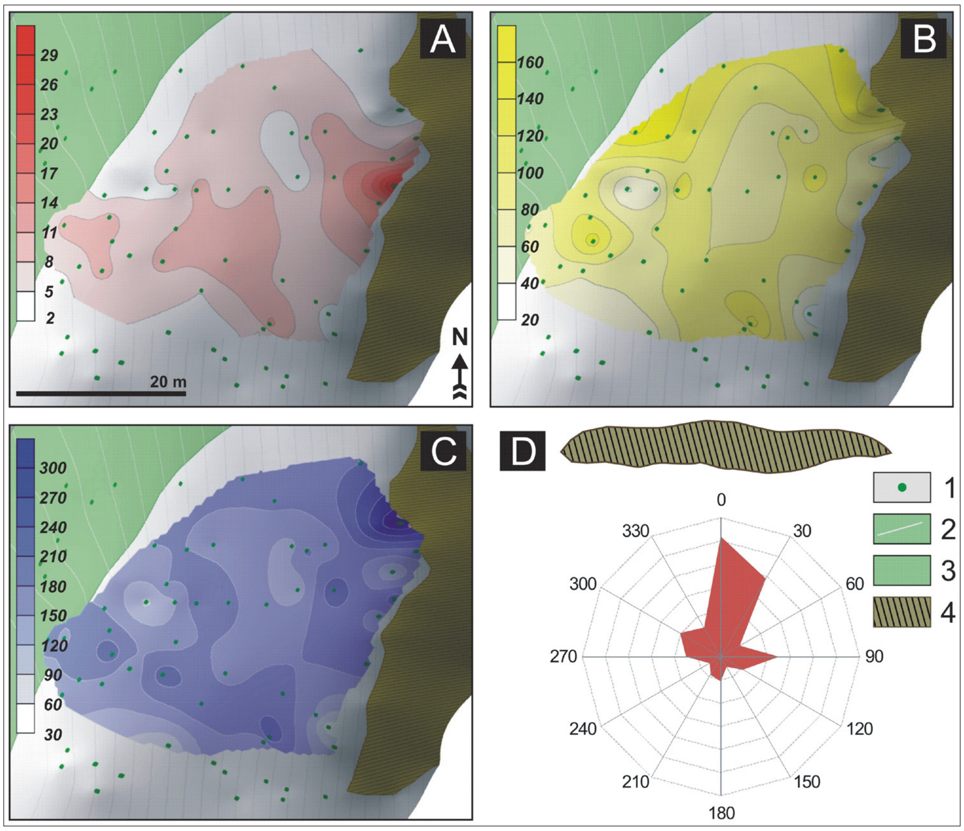


Fig. 3: Spatial aspects of visible scars on the surface of tree stems. A – A number of visible tree scars. B – Mean height of tree scars (cm). C – Maximum height of tree scars (cm). D – Orientation of scars towards the rock wall (°). 1 – Tree position, 2 – Contour lines (1 m), 3 – Alluvial fan, 4 – Rock wall.

	Number of sampled trees	Average age (years)	Maximal age (years)	Minimal age (years)	Average width of stem (cm)	Average year increment (cm)
Picea abies	12	46.6	56	36	35,9	0.78
Acer pseudoplatanus	29	44.7	57	25	23,2	0.51
Fagus sylvatica	1	45.0	45	45	16,5	0.37
all	42	45.3	57	25	26,9	0.58

Tab. 2: General characteristics of sampled trees

	Abrupt growth decrease	Abrupt growth increase	Traumatic resin ducts TRD	Callus tissue	Total
growth disturbances (%)	37.9	23.5	12.9	25.7	100
growth disturbances (number)					181

Tab. 3: Percentage representation of all scars evidence in increment cores

	Number of cores	Number of growth disturbances	Number of reconstructed scars	The oldest reconstructed scar
Picea abies	48	75	46	1964
Acer pseudoplatanus	116	102	76	1962
Fagus sylvatica	4	4	3	1986
all	168	181	125	1962

Tab. 4: Results of the identification of scars in boreholes

(e.g. abrupt growth decrease and/or TRD) or in more cores of identical tree, it was necessary to modify their number to eliminate double displays. The resulting number thus made a total of 125 dated scars, of which 46 scars were dated on *Picea abies*, 76 scars on *Acer pseudoplatanus* and three scars on one *Fagus sylvatica*. The oldest scar originated from the year 1962 (Tab. 4).

Spatial aspects of dated scars

The talus cone showed an even distribution of trees of various ages; no tree clusters were observed. Older trees occurred especially in the northern part of the talus cone (Fig. 4a). The highest number of dated scars was dated in the increment cores of trees on the northern fringe of the talus cone, whereas the fewest scars were dated in the lower part of the talus cone and in the proximity of the northern part of the rock-wall. The remaining parts of the talus cone showed on average 2–4 scars per tree (Fig. 4b).

The average time interval between the origin of two scars (tree age/number of dated scars) was low at the talus cone fringes as well as in the proximity of the central part of the rock wall. On the contrary, the longest time interval was measured in trees growing in the lower part of the talus cone (Fig. 4c). The highest 'rockfall rate' values appeared in the proximity of the central part of the rock-wall but they were decreasing with the fall line. An exception was represented by two trees with the increased 'rockfall rate' value, which grew in the lower part of the talus cone (Fig. 4d).

'Rockfall rate'

The 'rockfall rate' (RR) time path was studied in 42 trees (sample depth). Analysing the identical number of dated scars in individual years, values of this indicator depended indirectly on the total exposed diameter of all trees growing in a given year (exposed diameter – ED, Stoffel et al., 2005a). Its values also became less objective if the number of analyzed trees was very low. In this case, the limit of credibility was determined as a value corresponding to 30% of the exposed diameter of 2008. This limit was exceeded in 1975. The RR time path is shown in Fig. 5.

Because it was quite unbalanced in the individual years, its values were balanced by means of a moving average calculated for 5 years. The starting year is 1977 and the terminal year is 2006. The moving average shows a slight decrease in the rockfall intensity from 1977 to the mid-1980s. It increased in the early 1990s and culminated in the mid-1990s when a decrease started again.

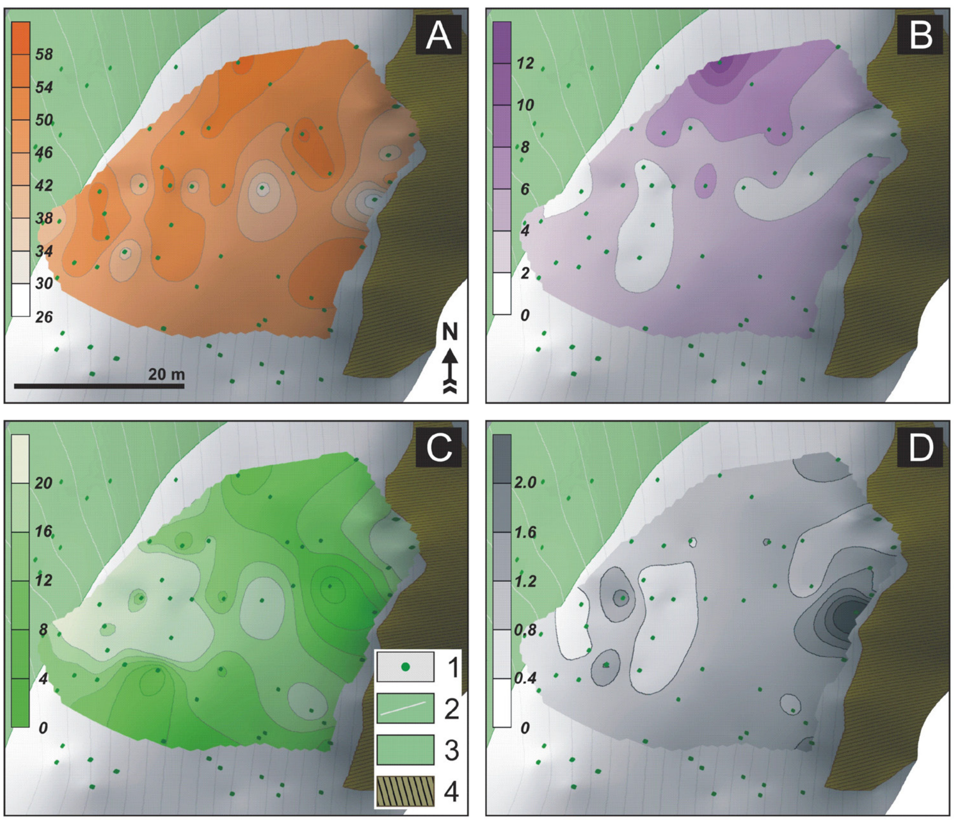


Fig. 4A–D: A – Age of tree on the talus cone (years). B – Number of dated scars per tree. C – Average interval of scar occurrence (years). D – "RR" values (scar.year-1m-1). 1 – Tree position, 2 – Contour lines (1 m), 3 – Alluvial fan, 4 – Rock wall

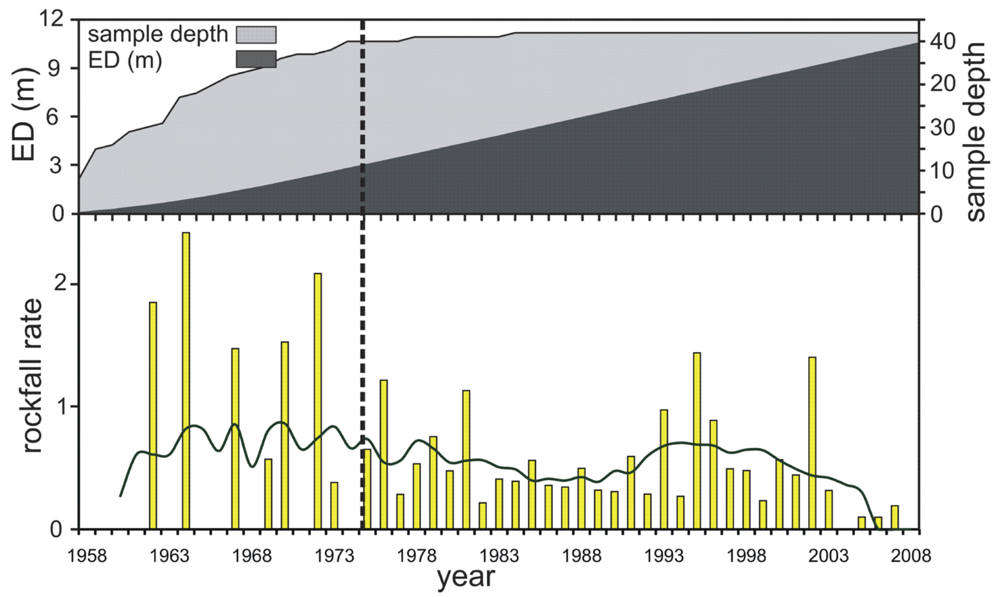


Fig. 5: Rockfall time development. "Rockfall rate" annual values (scar-1year-1m) (in a yellow colour) and their average over five years (black line). Development of stem exposed diameter (ED) depending upon the number of analyzed trees (upper part of the figure). The border of a minimal exposed diameter (30% ED from 2008) and "RR" curve relevant values (vertical discontinuous line).

5. Discussion

The survey of the surface of 57 trees revealed a total of 431 scars. The largest scars were recorded on the trees of *Picea abies* (18.8 cm), unlike 6.8 cm on *Fagus sylvatica*. The number of visible scars on *Picea abies* was lower than on *Fagus sylvatica*, as well. This finding is supported by the fact that in comparison with *Fagus sylvatica*, *Picea abies* has thicker bark, which significantly softens the energy of a moving fragment (Stoffel, 2005).

Thus, wood is damaged only when hit by a large fragment characterized by high dynamics. As a result of this, the average size of scars on the *Picea abies* trees is almost three times higher than on the *Fagus sylvatica* trees, whose surface may be damaged even by a relatively small fragment. A smaller number of visible scars on *Picea abies* can also be caused by the species' high annual increment values (Stoffel and Perret, 2006). *Picea abies* trees increment value of 0.78 cm a year indicates a much faster joining up of smaller scars than in the case of *Fagus sylvatica* trees increment value of 0.37 cm/year. The annual increment value of the trees (0.58 cm) corresponds to values measured on trees affected by rockfall (Stoffel and Perret, 2006).

In comparison with other studies (Stoffel, 2005), both the average (82.7 cm) and the maximum (300 cm) heights of scars are lower. The explanation can be a small rock wall height, a relatively small gradient of the talus cone and, as compared to Alpine areas, a shorter transport distance of moving fragments.

The comparison of the number of dated scars in increment cores also brought interesting results. While 48 *Picea abies* trees featured 46 scars, 116 *Acer pseudoplatanus* trees showed only 76 scars. In this case, more scars on average were identified on the individual *Picea abies* trees than on the *Acer pseudoplatanus* trees. A possible explanation is a different physiological response of coniferous and deciduous trees to scars (Schweingruber, 1996). Both groups of the tree species respond by means of a similar type of ring deformations. An exception is observed in connection with the response of the wood of tilted trees because conifers develop compression wood on the stem side, which is opposite to the side where deciduous trees form tension wood (Stoffel and Bollschweiler, 2008). In this respect, a fundamental difference is related to the formation of traumatic resin ducts that appear as a reaction to scars only in certain conifer species (Stoffel, 2006b). This evidence is thus absent in the identification of scars on broad-leaved trees. Bollschweiler et al. (2008a) use this evidence to date up to 50% of all scars and Perret et al. (2006b) even up to 70% of all scars in conifers. The comparison with the *Fagus sylvatica* species is irrelevant as the analysis involves only one *Fagus sylvatica* tree.

The majority of visible scars were found in the proximity of the central part of the rock wall. This part of the rock-wall shows very intensive rock jointing, even disintegration, which points to a higher frequency of fragment fall-off in this part and to a higher number of scars on the nearest trees. The higher rockfall intensity in this part is also supported by a significant "bite-off" of the rock-wall bottom in its ground-plan position. On the contrary, the fewest scars were found on trees that were in close alignment with trees growing higher up the slope. Stoffel et al. (2005a) refer to this as to a kind of protection effect of trees located in higher elevations.

A higher amount of scars found on trees in the central part of the talus cone was most likely caused by the absence of this effect as practically no trees capable of capturing the fragments occur between the trees in the central part of the talus cone and the rock wall. A small number of scars in the proximity of the talus cone fringes was explained by the character of the rock wall which is only slightly fragmented by cracks in these zones and which, in its northern part, passes into an almost vertical wall with striations. It is exactly the irregular tree distribution on the talus cone and the non-homogeneous rock wall character that cause anomalies in the spatial number of scars. Therefore, no significant dependence can be found between the number of scars on trees and the distance of trees from the rock wall ($r = -0.167$) or the stem diameter ($r = -0.097$) (Fig. 6), which is also proved by the research of Perret et al. (2006a).

The highest average height of scars on trees in the proximity of the northern part of the rock wall can also be connected with the rock wall height and with the character of protruding rocks. The rock wall is loosened only in the upper part of the outcrop and therefore rock fragments reach the tree surface falling from a relatively considerable height. The great average height of scars at the talus cone fringes can be explained by the movement of rock fragments down the talus cone in the form of rolling, sliding and especially bouncing, which can accelerate particularly at the talus fringes due to the low density of trees growing there.

The assumption that all tree scars originated following a rockfall activity is supported by the dominating orientation of scars that is vertical towards the wall. Very few scars on tree sides or rear sides may have originated through rock fragment bouncing off other trees and changing in their trajectory (Stoffel and Perret, 2006). Age distribution of trees on the talus cone (with older trees in its northern part) roughly corresponds with the number of scars in the respective increment cores. The higher number of dated scars on older trees indicates that these trees were longer exposed to moving rock fragments.

The recurrence interval of the origin of individual scars is again highest in the proximity of the central part of the rock-wall, which proves a high rockfall activity related to this area. On the contrary, the occurrence of scars in the interval of more than 20 years in the lower part of the talus cone indicates a gradual fade-out of the impact of falling rock fragments with the increasing distance from the rock-wall.

All these spatial aspects are supported by the distribution of the 'rockfall rate' values on the talus cone surface. Maximum values reached in the proximity of the central part of the rock-wall are represented by more than two $scars^{-1}year^{-1}m$. The gradual decline of values down the talus cone thalweg to below 0.4 $scars^{-1}year^{-1}m$ proves the hypothesis of the decreasing rockfall activity with the increasing distance from the source of fragments (Schneuwly and Stoffel, 2008).

Trees growing on the talus cone are very young (45.3 years old on average). No remainders of older trees (e.g. tree stumps) were found, which is limiting for the maximum length of rockfall activity record on the talus cone (~30 years). However, as compared with other analyzed localities it does not

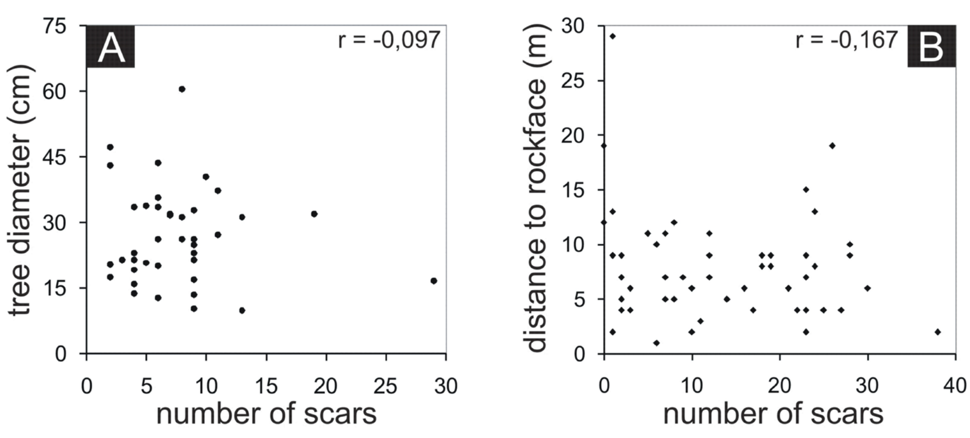


Fig. 6: Graphical representation of relations between the number of visible scars on a tree stem and its diameter (A) and the distance of the tree from the rock wall and the number of visible scars on the tree surface (B)

represent a very short range. For example, Stoffel et al. (2005a) obtained a range of 'rockfall rate' values for a period of 400 years. Other data can provide even shorter ranges (e.g. 50 years, Schneuwly and Stoffel, 2008). A smooth time curve of 'rockfall rate' values is a useful tool in the analysis of rockfall controlling factors. Further research should thus incorporate a more detailed analysis of the development of the curve, namely as compared with climatic data. The comparison with the time path of various climate variables proved a strong relation to e.g. average winter and summer temperatures (Stoffel and Perret, 2006), extreme rainfall (Schneuwly and Stoffel, 2008) or other factors such as human activity on slopes (Stoffel et al., 2005b).

6. Consclusion

The presented study brings new findings on the spatial and temporal rockfall distribution in the Flysch Carpathians. Answers to the questions asked in the introduction of our paper can be summarized as follows:

- Possibilities of the dating of both visible and hidden scars caused by rockfall were verified by means of dendrogeomorphic dating. In this respect, coniferous trees appear to be more suitable considering their ability to create traumatic resin ducts. However, despite the fact that it concerns rather larger fragments of higher dynamics that leave visible scars on the surface of conifers, the scars overgrow relatively quickly.
- The spatial analysis of rockfall aspects showed an important effect of the character of the rockfall source area on the distribution of its displays (scars). The most affected areas are found in the proximity of a very jointed, almost disintegrated rock-wall. On the contrary, high smooth walls become fragmented only sporadically, namely in their summit parts. The spatial distribution of scars is also influenced by the protective effect of trees, which "screen" the lower positioned trees. A combination of these factors contributes to decreased rockfall activity farther from the source of material.
- The experimentally created rockfall activity sequence demonstrated a significant fluctuation in the course of its intensity because periods of higher and lower rockfall activity are evident in the reconstructed record of ~30 years. Further stages of the research are intended to incorporate a comparison of time data with the climatic records and to identify factors initiating the rockfall.

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Author´s address:

RNDr. Karel ŠILHÁN, Ph.D.
Department of Physical Geograpy a Geoecology, Faculty of Science, University of Ostrava
Chittussiho 10, 710 00 Ostrava, Czech Republic
e-mail: *karel.silhan@osu.cz*