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Dendrochronologia 24 (2006) 1–15

DENDROCHRONOLOGIA

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ORIGINAL ARTICLE

Reconstructing past rockfall activity with tree rings: Some methodological considerations

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Received 18 February 2005

Abstract

This paper reports on methodological difficulties arising when trees and tree-ring series are used to reconstruct rockfall activity. Unlike disturbances from other processes such as debris flows, floods or snow avalanches, scars caused by rockfall are more randomly distributed on trees and may occur at considerable height on the stem. Therefore, the selection and the number of trees as well as the determination of sampling heights and sample depth, all require special care in investigations of spatio-temporal variations in rockfall activity. The purpose of this paper is to assess the reliability and potential standardization of methods used to determine rockfall impact heights occurring in trees. The data come from three case studies located in prealpine and alpine environments of Switzerland. The paper also addresses questions about the relationship between 'hidden' (masked) and visible scars. Furthermore, we investigate the relationship between scar data derived from one single cross-section or increment cores and the total population of scars on a stem.

Our results indicate that impact scars may be identified from almost ground level up to 9 m of height on the stem surface. The wound healing and the masking of scars, in contrast, greatly depend on the bark properties of the tree species, their annual increment rates and age, as well as on the predominant size class of rockfall fragments. As a result, as many as 90% of all scars were masked in thick-barked *Larix decidua* Mill., whereas the 'hidden' scars only counted for 16–25% in *Abies alba* Mill. or *Fagus sylvatica* L. The analysis of single cross-sections at a given height shows that, at best, 13–37% of the rockfall scars occurring on the entire tree can be detected. The data suggest that the number of events reconstructed at a given height can be considerably improved if other signs of growth disturbances such as reaction wood, abrupt growth reductions or, when present, rows of traumatic resin ducts are considered as well.

Keywords: Dendrogeomorphology; Rockfall events; Scars; Impact heights; Sampling strategies; Natural hazards

Introduction

Dendrogeomorphology can provide high-resolution data on frequencies, volumes or seasonal timing of past hydrological or geomorphological events (Bräuning, 1995). Tree-ring series have been extensively investigated to study past snow avalanche (Butler et al., 1992; Patten and Knight, 1994; Rayback, 1998; Stoffel et al., 2006a), debris flow (Strunk, 1997; Baumann and Kaiser, 1999; Stoffel et al., 2005a; Bollschweiler et al., submitted) or flooding activity (Hupp, 1988; Bayard and Schweingruber, 1991; LePage and Bégin, 1996; St. George and

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doi:10.1016/j.dendro.2006.04.001

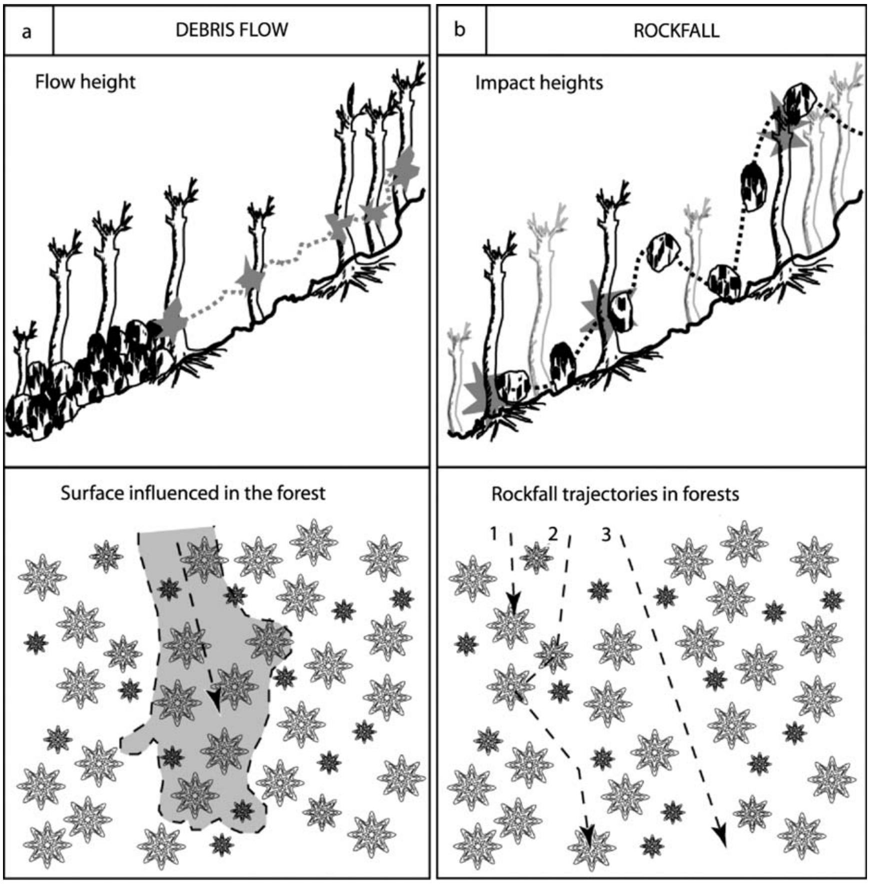

Fig. 1. (a) Flow height and vertical distribution of injuries occurring with a debris flow event: scars can be identified on a comparably large number of trees along the flow path and are restricted to the lowermost part of the trunk, i.e., the maximum flow height of a surge. (b) As rockfall represents the motion of individual rockfall fragments (= pebbles, cobbles and boulders), scars are found only along the rockfall trajectory and at heights ranging from almost ground level to several meters. Arrows indicate debris-flow/rockfall trajectories.

Nielson, 2003). Due to the contiguous mass displacement of these processes in a defined area, single events generally affect a large number of trees along their tracks. As a result, injuries can repeatedly be identified within an area and are – with the exception of windblast impacts caused by powder-snow avalanches – restricted to the lower parts of the trunk and their extension defined by the flow height of the process in question. A typical example of this type of flowing impact is a debris-flow event (Fig. 1a).

Rockfall, in contrast, is the free or rebounding fall of individual or a limited number of superficial rockfall fragments[1] from cliff faces down steep slopes (e.g., Selby, 1993; Luckman, 2004), with volumes involved generally $<5\,\mathrm{m}^3$ (Berger et al., 2002).[2] In the three case study sites presented in this paper, rockfall was triggered mainly by freeze-thaw cycle activity from the (sub-) vertical cliffs and generally consists of isolated and individual rockfall fragments. The release of volumes exceeding a few cubic meters remains very exceptional and single rockfall fragments may, as a result, only disturb a limited number of trees along their trajectories, as illustrated in Fig. 1b (Stoffel et al., 2005b). Although rockfall represents one of the most common geomorphic processes in mountainous regions (e.g., Whalley, 1984; Luckman and Fiske, 1995; Erismann and Abele, 2001), its assessment by means of dendrogeomorphological methods is not common (Stoffel, 2005a, 2006).

This paper points out problems arising when trees and tree-ring series are used to reconstruct return periods,

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[1] In this article, the term 'rockfall fragments' is used to describe the material involved during individual rockfall events and comprises pebbles (Ø 4–64 mm), cobbles (Ø 64–256 mm) and boulders (Ø 256–2048 mm) according to the Friedman and Sanders (1978) size scale.

[2] According to Luckman (2004) or Guzzetti et al. (2004), rockfall(s) may vary from the tiniest pebbles through very large boulders and topples to catastrophic failures of several million cubic meters.

volumes or spatial patterns of past rockfall activity. Analyses were conducted using data gathered from three sites in the Swiss Alps and Prealps. We focus on impact heights, the radial distribution of scars and the representativeness of scars visible on the stem surfaces. In addition, we compare the number of scars identified on single cross-sections or increment cores with the total population of scars on a tree and comment on sampling strategies for future studies.

Material and methodological difficulties of tree-ring–rockfall research

The material used comes from three different dendrogeomorphological studies conducted in the Swiss Alps and Prealps. Even though the case studies had different goals and sampling methods, they all aimed at assessing return periods and spatial patterns of rockfall activity on forested slopes. General information on the different datasets is provided in Table 1. The database contains records from 349 trees for a total of 3203 rockfall scars (69% conifers and 31% broadleaves).

Here we discuss the methodological difficulties encountered, provide an outline of existing knowledge and introduce the approaches we used. In the following section, we give detailed descriptions of the three case study sites, the feature of the rockfall damages and the results of the investigations.

Height and radial distribution of scars on stems

The success of dendrogeomorphological research on rockfall activity on forested slopes largely depends on the height and radial position at which samples are taken on the stem. In contrast to 'flow' processes (e.g., debris flow, flood, wet snow avalanche), rockfall may cause scars almost anywhere between ground level and several meters above. Consequently, tree-ring reconstructions run the risk of remaining rather incomplete by only reconstructing those injuries located at or directly next to the height at which cross-sections or increment cores are taken for analysis. Careful investigation of locally occurring impact heights must, therefore, imperatively precede sampling in order to determine 'optimal' positions for the extraction of cross-sections or increment cores.

At present, comprehensive quantitative data on the vertical distribution of rockfall impacts on stem surfaces do not exist. Rickli et al. (2004) presented results on maximum jump heights of rockfall fragments on slopes with a gradient of 35°, but their results are based on a limited number of field data and do not consider the influence of neighboring trees or changes in the slope gradient. Similarly, the height distribution reported by Gsteiger (1993) was based on a small number of samples taken from only seven individual trees.

We therefore present results on impact heights identified on cross-sections sampled from mainly adult trees. These trees were analyzed from stem base to apex, with samples taken every few centimeters. Impact heights refer to centimeters above ground level on the upslope side of the tree; scars were correlated vertically so as to avoid multiple counting of the same vertical scar occurring on multiple stem discs.

In addition to the height distribution of rockfall impacts, the radial distribution of scars must be assessed before sampling, as scars or related growth features (e.g., rows of traumatic resin ducts) may only be visible on a small portion of the tree ring. For the analysis of the radial distribution of scars on the stem surface, we determined the center of each scar with respect to the slope, where 0° represents the upslope and 180° the downslope position of the stem, while 90° and 270°

Table 1. Datasets from the three case study sites used for the analysis of rockfall activity

Datasets	Tree species[a]	Trees (number)	Tree age (mean) (yr)	CS (number)	IC (number)	Events (number)	Data sources (authors)
Altdorf 1, 2, 3	Ab, Fa, Pi	3	113	307	—	189	Stoffel (2005a, b)
Diemtigtal 1	Pi	33	180	33	—	301	Perret et al. (2006b)
Diemtigtal 2	Pi	3	121	100	—	68	Perret (2005)
Diemtigtal 3	Pi, So, Ac	157	—	—	—	1704	Perret et al. (2004, 2006a)
Täschgufer 1	La	135	297	—	564	761	Stoffel et al. (2005b)
Täschgufer 2	La	18	37	270	—	180	Stoffel et al. (2005c)
Total	—	349	—	715	564	3203	

Rockfall events have been assessed through the analysis of cross-sections (*CS*), increment cores (*IC*) or – in the case of Diemtigtal 3 – the inventory of scars visible on the stem surface.

[a] Abbreviations of tree species used in this study include: Ac = *Acer pseudoplatanus* L., Ab = *Abies alba* Mill., Fa = *Fagus sylvatica* L., La = *Larix decidua* Mill., Pi = *Picea abies* (L.) Karst, So = *Sorbus aria* (L.) Crantz and *Sorbus aucuparia* L.

stand for the two segments of the stem surface located perpendicular to the slope.

Visibility of scars on stem surfaces

A further problem of identifying impacts of past rockfall activity resides in the fact that trees possess the potential of overgrowing injured tissue and, thus, blur evidence of former rockfall events. In rapidly growing trees, small wounds may completely heal over within only a few years (Schweingruber, 1996). Similarly, data from Gsteiger (1989) show that the percentage of masked injuries greatly depends on the initial size of the scar. Among scars affecting less than 5% of the stem's circumference, four out of five were hidden, whereas when scars covered more than 15% of the stem's circumference, trees were in no single case able to completely overgrow them.

Not only the size of the scar, but also the time elapsed between impact and analysis plays an important role: Lafortune et al. (1997) realized that from injuries visible on the stem surface of 101 selected trees, only five events could be dated for the period 1571–1910, whereas the yearly number of dated scars in the 20th century rose constantly from 0.53 (1910–1949) to 3.2 after 1975. They believe that scars older than 80 years would have been completely masked and no longer remain visible externally. As a consequence, one might greatly overestimate recent rockfall activity by choosing visibly injured trees and, at the same time, unintentionally neglecting samples with hidden scars. Thus, scars visible on the stem cannot necessarily be used to investigate past frequencies (Schweingruber, 1996) unless there is quantitative data available on the number of masked scars.

We therefore investigate rockfall-induced wounds reconstructed on cross-sections and increment cores and quantify the number of injuries remaining visible on the stem surface. Besides indications on the number of visible scars, we provide data on tree age and diameter at breast height, consider averaged annual increment rates, predominant size classes of rockfall fragments as well as bark properties of the trees in question.

Scars and growth disturbances at a given height vs. injuries to the entire tree

In most parts of the European Alps, forests have protective functions and they can efficiently reduce the risk of rockfall fragments or avalanche snow from reaching inhabited areas or transportation corridors (Stoffel et al., 2006b). As a consequence, trees are protected and cannot normally be felled for analysis, which is why tree-ring studies often have to be realized with increment cores. On the other hand, it is sometimes possible to analyze cross-sections sampled from tree stumps remaining on slopes after logging activities. However, these stumps are normally quite short, leaving researchers uncertain as to whether or not tree-ring reconstructions of rockfall activity based on the lowermost decimeters of a trunk would be almost complete or – at least – representative for the event history of the entire tree. Finally, limited financial resources often do not permit extensive stem analysis when hazards and risks need to be assessed for large forested areas. Data gathered with such resource-limited investigations have repeatedly been presented as 'minimum frequencies', although no one has been able to specify what percentage of the total number of scars per tree such frequencies would represent.

We therefore want to estimate the loss of information occurring when only a limited number of increment cores are sampled or when cross-sections are taken at a predefined height. Based on observations of trunks remaining in managed mountain forest stands, we selected a 'virtual' section located at 50 cm above ground for this analysis. At this regard some questions arise: (i) can samples taken at a given height provide information on damages that occurred in the vicinity of the sampling location? (ii) can injuries occurring elsewhere on the stem be identified as well through the presence of abrupt growth reductions, reaction wood or rows of traumatic resin ducts (in conifers)?

Case study 'Altdorf' (ADF)

The protection forest above Altdorf (Uri, Swiss Prealps) extends from 440 to 1600 m a.s.l., covers more than 300 ha and has a mean slope inclination of 34° (Fig. 2a). The forest is a mixed stand dominated by beech (*Fagus sylvatica* L.) in the lower parts of the slope ($<$1200 m a.s.l.) and Norway spruce (*Picea abies* (L.) Karst.) in the subalpine zone. Rockfall is triggered by highly fissured clay and sandstone layers found on the slope and normally consists of largest cobbles or small boulders ($\varnothing \approx 40$ cm) and sometimes individual blocks of up to 10 m^3 ($>$30 tons). In summer 1973, major rockfalls (ca. 8000 m^3) originated from these clay and sandstone layers. Records of other important rockfalls can be found in local chronicles, indicating that major activities took place in AD 1268 and 1886, causing severe damage to the church and adjacent infrastructure on the valley floor.

Along the forested slope above the village of Altdorf, three adult trees were felled and a total of 307 cross-sections prepared to assess the vertical distribution and the visibility of rockfall scars on different tree species. Severely injured trees with a maximum of visible evidence of past rockfall activity were selected. These trees well record the striking effect of cobbles and

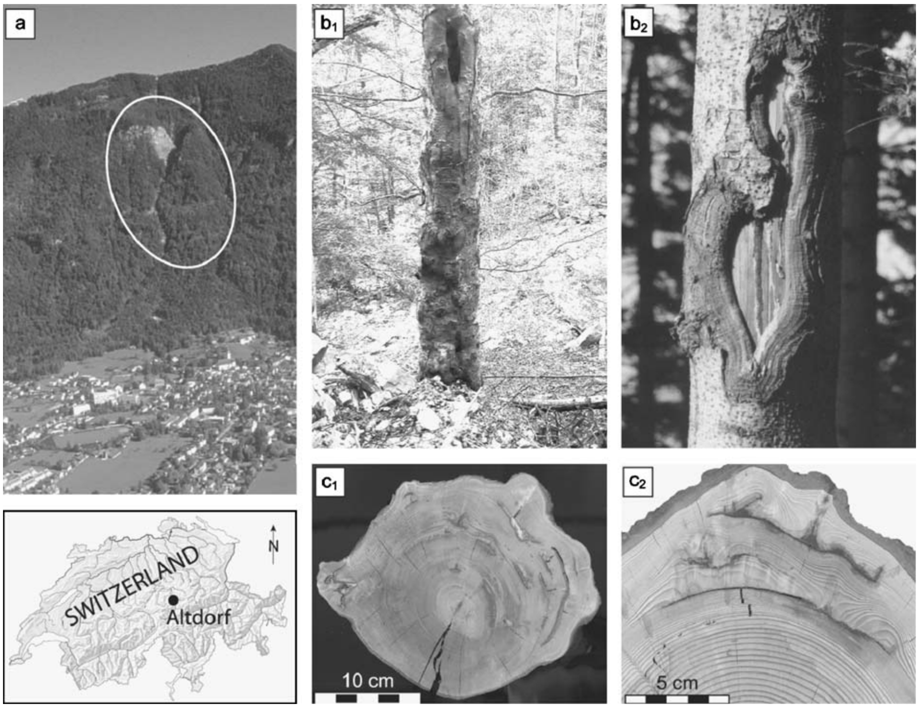


Fig. 2. Case study site 'Altdorf' (Uri, Swiss Prealps): (a) The protection forest above Altdorf prevents most rockfall fragments from reaching the settlement on the valley floor (Photo: Heinz Baumann); (b) scars visible on the stem surface of *Fagus sylvatica* L. (b$_1$) and *Picea abies* (*L.*) Karst. trees (b$_2$; vertical extension of scar: 35 cm; width: 8 cm) chosen for analysis; (c) selected cross-sections of the *P. abies* (c$_1$, sampling height: 161 cm; 3 scars) and the *F. sylvatica* trees (c$_2$, sampling height: 28 cm; 13 scars).

boulders on tree growth, but they are not suitable to assess the rockfall activity of the entire slope. Since geomorphic processes other than rockfall are absent on the investigated sites, injuries attributed to logging activity have not been considered for analysis as well as growth disturbances occurring during the juvenile phase of these trees were ignored since they could be due to ungulate browsing or fraying, we are highly confident that all injuries remaining in the selection are the result of rockfall activity alone.

Figs. 2b and c provide typical examples of how stem surfaces and cross-sections used for analysis look at ADF. Among the sampled scars, the largest one has a vertical extension of 37 cm and a width of 21 cm, while the smallest one is only $4 \times 2\,\text{cm}^2$. On the cross-sections, the average tangential length of injuries was 7 cm, with the largest scar being 27 cm and the smallest 2.5 cm.

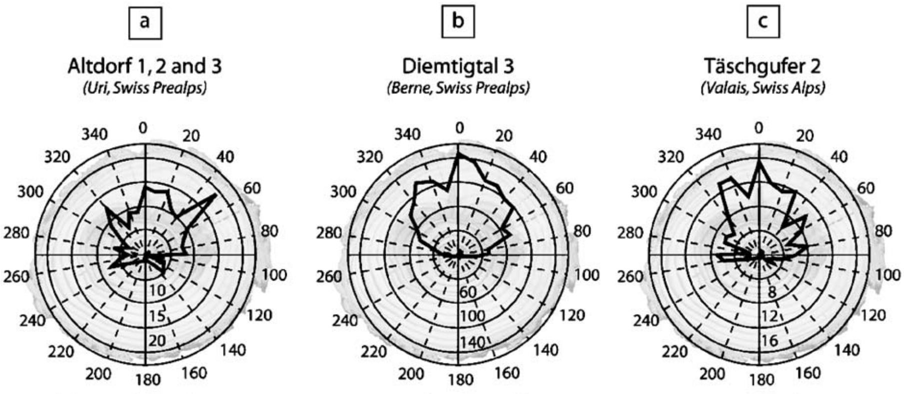
Impact heights and radial distribution of scars on the stem

Table 2 indicates that there is little difference in the mean impact heights of rockfall fragments in the selected trees (~240 cm above ground), even though at ADF 1 (*A. alba*) and ADF 2 (*F. sylvatica*) trees were located much farther away from the source area of rockfall activity than at ADF 3 (*P. abies*). In contrast, the slope steepness (45°) around the ADF 2 and 3 trees appears to influence bounce heights, resulting in some 50% of the scars occurring below ~190 cm and 75% of the wounds below ~385 cm. Maximum impact heights in these two trees are identified at ~610 cm and injuries located within the first 20 cm above ground remain rather scarce – due to the size of rockfall fragments. On the milder slope (35°) at site ADF 1, cobbles and boulders generally make lower bounces. Data, however, show that single rockfall fragments at ADF 1 are capable of extremely high bounces and, thus, cause considerable impact heights. Consequently, the uppermost impact can be identified at 930 cm, exceeding the values observed for ADF 2 and 3 by (more than) 3 m. Similarly, high bounces influence the mean impact height and the height containing 90% of all scars as well. The exceptionally high bounces of a limited number of large cobbles and small boulders at ADF 1 can only be explained by the position of the selected tree within the slope located next to a clear-cut surface. As no other trees or bushes can slow down rockfall fragments here, rocks may gain momentum and make high bounces.

Fig. 3a illustrates the radial distribution of the 307 rockfall scars identified in the sampled trees at ADF. As these adult trees expose a relatively large curved surface to

Table 2. Impact height of rockfall fragments (ro fr) reconstructed from three adult trees at Altdorf (ADF) 1, 2 and 3

Dataset	(A) General features				(B) Distribution of scar heights on stem surface					
	Trees (number)	Scars (number)	Slope	ro fr (∅)	50% (cm)	75% (cm)	90% (cm)	<0.2 m (%)	Max. (cm)	Mean (cm)
ADF 1	1	33	35°	Cobble	<162	<216	<632	6	930	233
ADF 2	1	103	45°	Cobble	<206	<392	<513	7	628	244
ADF 3	1	53	45°	Cobble	<183	<381	<499	3	596	238



Altdorf 1, 2 and 3
(Uri, Swiss Prealps)
3 adult trees (fir, beech, spruce)
307 cross-sections; 189 scars
(Stoffel 2005a, b)

Diemtigtal 3
(Berne, Swiss Prealps)
157 trees from a mixed forest
no cross-sections; 1704 scars
(Perret et al. 2004, 2006a)

Täschgufer 2
(Valais, Swiss Alps)
18 juvenile larch trees
270 cross-sections; 180 scars
(Stoffel et al. 2005c)

Fig. 3. Radial distribution of scars at the case study sites (a) ADF 1, 2 and 3 (b) DMT 3 and (c) TGF 2: In the field, 0° represents the upslope position of the tree, which more or less corresponds with the fall line of rockfall. 180° stands for the downslope position.

rockfall fragments, scars can occur almost anywhere on the upper half of the stem in the form of direct hits or glancing blows. Interestingly, a limited number of scars can be observed on the downslope side of the trunk as well, which is probably due to deflected rockfall fragments.

Visibility of scars on stem surfaces

During its 129 years of existence, the silver fir tree (ADF 1) has recorded 33 rockfall impacts. Since it was not suppressed and shows reasonable annual increment rates (0.25 cm), 84% of all wounds remain visible on the stem surface (Table 3). In a similar way, the 112-year-old beech tree (ADF 2) still shows 75% of its scars on the stem surface. It appears that as a result of the smooth and relatively thin bark as well as the lack of bark renewal ('peeling'), the stem surface of these two trees did not very efficiently mask evidence of rockfall activity and, thus, keep most of the scars caused by striking rocks visible from outside inspection.

At ADF 3 (Table 3), the Norway spruce tree has the best growth with more than 0.6 cm year^{-1}. Also, the relatively thicker bark as well as its sporadic 'peeling' determined that almost half (49%) of the 53 scars are no longer visible on the stem surface.

Scars and growth disturbances at a given height vs. injuries to the entire tree

In the silver fir of ADF 1, scars occurred from almost ground level to more than 9 m above ground. Table 4 clearly indicates that reconstructions based on one single cross-section sampled at 50 cm remain rather incomplete and more than two thirds of the scars would have remained undetected. The introduction of other growth disturbances into the analysis would have been of little help, as only a limited number of abrupt growth reductions or reaction wood were available on the cross-section. Had the investigation of the *A. alba* tree been based on the study of increment cores, only four of the 33 scars would have been identified and six other impacts inferred through the presence of anomalous growth-ring features.

In the beech tree at ADF 2, the analysis of only one cross-section would have allowed identification of 13% of all scars (Table 4). A consideration of other growth

Table 3. Presence of rockfall scars on the stem surface of trees sampled at ADF 1, 2 and 3: (A) General features. (B) Total number of scars identified on cross-sections and frequency of visible and masked scars (ro fr = size class of rockfall fragments; BH = breast height; DBH = diameter at BH; inc. yr^{-1} = annual increment rate)

Dataset	(A) General features						(B) Scar analysis		
	Species	Sample depth (no. of trees)	ro fr (∅)	Age BH (mean)	DBH (mean)	Inc. yr^{-1} (mean)	Total (number)	Visible (%)	Masked (%)
ADF 1	*Abies*	1	Cobble	129 yr	31 cm	0.25 cm	33	84	16
ADF 2	*Fagus*	1	Cobble	112 yr	21 cm	0.18 cm	103	75	25
ADF 3	*Picea*	1	Cobble	97 yr	59 cm	0.61 cm	53	51	49

Table 4. Absolute and relative numbers of the total population of scars and other rockfall-induced growth disturbances (= GD; i.e., reaction wood, abrupt growth suppression, rows of traumatic resin ducts) identified on single cross-sections (= CS) and on a series of four increment cores (= IC; 0°, 90°, 180°, 270°) at 50 cm above ground in two individual trees at ADF 1 (*Abies alba* Mill.) and 2 (*Fagus sylvatica* L.)

Dataset	General features				(A) Counted scars				(B) Other GD			
	Trees	DBH	Age	Scars	1 CS		4 IC		1 CS		4 IC	
	(number)	(cm)	(yr)	(number)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
ADF 1	1	31	129	33	10	30	4	12	12	36	10	30
ADF 2	1	21	112	103	13	13	5	5	13	13	9	9

disturbances would not have improved the results. Even less evidence of rockfall activity would have been identified on a series of four increment cores sampled at ca. 50 cm.

Since *A. alba* only exceptionally produce rows of traumatic resin ducts, the analysis of growth disturbances other than scars may only yield a very limited number of additional data on wounds located elsewhere in the stem.

Recommended sampling strategy

Dendrogeomorphological analyses of trees affected by rockfall activity generally aim at assessing the history of events for one tree in particular or – more usually – the return periods, volumes and spatial pattern of rockfall activity on entire slopes. In the case of the thin-barked *F. sylvatica* and *A. alba* trees chosen for analysis, a simple assessment of the tree age combined with counting the scars remaining visible on the stem surface would have provided a reasonable idea of how frequently rockfall occurred on the sites. In the case of the *P. abies* tree investigated, the sporadic 'peeling' of the bark removes too much evidence from the stem surface. As a result, several cross-sections should be analyzed per tree in order to improve results. As rows of traumatic resin ducts resulting from injuries located elsewhere in the stem are readily available in the tree-ring series of *P. abies*, the analysis of one cross-section every 50 cm should be sufficient to (directly or indirectly) identify most impacts caused by the large cobbles and small boulders at ADF.

Case study 'Diemtigtal' (DMT)

The second case study site is a forest stand in the Diemtigtal (Berne, Swiss Prealps). The site lies at the foot of an approximately 400 m high limestone cliff on a southeast exposed talus slope with a mean inclination of 40° (Fig. 4a). The stand is dominated by Norway spruce (77%), but other species such as *Sorbus aria* (L.) Crantz, *Sorbus aucuparia* L. or *Acer pseudoplatanus* L. occur as well (23%). The study site covers 0.3 ha, located between 1210 and 1280 m a.s.l. in the uppermost part of the talus slope. This area is in the transit zone of frequently falling pebbles and small cobbles (∅ ≈ 0.2 m). Below the study site, hiking trails and forest roads are crossing and could be endangered by rockfall.

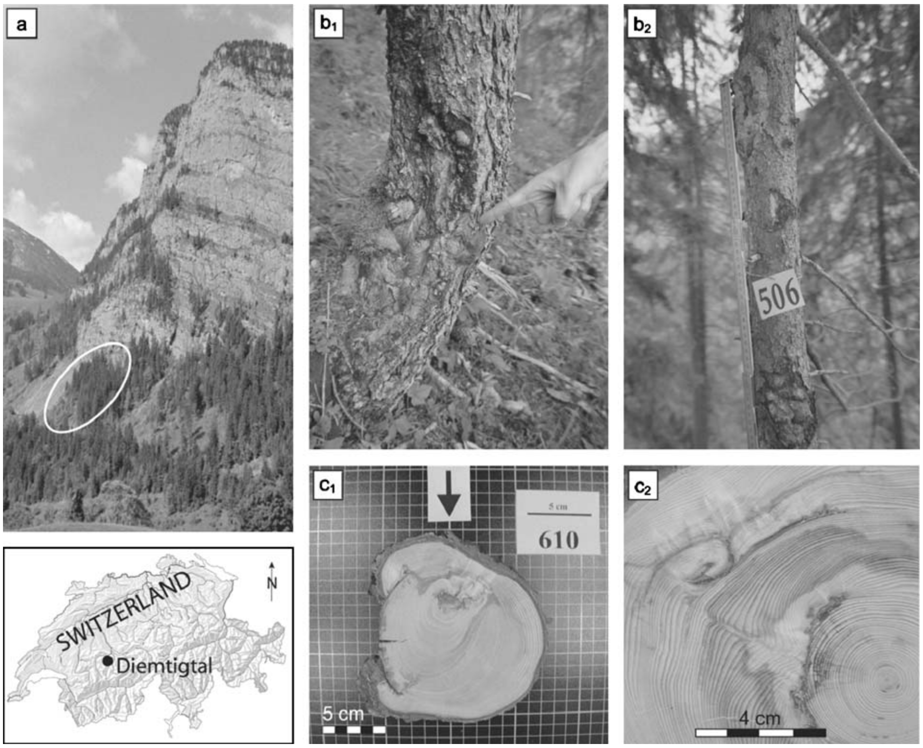


Fig. 4. Case study site 'Diemtigtal' (Berne, Swiss Prealps): (a) The protection forest at Diemtigtal is located at the foot of a 400 m high limestone cliff; (b) several fresh and old scars visible on the stem surface of two different *Picea abies* (*L.*) Karst. trees; (c$_1$) cross-section of *P. abies* (sampling height: 10 cm, 4 visible scars) and (c$_2$) two scars from another cross-section.

Table 5. Impact heights of rockfall fragments (ro fr) reconstructed at case study site Diemtigtal (DMT) 2 and 3

Dataset	(A) General features				(B) Distribution of scar heights on stem surface					
	Trees (number)	Scars (number)	Slope	ro fr (∅)	50% (cm)	75% (cm)	90% (cm)	<0.2 m (%)	Max. (cm)	Mean (cm)
DMT 2	3	68	40°	Cobble	<49	<91	<165	22	331	73
DMT 3	157	1704	40°	Cobble	<69	<121	<199	14	365	85

Data from DMT 3 are based on an inventory of scars visible on the stem surface.

On the site, an inventory of visible rockfall scars has been produced for the entire stand consisting of 157 trees with a DBH $\geqslant$ 5 cm (DMT 3). The inventory was implemented to provide forest managers with a simple but efficient tool for the assessment of rockfall activity in protection forests. Three small *P. abies* trees were felled and sections cut from base to top (DMT 2). At DMT 1, cross-sections were obtained from 33 Norway spruce trunks that remained on site after logging carried out for bark beetle control. While the analysis at DMT 2 had merely scientific goals, the study at DMT 1 aimed at assessing spatio-temporal variations of rockfall activity on the slope. As snow avalanches and excessive surface runoff have never been recorded on the slope, we are confident that all scars and rows of traumatic resin ducts selected are due to rockfall activity.

Figs. 4b and c provide examples of the stem surfaces and the cross-sections used for analysis. Scar size averaged 10.6 cm in diameter with the largest scar extending vertically for 35 cm and horizontally for 22 cm.

Impact heights and radial distribution of scars on the stem

Differently from ADF, the smaller rockfall fragments and the nearness of the source area in DMT only causes impact scars at heights well below 400 cm. Table 5 shows

Table 6. Presence of rockfall scars on the stem surface of *Picea abies* trees sampled at DMT 1 and 2: (A) general features; (B) total number of rockfall scars identified on cross-sections and frequency of visible and masked scars (ro fr = size class of rockfall fragments; BH = breast height; DBH = diameter at BH; inc. yr^{-1} = annual increment rate)

Dataset	(A) General features						(B) Scar analysis		
	Species	Sample depth (no. of trees)	ro fr ($\varnothing$)	Age BH (mean)	DBH [a] (mean)	Inc. yr^{-1} (mean)	Total (number)	Visible (%)	Masked (%)
DMT 1	*Picea*	33	Cobble	180 yr	34 cm	0.19 cm	315	32	68
DMT 2	*Picea*	3	Cobble	121 yr	7 cm	0.06 cm	68	74	26

[a] DBH measurements at *Diemtigtal II* were not taken at breast height, but at $\approx$30 cm.

Table 7. Absolute and relative numbers of the total population of scars and other rockfall-induced growth disturbances (= GD; i.e., reaction wood, abrupt growth suppression, rows of traumatic resin ducts) identified on single cross-sections (= CS) and on a series of four increment cores (= IC; 0°, 90°, 180°, 270°) at 50 cm above ground

Dataset	General features				(A) Counted scars				(B) Other GD			
	Trees	DBH	Age	Scars	1 CS		4 IC		1 CS		4 IC	
	(number)	(cm)	(yr)	(mean)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
DMT 2	3	7	121	23	3	13	2–3	10	5–6	24	5–6	24

Results represent mean values of three *Picea abies* trees sampled at DMT 2.

that there are only slight variations in maximum impact heights, with the uppermost wounds identified between 331 and 365 cm above ground. Mean impact heights of scars occurring on the 40° steep slopes at DMT 2 and DMT 3 are around $\sim$80 cm, with 90% of the injuries located below 2 m above ground.

The radial distribution of rockfall scars was assessed by means of 1704 wounds visible on the stems of 157 trees (DBH $\geqslant$5 cm) at DMT 3. Fig. 3b shows that almost two thirds of the rockfall-induced scars (63%) are located within a 90° sector of the upslope half of the tree (i.e., 315° to 45°). Differently from what we found in the three adult trees at ADF, scars are completely missing on the downslope half of the stem surface here.

Visibility of scars on stem surfaces

The visibility of scars was assessed using the datasets DMT 1 and 2. Even though Norway spruce trees were analyzed in both cases, Table 6 illustrates that the number of scars remaining visible on the stem surface and those that are masked varies widely. The covering-up process is much more complete at DMT 1, where two thirds of the scars caused by large pebbles and small cobbles can no longer be seen on the stem surface of these 180-year-old trees. We believe that relatively high increment rates as well as the sporadic scaling off of small rounded pieces of the bark helped considerably in masking evidence of past events. In contrast, three out of four scars remained discernible on the stem surface of smaller trees (7 cm DBH) at DMT 2. Here, small annual increment rates (0.06 cm) were apparently not sufficient to completely mask scars caused by the rockfall fragments.

Scars and growth disturbances at a given height vs. injuries to the entire tree

The analysis of rockfall scars at the height of 50 cm would have provided a rather incomplete picture of the real number of scars existing in the three thin stems sampled at DMT 2. In Table 7, only 13% of all scars would have been identified on the cross-section. As scars located elsewhere in the tree are often accompanied by rows of traumatic resin ducts, results can be partly improved when these signs are considered as well. Nonetheless and due to the small size of rockfall

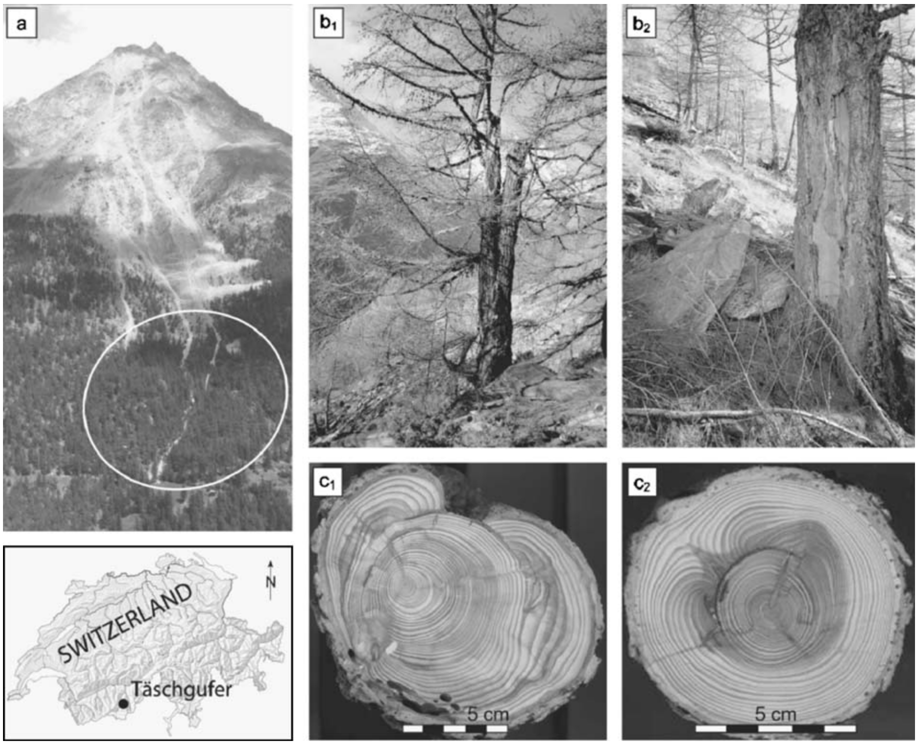


Fig. 5. Case study site 'Täschgufer' (Valais, Swiss Alps): (a) The open forest stand at Täschgufer absorbs rockfall fragments and prevents many of the boulders from reaching the transportation corridors and infrastructure in the valley floor (Photo: Theo Lauber); (b) scars visible on the stem surface of old-grown *Larix decidua* trees (vertical extension of scar: 130 cm [b_1], 85 cm [b_2]; width: 18 cm [b_1], 12 cm [b_2]); (c) cross-section of juvenile *L. decidua* trees (c_1, c_2).

fragments, only 24% of the events have been identified on a single cross-section in these slow-growing trees.

Recommended sampling strategy

As the bark of the Norway spruce trees at DMT quite efficiently masks signs of the rockfall impacts of large pebbles and small cobbles, the sole inspection of scars visible on the stem surface may not be sufficient to assess spatio-temporal variations of rockfall activity. Similarly, selection of trees must guarantee an even distribution of the samples within the study site rather than concentrating on those individuals with a large number of mostly recent and, thus, visible scars. As large pebbles and small cobbles occurring at DMT 2 appear to cause growth disturbances only in those areas of the stem located around the impact, signs of past rockfall activity would not necessarily be present on cross-sections or increment cores taken at a given sampling height. We therefore believe that an analysis of injuries caused by small rockfall fragments should preferably be performed with cross-sections and – even though rows of traumatic resin ducts are available next to the scar – samples should at least be taken every 10–20 cm in order to obtain as much data as possible on past events.

Case study 'Täschgufer' (TGF)

Rockfall fragments occurring at Täschgufer (Valais, Swiss Alps) normally consist of small and medium-sized boulders ($\varnothing \approx 80$ cm). During snowmelt, boulders are almost continuously released from the heavily disintegrated paragneissic rockwalls. The study site covers 26 ha and mean slope gradients vary between 48° in the upper part of the slope (3214 m a.s.l.), before they gradually decrease to 20° near the valley floor (1430 m a.s.l.; Fig. 5a). In the area interested by rockfall, continuous forest cover reaches 1780 m a.s.l. The stand is an almost pure forest of *Larix decidua* Mill. (95%) with sporadic *P. abies* (L.) Karst. and *Pinus cembra* ssp. *sibirica* trees. In the recent past, rockfall regularly reached the valley floor, causing damage to roads, hiking trails and farm infrastructures.

At TGF 1, 135 larch trees were analyzed using at least four increment cores per tree in order to reconstruct spatio-temporal variations of rockfall activity on the slope. The reconstruction of rockfall events was based

Table 8. Impact heights of rockfall fragments (ro fr) reconstructed at Täschgufer (TGF) 1

Dataset	(A) General features				(B) Distribution of scar heights on stem surface					
	Trees (number)	Scars (number)	Slope	ro fr (∅)	50% (cm)	75% (cm)	90% (cm)	<0.2 m (%)	Max. (cm)	Mean (cm)
TGF 1	135	761	25°	Boulder	<150	<210	<360	2	400	174

Table 9. Presence of rockfall scars on the stem surface of *Larix decidua* trees at TGF 1 and 2: (A) general features; (B) total number of scars identified on increment cores (TGF 1) and cross-sections (TGF 2) and frequency of visible and masked scars (ro fr = size class of rockfall fragments; BH = breast height; DBH = diameter at BH; inc. yr^{-1} = annual increment rate)

Dataset	(A) General features						(B) Scar analysis		
	Species	Sample depth (no. of trees)	ro fr (∅)	Age BH (mean)	DBH (mean)	Inc. yr^{-1} (mean)	Total (number)	Visible (%)	Masked (%)
TGF 1	*Larix*	135	Boulder	297 yr	49 cm	0.16 cm	761	10	90
TGF 2	*Larix*	18	Boulder	24 yr	7 cm	0.29 cm	180	47	53

on scars, the presence of callus tissue, abrupt growth reductions and rows of traumatic resin ducts. In the upper parts of the forest stand, 18 small *L. decidua* trees were felled and analyzed from base to top (TGF 2) in order to assess the intra-seasonal dynamics of rockfall activity. A total of 270 cross-sections were prepared for analysis and events reconstructed with scars and rows of traumatic resin ducts. Disturbances during the juvenile growth period of the larch trees were not considered, as these could be the result of ungulate browsing and fraying, or a reaction to snow pressure. We also excluded those areas of the slope subjected by debris-flow activity to avoid misinterpretation. In this way, we are very confident that we interpreted rockfall activity exclusively from growth disturbances (i.e., scars, reaction wood and rows of traumatic resin ducts).

Figs. 5b and c provide examples of material used at TGF. Detailed information on the nature of scars on stem surfaces exists for TGF 2, indicating a mean scar surface of 75 cm^2. Due to the small DBH of the young trees of this dataset, the horizontal dimension of injuries remained quite limited, whereas the vertical extension reached a maximum of 75 cm (mean: 16 cm, min.: 4 cm). Among the scars still visible on stem surfaces at TGF 1, very large ones can frequently be observed, with vertical extensions attaining a height of up to 2.5 m (Schneuwly, 2003).

Impact heights and radial distribution of scars on the stem

Data on the vertical distribution of scars at TGF 1 are based on impacts remaining visible on the stem surface of 135 trees. Even though the study site is located several hundred meters away from the source area, the rockfall fragments involved are of considerable size and the forest stand is loosely structured with only 150 trees ha^{-1}, the small-to-medium-sized boulders apparently do not gain enough momentum to make very high bounces. Table 8 shows that the moderate slope (25°) as well as the roughness and damping of the underground determined a mean boulder impact height of 174 cm and a maximum at 400 cm. As half of the scars occur (well) below 150 cm above ground, it is also conceivable that some impacts are the result of rolling rather than jumping rockfall fragments.

Data on the radial distribution of scars at TGF 2 are presented in Fig. 3c. Results again show that most of the scars are located externally on the upper half of the stem. As rather large fragments hit rather thin stems, in the present case, we have found a concentration of scars between 330° and 30°. Scars located elsewhere on the stem surface are far less abundant. Injuries occurring on the downslope half of the stem probably are secondary effects of rockfall impacts such as tension cracks or scars caused through the propagation of sinusoidal shock-waves in the stem itself (so-called 'hula-hoop effects'; Dorren and Berger, 2005).

Visibility of scars on stem surfaces

The results from ADF and DMT pointed out that major differences exist in the number of visible scars, depending on the tree species, the age and the annual increment rates of trees. Data from the larch trees at TGF 1 and 2 seem to confirm these assumptions.

In Table 9, the percentage of scars remaining visible on the stem surface proves to be very low in the 297-year-old larch trees at TGF 1. Here, as little as ~10% of

Table 10. Absolute and relative numbers of the total population of scars and other rockfall-induced growth disturbances (= GD; i.e., reaction wood, abrupt growth suppression, rows of traumatic resin ducts) identified on single cross-sections (= CS) and a series of four increment cores (= IC; 0°, 90°, 180°, 270°) at 50 cm above ground

Dataset	General features				(A) Counted scars				(B) Other GD			
	Trees	DBH	Age	Scars	1 CS		4 IC		1 CS		4 IC	
	(number)	(cm)	(yr)	(mean)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
TGF 2	18	7	24	8	3	37	2	25	4	50	3–4	44

Mean values of 18 *Larix decidua* trees sampled at TGF 2.

all reconstructed rockfall impacts are still visible on the stem surface today.

Although short time elapsed between impact and assessment in the relatively young larch trees at TGF 2, more than half of all scars caused during only the last two decades are no longer visible externally (Table 9). These results are even more surprising since scars at TGF tend to be much larger than in the other study sites due to the considerable size of rockfall fragments. We believe that the thick bark of *L. decidua* could efficiently mask evidence of past events, as it grows abundantly and sporadically scales off its outermost layers.

Scars and growth disturbances at a given height vs. injuries to the entire tree

The small- and medium-sized boulders caused relatively large scars in the larch trees at TGF 2. As a result, 37% of the scars could be identified on one single cross-section at the height of ca. 50 cm (Table 10). Rows of traumatic resin ducts are frequent in the tree rings following cambial damage and they help – together with reaction wood and abrupt growth reductions – to identify 50% of all rockfall-induced evidence on only one cross-section of these larch trees (Table 10).

The size of scars and the abundant presence of resin ducts also facilitate the identification of rockfall events in increment cores. Here, 25% of the scars have been found and 44% of all events assessed on the increment cores (Table 10).

Recommended sampling strategy

Like in the *P. abies* at ADF 3 and DMT, larch barks mask a considerable part of the past impacts, even if these are caused by small to medium-sized boulders. This means that the sole analysis of scars visible on the stem surface cannot provide reliable information on spatio-temporal patterns of rockfall. An assessment of past activity should also be based on tree-ring analysis. Best results are obtained with multiple cross-sections, but increment cores were used successfully since scars were quite large. In addition, rows of traumatic resin ducts are available at various levels, even if the damage itself is located meters away from the sampling height. We believe that a reconstruction of rockfall activity at TGF could be realized even with three cross-sections taken, respectively, at 1, 2 and 3 m from the ground or with at least a set of four increment cores each extracted at the same height.

General discussion and conclusions

The objective of the present article was to point out problems arising during reconstruction of past rockfall activity using trees and tree-ring series. Data from three case study sites located in the prealpine and alpine environments of Switzerland were used to investigate impact heights and the radial distribution of scars on stem surfaces. In addition, we quantified the number of hidden scars (i.e., 'masked' or 'blurred evidence') and the loss of information involved when samples are only taken at one specific height. Even though results obtained in this paper cannot claim to be either conclusive or exhaustive, they provide valuable insights on different aspects of rockfall–tree interactions on forested slopes.

In this sense, we are able to compare mean and maximum impact heights occurring in forests with different slope gradients and varying size classes of rockfall fragments. Results clearly show that impact heights generally increase on steeper slopes and that the size of rockfall fragments, the distance of the source area or surface parameters (i.e., roughness and damping) would influence momentum and bounce heights.

The present study also focused on the number of scars remaining visible on the stems of trees. The results indicate that the visibility of scars depends on the tree species, the thickness and other properties of the bark. Old scars were most efficiently masked in *L. decidua* trees due to the sporadic scaling off of the outermost layers of their thick and rough bark. In trees with thinner and smoother barks, such as *A. alba* or *F. sylvatica,* old scars remained largely visible on the stem. Studies based on visible scars (Jahn, 1988; Gsteiger, 1993; Baumgartner, 2002; Perret et al., 2004) should as well take account of the most frequent size classes of rockfall fragments and annual increment rates of trees, as these factors strongly influence the number of visible scars.

We also suggest that trees should be selected more randomly in this type of studies in order to avoid that recent rockfall activity, large injuries or disturbances in slowly growing trees are overestimated and, on the other hand, past rockfall activity, small scars or wounds in fast growing trees underestimated. The distribution of visible scars should be used as an indicator for the sampling height, but not as the main criterion for the selection of trees. Sampling a large number of trees may further reduce the risk of incomplete or unbalanced reconstructions.

The co-occurring analysis of rockfall-related growth disturbances – such as rows of traumatic resin ducts, reaction wood or abrupt growth reductions – would considerably improve results (i) in studies where tree felling is not possible and only increment cores can be extracted for analysis or (ii) on sites where only tree stumps remain after timber harvesting.

On study sites with medium- to large-sized rockfall fragments and resin-producing trees, as at TGF 1 and 2, signs of past events are abundantly present on single cross-sections or on a series of increment cores sampled at 50 cm above ground. As a consequence of the considerable impact forces and the large scars produced, chances are that signs of past rockfall activity would be present at sampling height in these trees, even though they have been hit elsewhere on the stem. In contrast, Perret et al. (2006b) report that the large pebbles and small cobbles occurring at DMT 2 would only cause growth disturbances around the impact and, thus, marks would not be necessarily present on cross-sections or increment cores taken at a given sampling height. We therefore recommend analyzing multiple cross-sections instead of increment cores and assessing growth disturbances other than scars, when impacts are caused by small-sized rockfall fragments.

As previously stated, research should further investigate the wound healing process and ask questions like: how long does a tree need to completely mask external scars? What are the driving factors of this process and to what degree can they be influenced by the difference of sites, species or growth conditions?

Particular attention should also be given to the influence of bark properties on the occurrence of scars in trees, aspect largely unexplored in tree-ring–rockfall research. Analyses of impacts caused by forest fires clearly indicate that trees are more susceptible to cambium damage and scarring as long as their trunk circumference remains <40 cm (Hengst and Dawson, 1994; Pinard et al., 1997; van Mantgem and Schwartz, 2003; Wilson and Witkowski, 2003; Schoonenberg et al., 2003). Would young and slowly growing trees be more vulnerable, with scarring influenced both by the age and growth rate, as suggested by Guyette and Stambaugh (2004)? Even so, future investigations should try to differentiate impact intensities and study their effect on scar formation or growth disturbances, as Hohl et al. (2002) emphasize that, in the case of hail, only extreme events would be able to leave injuries on branches of Mountain pine (*Pinus mugo* var. *uncinata*). To what extent can bark properties prevent the occurrence of cambial damage in trees and, as a consequence, hinder researchers from studying signs of past rockfall activity? Further, is there a threshold bark thickness at which a tree may prevent cambial damage caused by a specific size class of rockfall fragments, as suggested for trees suffering from fires (Pinard et al., 1997)?

Overall, the present study has furnished valuable data on methodological problems occurring when trees and tree rings are assessed to study past rockfall activity. However, future studies will need to further investigate methodological aspects of dendrogeomorphology in order to confirm or, possibly, replace currently used approaches.

Acknowledgements

The authors express their gratitude to Marc Baumgartner and Dominique Schneuwly, whose raw data collected on different study sites allowed investigation of various aspects of tree-ring–rockfall research in this paper. We are also grateful to Michelle Bollschweiler for comments on an earlier version of the manuscript and to Heather Murray for improving the English. The reviewers Brian H. Luckman and Stella M. Moreiras are most warmly acknowledged for providing useful comments.

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