Tree-Ring Analysis and Rockfall Research: Possibilities and Limitations

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Abstract

Over the last few years, rockfall research has increasingly focused on hazard assessment and risk analysis. Input data on past rockfall activity were gathered from historical archives and lichenometric studies or were obtained through frequency-volume statistics. However, historical records are generally scarce, and lichenometry may only yield data with relatively low resolutions. On forested slopes, in contrast, tree-ring analyses may help, generally providing annual data on past rockfall activity over long periods. The purpose of the present literature review is to survey the current state of investigations dealing with tree-ring sequences and rockfall activity, with emphasis on the extent to which dendrogeomorphology may contribute to rockfall research. A brief introduction describes how dendrogeomorphological methods can contribute to natural hazard research. Secondly, an account is provided of the output of dendrogeomorphological studies investigating frequencies, volumes, spatial distributions or triggers of past rockfall activity. The current and potential strengths of dendrogeomorphology are then presented. In a final step, we mention weaknesses of tree rings as natural archives of past rockfall activity are discussed and promising directions for further studies outlined.

Keywords: rockfall, tree rings, dendrogeomorphology, frequency, spatial patterns, seasonality

Introduction

In mountainous regions, rockfalls repeatedly impinge on inhabited areas or transportation corridors, where they occasionally destroy buildings or even cause fatalities. As a result, rockfalls have become one of the most intensely studied geomorphic processes of the cliff zone. Initially, studies mainly relied on direct observations in the field (Gardner 1983) or lichenometric analysis (McCarroll *et al.* 2001) to derive frequencies, volumes or spatial aspects of past rockfall activity.

More recently, research has gradually evolved in the direction of hazard assessment and risk analysis. Data on past rockfall activity is commonly gathered from historical archives (Barnikel 2004) and further investigated with frequency-volume statistics (Dussauge *et al.* 2003) or frequency densities (Malamud *et al.* 2004).

However, Guzzetti *et al.* (1999) pertinently emphasize that historical records are only rarely available and difficult to obtain for single events or event-prone areas. Lichenometry also has its limitations, as the method (i) is hindered by a paucity of widely accepted measurement and analytical procedures (Bull & Brandon 1998) and (ii) may only yield relatively low-resolution data. Finally, observation-based rockfall studies consider present rates of activity and rarely extend for more than a few years, thus making it difficult to scale-up results either spatially or temporally (McCarroll *et al.* 1998). As a consequence, information on frequencies (*how often?*), volumes (*how large?*), spatial distributions (*where?*), the influence of climatic parameters (*why?*) or seasonality (*when?*) of past rockfall activity remains scarce and, for the most part, fragmentary.

Tree rings, in contrast, have the potential to yield yearly resolved data on frequencies, volumes, spatial distributions and the seasonal timing of past events (DeGraff & Agard 1984). Consequently, tree rings have been widely used, over the last decades, in the analysis of landslides (e.g., Fantucci & Sorriso-Valvo 1999, Stefanini 2004), debris flows (e.g. Baumann & Kaiser 1999, Stoffel *et al.* 2005a), flooding (e.g. LePage & Bégin 1996, St. George & Nielson 2003) or snow avalanches (e.g. Hebertson & Jenkins 2003, Stoffel *et al.* 2006a).

In contrast, tree rings have only rarely been taken into account when investigating rockfall on forested slopes (Stoffel 2006a), even though Schweingruber (1996: 272) persuasively argued that "geomorphological

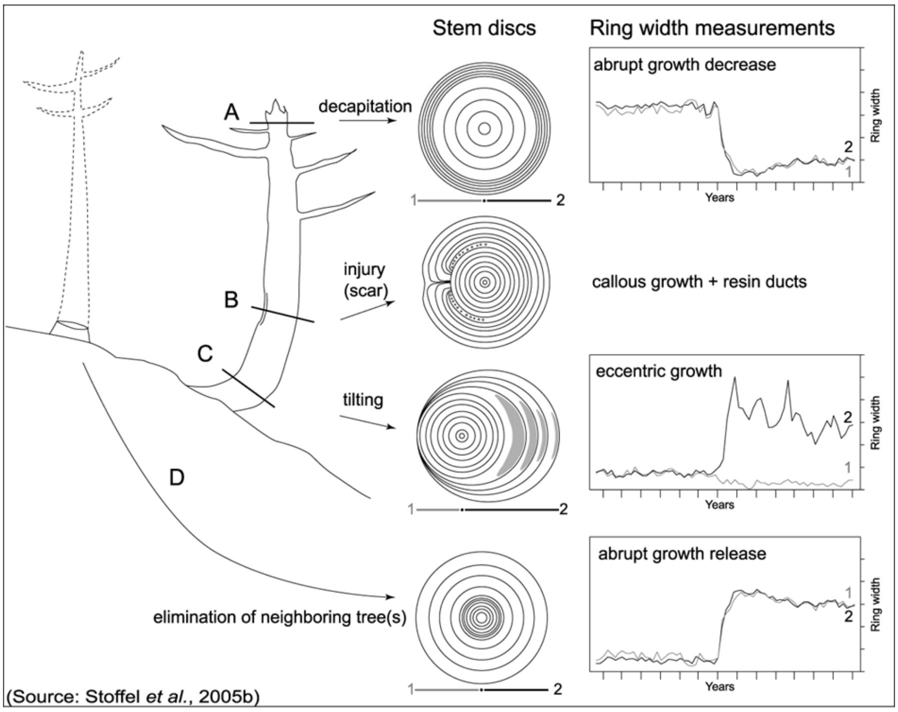

Fig. 1. Evidence used to infer rockfall events from tree-ring series.

processes in mountain forests are very common and only dendrochronology is able to provide information about the frequency and extent of the past events". Therefore, the aim of this literature survey is to illustrate the potential of dendrogeomorphology. Examples from the Swiss Alps are given of how past frequencies, the spatial distribution or seasonality of rockfall have been studied using dendrogeomorphological techniques. Finally, the strengths and weaknesses of tree rings as natural archives of past rockfall activity are discussed and promising directions for further studies outlined.

Methods

Dendrogeomorphological analyses are based on the fact that trees react to any kind of geomorphic events with growth anomalies in the tree-ring structure. Figure 1 illustrates that geomorphic impacts caused by rockfall can lead to cell formation concentrating in areas vital for survival after decapitation and the loss of main branches; scars that become overgrown after injury and a gradual straight- tening of the stems after tilting (i.e. instability or unilateral pressure) through the formation of reaction wood. The elimination of trees through geomorphic events can result in growth release in undamaged neighboring trees as they take advantage of improved environmental conditions. Finally, cambial damage also leads to the formation of rows of traumatic resin ducts in certain conifer species (Stoffel 2006b).

As growth cycles in trees are driven by the seasonality of climate in temperate zones, the 'vegetation period' (i.e. cell growth) roughly lasts from May to September in the Northern Hemisphere and can be divided into two distinct periods: At the beginning of the growth cycle, large thin-walled earlywood cells are formed in conifers. Later on, reproductive cambium cells start producing smaller and denser latewood cells. Thereafter, cell growth ceases and 'dormancy' sets in (October to April). As trees react immediately to any type of disturbance, the position of abnormal growth features affecting a tree ring, such as scars, callus tissue, rows of traumatic resin ducts or reaction wood, can be used as dating indicators for the intra-seasonal timing of events with (almost) monthly resolutions (Stoffel & Beniston 2006). Further information on the different approaches used in tree-ring-rockfall research can be found in Wiles *et al.* (1996) or Stoffel (2005b)

In this article, the term "rockfall" is used to describe the free or rebounding fall of individual or a limited number of superficial rockfall fragments from cliff faces down steep slopes (Selby 1993), with volumes involved generally < 5 m^3 (Berger *et al.* 2002).

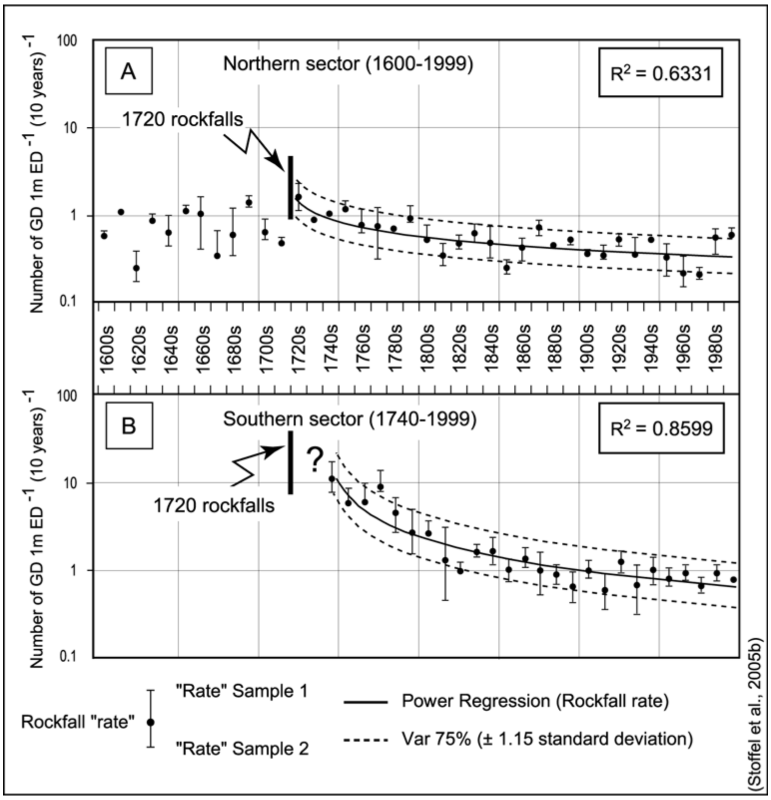

Fig. 2. Reconstructed "rockfall rate" at Täsch (Swiss Alps): (A) In the northern sector, analyses cover the last four centuries (1600–1999), indicating that the large 1720 rockfalls temporarily reduced the protection afforded by the forest. (B) After the elimination of the forest in the southern sector by the 1720 event, the recolonizing trees permanently improved their protective function, reducing the number of rockfall impacts on the trees sampled by almost 13 times since the 1740s (for localization see Fig. 3).

Rockfall frequencies (*how often?*) and volumes (*how large?*)

Rockfall frequencies and volumes can be assessed through the analysis of a sufficient number of trees growing on forested rockfall slopes. In old-growth forest stands, scars may become overgrown and no longer visible on the stem surface. As a result, special care has to be addressed to the selection of trees which should be chosen more randomly so as 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 (Stoffel & Perret 2006).

An example of reconstructed rockfall frequencies is illustrated in Figure 2. On this forested slope near Täsch (Valais Alps, Switzer- land), the assessment of rockfall frequencies was realized in two different sectors of the slope and past rockfall frequencies recon- structed with a rockfall rate for the last four centuries (Stoffel *et al.* 2005b). Results clearly show that rockfall has continuously caused injuries to the trees sampled for analysis. There seems to have been no period since AD 1600 without rockfall, and activity most commonly consisted of low magnitude-high frequency events. Tree-ring and age structure analyses also allowed identification of one high magnitude-low frequency event, which almost completely destroyed the forest stand in the southern sector of the slope in 1720 and lead to largely increased rockfall activity in this part of the slope in the subsequent decades. In the northern sector, trees sampled were disturbed considerably during the rockfalls but largely survived. Reconstructed data further show that the forest recolonizing the southern sector after the 1720 event gradually improved its protective function, reducing "rates" by a factor of 13 between the 1740s and the 1990s.

The "rockfall rate" represents the decadal number of rockfall injuries recorded in all samples per meter of DBH (diameter at breast height) exposed to rockfall. The integration of decadal DBH increment rates of every individual tree is crucial for the assessment of rockfall frequencies, as thick stems expose a larger target (DBH) to falling rocks and boulders than thin ones and large trunks are more likely to be subject to impacts. For further details see Stoffel *et al.* (2005b) or Perret *et al.* (2006).

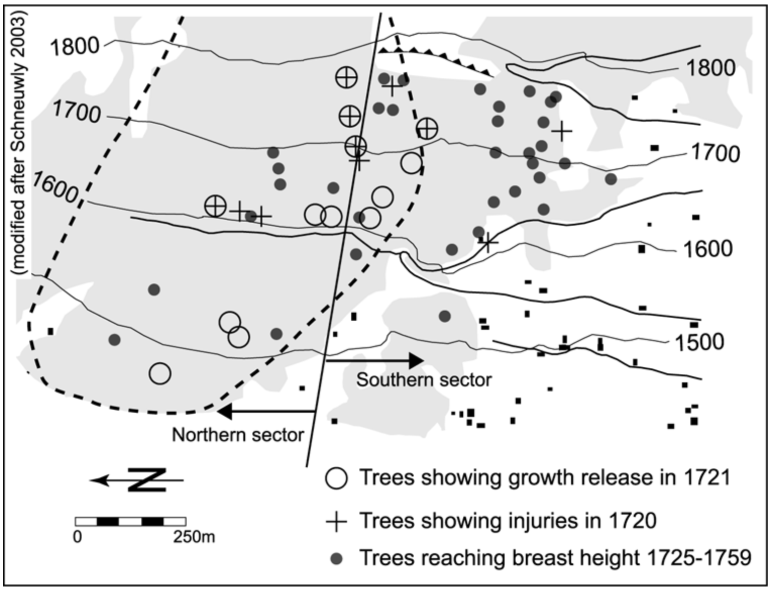

Fig. 3. Damage resulting from the 1720 rockfall at Täsch (Swiss Alps). Thirteen trees have been injured (+) and 11 trees show an abrupt growth release starting in 1721 (∘). The recolonization of the rockfall slope (•) in the succeeding decades (1725–1759) most probably represents a reaction to the 1720 rockfall event.

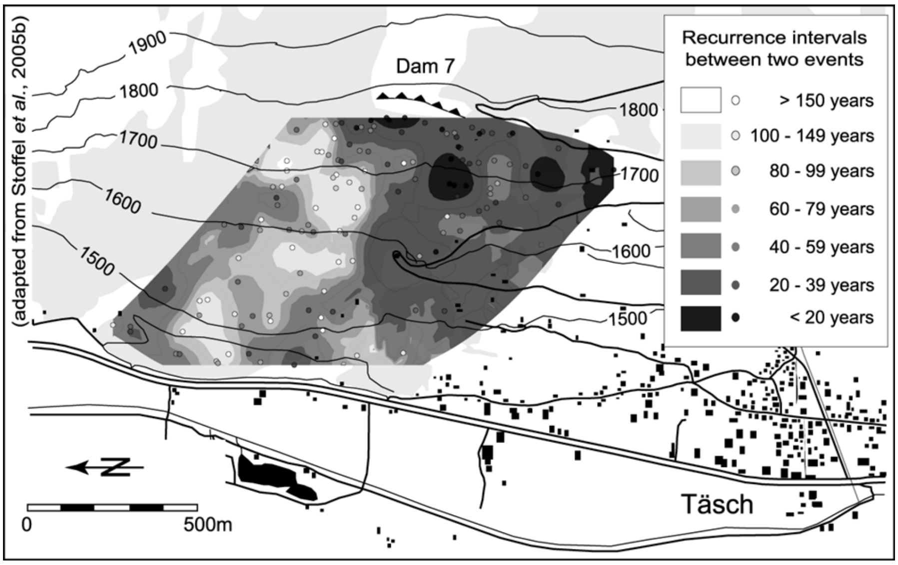

Fig. 4. Recurrence intervals of injuries for the forest stand investigated at Täsch (Swiss Alps). Intervals designate the number of years passing between two reconstructed growth disturbances on a single tree.

The damage caused by the high magnitude event in 1720 is given in Figure 3, indicating that 13 trees were injured, whereas 11 trees reacted with a growth release starting in 1721. These trees presumably benefited from the sudden elimination of neighboring trees, which improved their own growth conditions. Figure 3 also shows that, as a consequence of the high magnitude event in 1720, trees abundantly re-colonized the slope. Between 1725 and 1759, 25% of all sampled trees reached breast height. Most of the successor trees were located in the southern sector of the slope.

Spatial variations of rockfall activity (*where?*)

The spatial distribution of rockfall activity can reveal the maximal range, lateral dispersion or the distribution of recurrence intervals on forested slopes. Gsteiger (1993) was the first to attempt to illustrate spatial variations in rockfall activity by analyzing the number and distribution of scars visible on stem surfaces to derive rockfall activity maps. While Gsteiger's approach nicely illustrated the presence or absence of rockfall impacts on trees, no information was given on recurrence intervals or the number of reconstructed scars.

So far, the spatial distribution of recurrence intervals of rockfall activity was only reconstructed in two sites of the Swiss Alps using dendrogeomorphological approaches. Based on 564 increment cores sampled from century-old trees growing on the Täschgufer slope (Täsch, Valais Alps), Stoffel *et al.* (2005b) used interpolations to represent the position of scarred trees and the time elapsed between single events. As can be seen from Figure 2, data reveal considerable spatial differences in recurrence intervals across the slope, ranging from < 10 years in some areas to > 150 years in others. In general, rockfall seems to have caused more damage in the southern part of the slope than in its northern part.

Influence of climatic parameters on the release of rockfall (*why?*)

The influence of changes in seasonal temperature and precipitation regimes on rockfall activity was analyzed on a forested slope located at the foot of Schwarzenberg (Diemtigtal, Bernese Prealps). Here, Perret *et al.* (2006) assessed spatial and temporal variations of rockfall activity since AD 1881. Their data show a highly significant, positive trend in rockfall frequencies over the last century and especially since the 1950s, reason why they have been compared to century-long temperature and precipitation records from neighboring stations.

The results of this comparison are given in Figure 5, indicating that mean annual as well as summer and winter temperatures are positively correlated with the rockfall rate at a high level of statistical significance ($p = 0.000$ for all correlations). Thus, high temperatures are connected with increased "rockfall rates" on this site, whereas low temperatures result in decreased activity. On the other hand, precipitation totals showed no significant correlation with the "rockfall rate".

In line with findings of Matsuoka & Sakai (1999), temperature presumably plays a predominant role for the release of rockfall at Schwarzenberg. Increased winter temperatures could favor the occurrence of more frequent freeze-thaw cycles in the rock cliff and thus facilitate weathering and the production of rockfall fragments. However, for a detailed exploration of frost action in rock layers, temperatures within the cliff as well as local topographic conditions should be investigated in greater detail, as they play a decisive role in determining whether freezing occurs or not (Carey & Woo 2005).

Seasonality of rockfall activity (*when?*)

The seasonal timing of rockfall activity can be assessed by analyzing the position of scars or rows of traumatic resin ducts within individual tree rings, as illustrated in Figure 6A. Stoffel *et al.* (2005c) analyzed the seasonality of rockfall activity with 180 scars and adjacent rows of traumatic resin ducts identified in 18 European larch trees at Täschgufer (Täsch, Valais Alps). Results cover 25 years of rockfall activity (1977–2001) and are given in Figure 6B, demonstrating that the occurrence of rockfall was mostly restricted to the dormant season of trees (88%). In contrast, only 12% of the injuries occur within the vegetation period, with scars identified less frequently during the period of earlywood (5 %; June to mid July) than latewood formation (7 %; mid July to September). Direct observations on the slope confirm these findings, indicating that rockfall activity is highest in April and May, when global insolation on the west-facing Täschgufer slope gradually rises and the active layer of locally existing permafrost (> 2500 m a.s.l.) starts to thaw along with the ice formed in bedrock joints. In contrast, rockfall at Täschgufer seems to be neither influenced by thunderstorms in summer nor abundant rainfall in autumn.

The same approach was also used by Perret *et al.* (2006) who analyzed the seasonal timing of events in growth rings of Norway spruce trees at Schwarzenberg (Diemtigtal, Bernese Prealps). Here, seasonal frost prevails and there is no permafrost. As can be seen from Figure 6C, scars and resin ducts most commonly occurred before the onset of the 'vegetation period' (74%) between 1950 and 2002. However, scars caused during 'dormancy' are less predominant at Diemtigtal and rockfall events during the 'vegetation period' are more frequent; with 15 % of all scars found in earlywood and 11 % in latewood cell layers.

The approach used for this investigation of intra-annual differences in rockfall activity on forested slopes can be given with almost monthly resolution for events occurring within the vegetation period. For rockfall occurring within the dormant season, tree-ring analysis needs, however, to be completed with direct observations on the site.

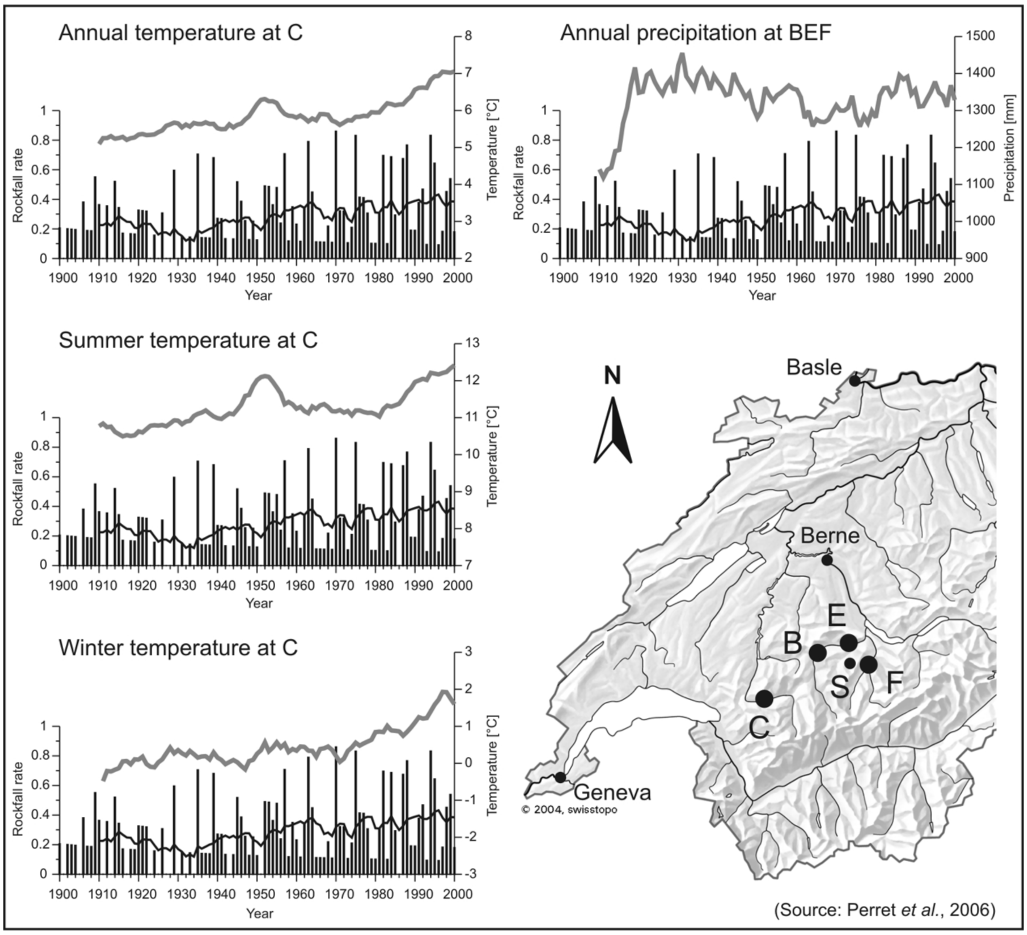

Fig. 5. Correlation between the 10-yr moving averages of the "rockfall rate" at Schwarzenberg (S) in Diemtigtal (Swiss Prealps) and the annual as well as summer and winter temperatures of Château d'Oex (C), and the annual precipitation at BEF from 1901–2000 (B = Boltigen, E = Erlenbach i. S.., F = Frutigen).

Strengths and limitations of tree-ring-rockfall analyses

One of the primary strengths of dendrogeomorphology is that it can be used to supply data on rockfall activity on forested slopes where historical records are either incomplete or lacking. In such situations it can provide researchers with data on the frequencies, spatial distributions and seasonality of past rockfall events. Results from dendrogeomorphological rockfall research may be used to improve the quality of data in studies dealing with hazard or risk assessment in a number of ways:

(a) The seasonal timing of rockfall activity can be estimated to help in the better management of risks on hiking trails allowing them to be closed during periods of enhanced rockfall activity;

(b) Seasonal differentiation of events may also be integrated with analysis focusing on other features such as transportation corridors or inhabited areas;

(c) Engineers can be provided with information on where and how often rockfall events recurred in the past as well as to what maximal height rocks and boulders may bounce (Stoffel 2005a) and, thus, improve the quality of the data upon which countermeasures such as rockfall dams, barriers or restraining nets are based;

(d) The influence of rockfall protection dams on the range and distribution of rockfall events can be determined;

(e) Tree-ring data can be used so as to control results from rockfall modeling, as recently demonstrated on different slopes in Switzerland by Stoffel *et al.* (2006b);

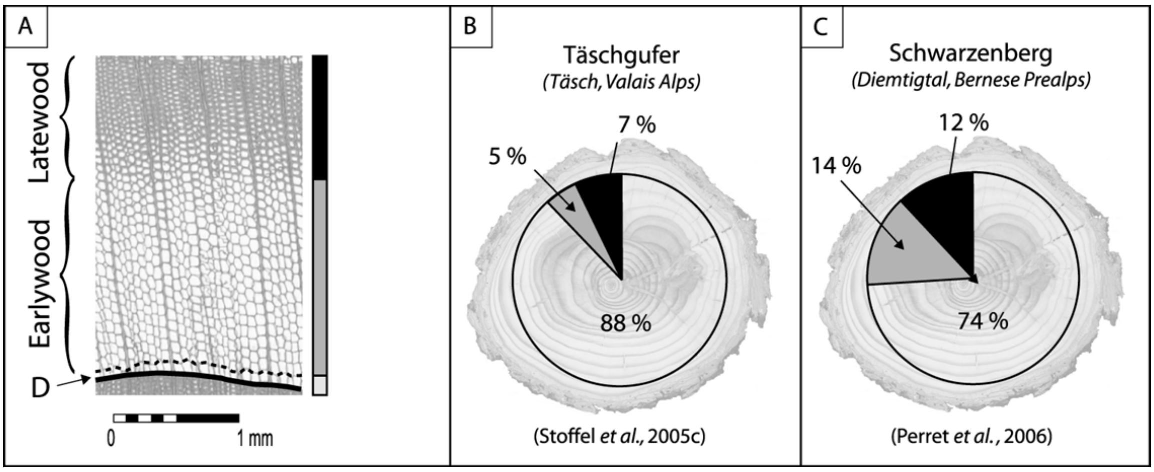

Fig. 6. (A) During the period of cell growth, trees first form thin-walled earlywood cells before they start to produce thick-walled latewood cells. At the end of the vegetation period, cell formation ceases and dormancy sets in. The seasonal timing of rockfall activity was assessed on two different slopes in Switzerland, namely on the (B) Täschgufer (Swiss Alps) and at (C) Schwarzenberg (Diemtigtal, Swiss Prealps).

(f) Forest managers can use dendrogeomorphological studies to define their future priorities (Kienholz & Mani 1994, Berger & Rey 2004). As Motta & Haudemand (2000) pertinently argue, appropriate management and accurate evaluation of the ecosystem integrity of protection forests not only relies on information dealing with past silvicultural treatments, but also has to consider past evidence of disturbances such as rockfall.

Although this review clearly shows that dendrogeomorphology has an enormous potential for showing yearly fluctuations, decadal ratios or spatial distribution in rockfall activity over several centuries, there are a number of weaknesses. Techniques and methods need further refinement, and sampling strategies such as the determination of sampling heights or the choice of trees have to be carefully established, as they strongly influence the quality and quantity of results. Similarly, because trees may overgrow wounds and blur evidence of past events on the stem surface, cross-sections and increment cores should be selected randomly within the forest stand. Otherwise, there is a danger of overestimating recent and underestimating older rockfall events.

Future directions

In the future, tree-ring analysis will need to incorporate further promising research directions, such as the analysis of rockfalls triggered during seismic activity. The role of earthquakes on rockfall activity has so far only been investigated through lichenometric (Bull & Brandon 1998) or radiocarbon methods (Becker & Davenport 2003), but not with dendrogeomorphology. There is thus a great need to incorporate this promising aspect into tree ring and rockfall research as well. While snow avalanches, debris flows or flooding have been analyzed extensively using tree-ring series, studies of past rockfall activity are comparatively scarce. The considerable potential of dendrogeomorphology for rockfall research has been largely ignored. Thus, we should need Solomina's (2002) plea for comparative studies conducted in different regions aimed at identifying or possibly even quantifying the influence of past and current climate variations on rockfall activity.

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