Analyzing rockfall activity (1600–2002) in a protection forest—a case study using dendrogeomorphology

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Abstract

For the first time, dendrogeomorphology has been used to investigate spatial and temporal variations of rockfall activity in a protection forest. We report results of 564 cores from 135 severely injured *Larix decidua* Mill. trees on the west-facing Täschgufer slope, Swiss Alps. While trees sampled reached an age of 297 years on average, the oldest one attained breast height in AD 1318. For reasons of sample depth, the analysis was limited to the period 1600–2002. In total, we reconstructed 741 growth disturbances (GD) during the last four centuries. Impacts were most commonly found in trees located in the southern part of the slope, where GD recurred more than once per decade. In contrast, trees in the northern part were less frequently disturbed by rockfall and define recurrence intervals of more than 150 years.

Throughout the last four centuries, rockfall has caused GD to the trees sampled on the Täschgufer slope, most frequently in the form of low magnitude–high frequency events. In addition, we identified one high magnitude–low frequency event in 1720, which displaced the forest fringe of the northern sector a considerable distance downslope and eliminated an entire forest stand. To analyze past rockfall activity, we introduce a "rate" defined as the number of impacts per meter width of all tree surfaces sampled per decade. Results clearly demonstrate that this rockfall "rate" continually decreased in both sectors after the large 1720 rockfall event. Significantly low rockfall "rates" can be observed during the 1850s, 1960s and 1970s in the northern and during the 1820s in the southern sector. In contrast, high rockfall "rates" were identified during the 1870s and 1990s in the northern, and during the 1770s in the southern sector.

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. In the recent past, "rates" oscillated around 0.7 GD 1 meter width^{-1} (10 years)$^{-1}$. In the well-established forest of the northern sector, the efficacy of the protective forest was temporarily reduced by the rockfalls in 1720, resulting in increased rockfall "rates". Since then, the protective

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function of the forest stand has increased again, resulting in a rate of 0.4 GD 1 m width^{-1} (10 years)$^{-1}$ during the late 20th century.

1. Introduction

Rockfall represents the most intensely studied geomorphic process of the cliff zone in mountainous areas (Luckman and Fiske, 1995). Nevertheless, little information exists on how rockfall frequencies and magnitudes vary over time. So far, studies have mainly been based on short-term observations of contemporary rockfall activity in the field (e.g., Luckman, 1976; Douglas, 1980; Gardner, 1980, 1983), rendering it difficult to estimate long-term accretion rates. Long-term estimates of rockfall accumulation rates have, in contrast, been derived from accumulated talus volumes (e.g., Rapp, 1960). But such rates may, as Luckman and Fiske (1995) pertinently object, neither be representative of the present-day rockfall activities nor of those that prevailed in the past. Hétu and Gray (2000) managed to avoid this problem by combining present-day processes and stratigraphic data to study the dynamics of scree slopes throughout the post-glacial period. On slopes composed of siliceous lithologies, lichenometry has repeatedly been used to evaluate the mean age or activity of talus surfaces (André, 1986, 1997) or to estimate 50-year and long-term rates of rockfall accretion (Luckman and Fiske, 1995). Finally, McCarroll et al. (1998) combined a lichen-based analysis of spatial and temporal patterns of past rockfall activity with a modeling approach.

Simultaneously, investigations of forest–rockfall interactions have tended to evolve towards the analysis of mountain forests as a means of protection against rockfall (e.g., Bebi et al., 2001; Berger et al., 2002). Hétu and Gray (2000) indicated that forest cover would provide effective protection in the case of low magnitude–high frequency rockfall events, but could not prevent the devastating effects of high-magnitude events.

However, quantitative information on the effect of forest stands on the downslope movement of rockfall boulders remains insufficient. The previously mentioned studies on rockfall activity or the distribution of scree give a reasonable overview of long-term fluctuations, but they lack more detailed data on decadal or even yearly variations in rockfall activity on a slope. In contrast to their use in other mass movement processes (e.g., Shroder, 1980; Wiles et al., 1996; Fantucci and Sorriso-Valvo, 1999; Solomina, 2002, Stoffel et al., in press), tree-ring analyses have been used only rarely in rockfall research, where the focus in these few cases has been on sedimentation rates, the dynamics of forest fringes on scree slopes (Lafortune et al., 1997) or the seasonal timing of past rockfall activity (Stoffel et al., in press).

It is therefore the purpose of the present paper to use tree-ring analysis in order to: (1) analyze the magnitude and frequency; (2) determine spatial variations; (3) derive decadal and yearly variations in rockfall activity on a forested slope. In it, we use a rockfall "rate" to reconstruct and evaluate fluctuations in rockfall activity. Results were obtained from two neighboring sectors differing in both their age structure and recurrence intervals. In total, 564 increment cores of 135 European larch trees (*Larix decidua* Mill.) were analyzed, documenting decadal and yearly variations in rockfall activity on a forested slope at Täschgufer (Valais, Swiss Alps) over more than 400 years.

2. Study area

The area investigated was the west-facing Täschgufer slope. As can be seen from Fig. 1, the Täschgufer slope descends from the Leiterspitzen summit (3214 m a.s.l.) in the Siviez–Mischabel nappe, southern Swiss Alps. Rockfall frequently occurs on the slope, originating from the heavily disintegrated gneissic rockwalls below the Leiterspitzen summit. Layers of this weak bedrock generally strike SSW and dip WNW with angles of 40–80° (Lauber, 1995), thus containing joints dipping out of the slope. The main rockfall source areas on the slope are located between
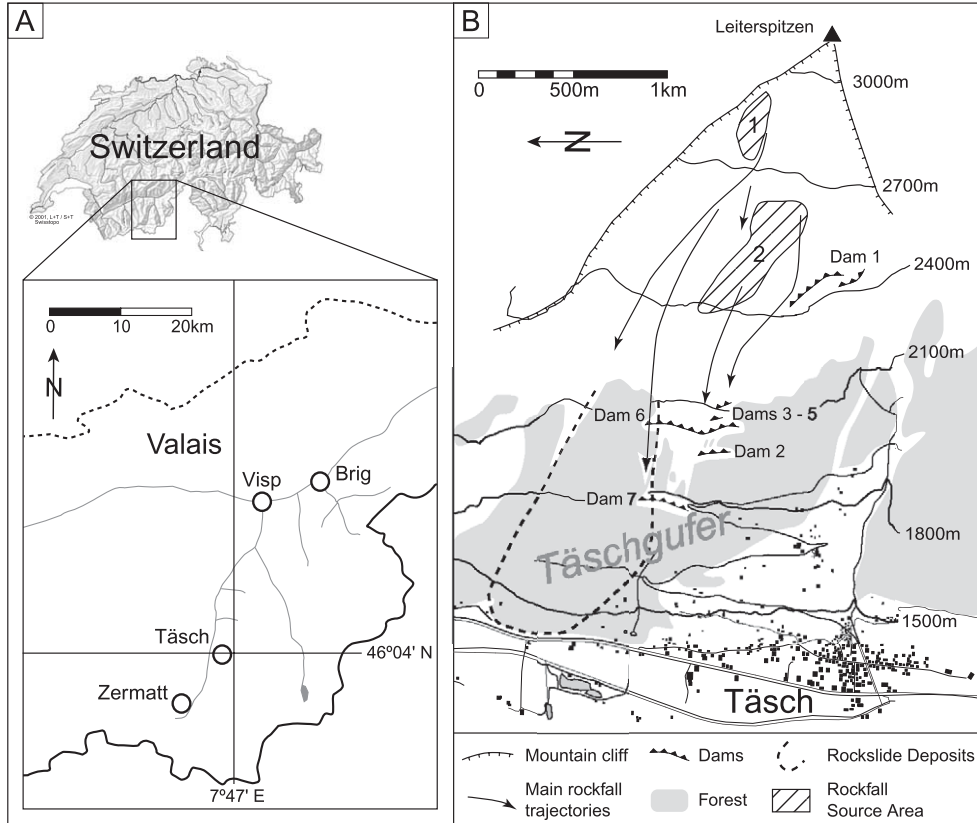
Fig. 1. Location of the study site. (A) The Täschgufer slope is located in the southern Swiss Alps, northeast of the village of Täsch. (B) The detailed sketch illustrates the rockfall slope with the main rockfall source areas and trajectories, the rockslide deposits and the dams built after 1988 (Dams 1–7).

2300 and 2600 m a.s.l. (Rockfall Source Area 2) and above 2700 m a.s.l. (Rockfall Source Area 1), where bedrock is highly fractured with many joints. As suggested by a locally calibrated permafrost distribution model (Gruber and Hoelzle, 2001), Rockfall Source Area 2 would be located on the borderline between seasonal frost and permafrost environments. The presence of contemporary permafrost is confirmed on the southern edge of the slope between 2400 and 2500 m a.s.l., where ground ice was encountered during construction work (Haeberli, 1992; see Fig. 2).

On the upper slope, mean slope gradients locally rise up to 48° and gradually decrease to 20° near the valley floor. The volume of single rockfall fragments normally does not exceed 2 m³. Besides frequent rockfall activity, one rockslide is noted in chronicles (Zurbriggen, 1952). Its age was estimated with lichenometry to be at least 600 years BP (Joris, 1995). The spatial extent of the rockslide deposits can be seen in Fig. 1B. Furthermore, small debris flows may occur at Täschgufer. Single events generally amount to a few cubic meters and move downslope in well-defined channels. In contrast, snow avalanches have never been witnessed on the slope.

The forest at Täschgufer predominantly consists of *L. decidua* Mill. trees, accompanied by single *Picea abies* (L.) Karst. and *Pinus cembra* ssp. sibirica trees. Although the regional timberline is located at approximately 2300 m a.s.l. in the immediate neighborhood, continuous forest cover reaches only 1780 m a.s.l. in the most heavily affected areas of the active rockfall slope. As shown in Fig. 1B, surfaces are sparsely wooded in this part of the slope and large areas remain free of vegetation.
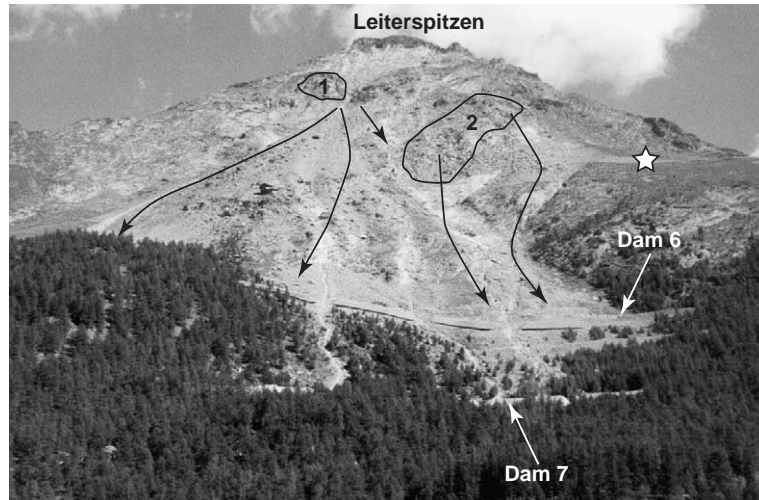
Fig. 2. View of the upper Täschgufer slope and the Leiterspitzen summit (3214 m a.s.l.): Note the main Rockfall Source Areas (1, 2), the main rockfall trajectories (arrows) and the zone where ground ice has been encountered (star) during construction works (Photo: D. Schneuwly).

In the recent past, rockfall regularly caused damage to roads and hiking trails. For example, on October 6, 1985, single blocks reached the valley floor, damaging agricultural buildings in the village of Täsch (Valais). According to Lauber (1995), rockfall activity at Täschgufer apparently increased in the 1980s and again after 1993. These observations have recently been confirmed with dendrochronological analysis (Stoffel et al., in press), which further indicated that almost 90% of the intra-annual rockfall activity at Täschgufer occurs in April and May. As a response to the increased rockfall activity, five deflection dams were erected in 1988 (Dam 1) and 1989 (Dams 2–5; see Fig. 1B). In the late 1990s, two large protection dams completed the construction works on the slope (Dams 6–7, see Fig. 2).

3. Material and methods

3.1. Sampling strategy

As shown in Fig. 3, dendrogeomorphological investigations were conducted in the protection forest[1]

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[1] Protection forest: forest stand which directly protects people, buildings and infrastructure against the impacts of mass wasting events such as landslides, rockfall or snow avalanches (see Brang, 2001).

north of Täsch (1440 to 1760 m a.s.l.). Within the study area covering approximately 39 ha, virtually all trees (*L. decidua* Mill.) show visible damage related to rockfall activity (i.e., broken crowns or branches, scars, tilted stems). We sampled severely affected trees with obvious signs of growth disturbances (GD) from both the rockslide deposits (northern sector) and the southern sector of the slope. The separation of the two parts of the slope (Fig. 3) is based on the different origins of rockfall material. As indicated in Fig. 1B, trees located in the northern sector are normally subject to rockfall fragments from the Rockfall Source Area 1, while the samples growing in the southern sector are predominantly influenced by boulders originating at Rockfall Source Area 2. We therefore analyze the two parts of the slope separately and refer to them as "northern sector" and "southern sector". In addition, we excluded a well-defined area in the southern sector, which is influenced by both rockfall and debris flow activity (Fig. 3).

In this investigation, at least 4 cores were extracted per tree using increment borers. Fig. 4 illustrates that one core was taken upslope (core c), one downslope (core d) and two cores perpendicular to the slope (cores a, b). In the case of visible scars, further increment cores were extracted from the wound and the overgrowing callous tissue. In addition to the disturbed trees sampled at Täschgufer, we sampled undisturbed reference trees from a forest stand located
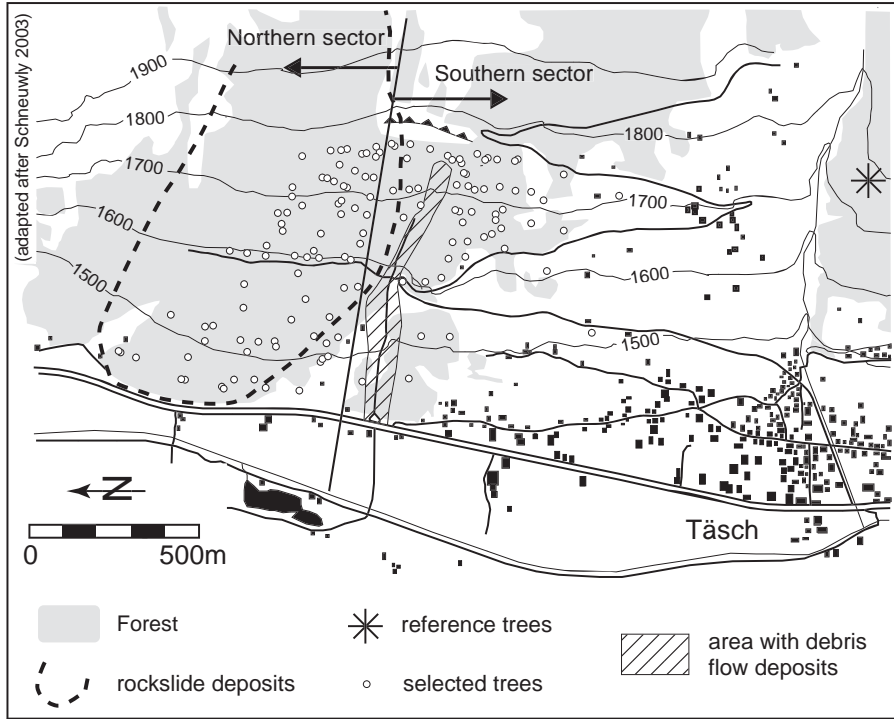
Fig. 3. Distribution of the 135 *L. decidua* Mill. trees sampled on the Täschgufer slope (1440 to 1780 m a.s.l.). The area influenced by both debris flow and rockfall activity (hatched surface) has been excluded.

south of the rockfall slope, indicated in Fig. 3. For every reference tree, two cores per tree were extracted perpendicular to the slope (cores a, b). In total, 154 *L. decidua* Mill. trees were sampled (598 cores) in the
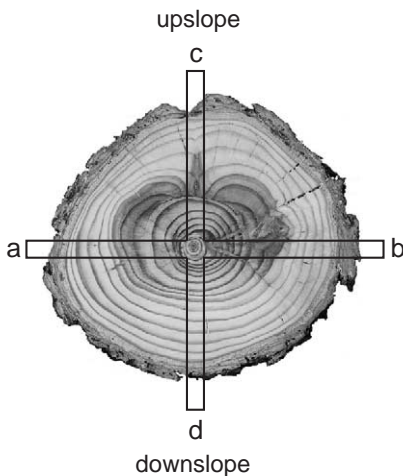
fall of 2002: 135 trees (564 cores) from the rockfall slope and 17 trees (34 cores) from the undisturbed reference site south of the rockfall slope. Increment cores of the reference trees were extracted at breast height (≈ 130 cm), whereas those from the disturbed trees were–whenever possible–taken at the height of the visible damage.

Data recorded for each tree sampled included (1) determination of its 3D-position on the slope with a compass and an altimeter (x- and y-values, elevation a.s.l.); (2) sketches and position of visible defects in the tree morphology such as scars, broken crowns or branches, candelabra trees and tilted stems; (3) the position of the sampled cores (i.e., a, b, c, and d); (4) diameter at breast height (DBH) derived from circumference measurements; (5) data on neighboring trees, micro-topography and/or rockfall deposits.

3.2. Tree-ring analysis and rockfall

Samples were analyzed and data processed following the standard procedures described in

Fig. 4. Core sampling procedure for individual trees.

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Bräker (2002). Single steps of sample analysis included surface preparation, skeleton plots as well as ring-width measurements using digital LINTAB positioning tables connected to a Leica stereomicroscope and TSAP 3.0 (Time Series Analysis and Presentation) software (Rinntech, 2003). Growth curves of the disturbed samples were then crossdated with the reference chronology (1596–2002) constructed from 17 undisturbed *L. decidua* Mill. trees. This procedure allowed differentiation of climatically driven fluctuations in tree growth within the study area from GD caused by rockfall activity (Cook and Kairiukstis, 1990).

Growth curves were then used to determine the initiation of abrupt growth reductions or recovery (Schweingruber, 1996). In the case of tilted stems, both the appearance of the cells (i.e., structure and color of the reaction wood cells) and the growth curve data were analyzed (e.g., Shroder, 1980; Braam et al., 1987; Fantucci and Sorriso-Valvo, 1999). Further focus was placed on the visual analysis of callous tissue overgrowing rockfall scars and traumatic rows of resin ducts (Larson, 1994; Schweingruber, 2001). As resin ducts may result from causes other than rockfall (e.g., climate, wind, insects, fraying or browsing by ungulates), thresholds were needed to determine "resin duct events" caused by rockfall activity. Criteria were defined using 270 stem discs sampled on the same slope (Stoffel et al., in press) that showed both tree damage (scars, decapitation) and resin ducts. As a result, resin ducts were only considered the product of rockfall activity if they formed (a) traumatic, (b) extremely compact and (c) continuous rows. Both the presence of resin ducts on multiple radii in a single year and the occurrence of multiple consecutive years with traumatic rows of resin ducts were used as further indicators but not a compulsory criterion. In contrast, neither dispersed resin ducts within a single tree ring nor the presence of traumatic rows of resin ducts occurring in the years following an event represents "resin duct events". Characteristic examples of disturbed stem discs and respective growth curves are illustrated in Fig. 5. Reconstructed GD of individual trees were then compiled in a database (Schneuwly, 2003). For every individual tree, we determined recurrence intervals by dividing its age at breast height by the number of dated GD.

Judging the frequency or magnitude of single event years or decadal fluctuations in the number of GD proved to pose a considerable problem: So far, dendrogeomorphology has mainly involved the analysis of impacts by geomorphic processes that have a relatively large volume or surface area, such as debris flows, snow avalanches or floods. In contrast, rockfall consists of single falling, bouncing or rolling stones which may only disturb trees along their trajectories and within a range defined by the size of the clast. Further, only the effects of a single boulder are recorded, whereas the fall itself may be composite. Finally, important differences emerged as to the age of the individual trees, their DBH and their decadal DBH increment which rendered absolute comparisons of past rockfall activity difficult.

We therefore use a rockfall "rate"[2] expressed as number of rockfalls (GD) per meter width of all tree surfaces sampled per decade instead of analyzing absolute values. The "rate" is based on the idea that thick stems expose a larger target (DBH) to falling rocks than thin ones and so large trunks are more likely to be subject to GD. We then determined the yearly DBH increment of every individual tree by dividing its DBH by the number of rings between pith and sample year (2002) at breast height. In a further step, values were multiplied by the number of years a tree had existed at the beginning of a particular decade. The DBH values of all trees existing at the beginning of a particular decade were then summarized to comprise what we refer to as exposed diameter (ED; in m). To obtain the rockfall "rate", the decadal sum of GD was finally divided by the ED, indicating the number of GD recorded per meter ED and per decade. Within this study, increment rates in trees were considered to remain constant, disregarding juvenile growth or ageing trends.

In addition to the decadal rockfall "rates", the trees sampled in the two sectors were classed according to their age at breast height (oldest to youngest) and split into two samples each. In both cases, Sample 1 was formed with the uneven samples (i.e., oldest, 3rd oldest, 5th oldest, …), while Sample 2 contained the even ones (i.e., 2nd oldest, 4th oldest, 6th oldest, …).

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[2] The term 'rockfall "rate"' used in this paper is only a proxy for the true rate. We therefore keep the quotation marks whenever using this term.
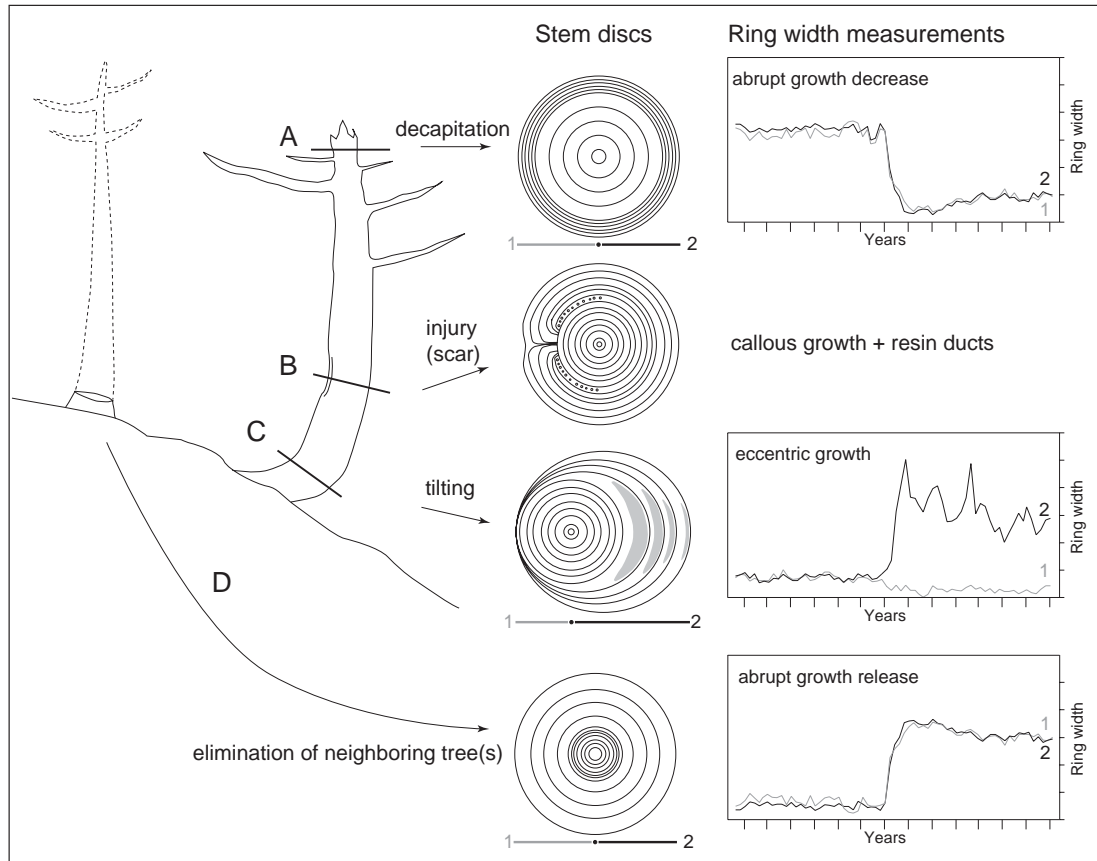
Fig. 5. Evidence used to infer rockfall events.

We then calculated rockfall "rates" for these samples as well.

In a further step, the rockfall "rates" of the entire populations as well as those of Samples 1 and 2 were converted from real into logarithmic values, a power regression trend line calculated and residuals from the regression model determined.

Due to the difficulties of dendrogeomorphological analysis in rockfall research and in order to analyze variations in decadal rockfall "rates", we arbitrarily chose a range of ± 1.15 standard errors on the regression fit, assuming a normal distribution of the residuals from the regression model, as a criterion for identifying exceptional rockfall "rates". Indeed, decadal rockfall "rates" located within these ± 1.15 standard errors (called $Var_{75\%}$) were considered to be noise and therefore insignificant. In contrast, the 25% of rockfall "rates" lying beyond these limits were subject to analysis in greater detail.

Finally, we used yearly rockfall "rates" (real values) to analyze short-term fluctuations in rockfall activity for the period 1950–2002. This use of yearly resolved data on GD also allowed estimation of the influence of anthropogenic rockfall triggering during the periods of dam construction work in 1988/89 (Dams 1–5; see Figs. 1B, 2) and 1996–1998 (Dams 6 and 7) as well as the distribution of GD thereafter.

3.3. Spatial visualization of single-tree data

Data on single trees included their position, their age at breast height, and the number as well as the years of GD. Tree coordinates were transformed into geo-objects and information from the database linked as attributes to the single trees, allowing spatial visualization of the data in a Geographical Information System (GIS). Data were investigated with the ArcGIS Geostatistical Analyst software (ESRI,

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2003a) in order to examine spatial relationships between all sample points. Following the procedure described in Johnston et al. (2001), skewed data were first transformed to make them normal. Trend analyses were then used to identify directional influences (global trends), and data detrended using second-order polynomials. In a next step, spatial autocorrelations were analyzed using spherical semi-variogram models and covariance clouds. As a result, the numbers of lags and bin sizes have been adapted. Finally, cross-validation of measured with predicted points allowed determination of mean prediction errors of the interpolations. After the exploration of the data, the Ordinary Kriging model (Johnston et al., 2001) was chosen for the visualization of continuous surfaces. Interpolations were performed including data from five neighboring trees. In angular sections, at least two trees were taken into consideration. Results were edited using ArcView 8.3 software (ESRI, 2003b). Within this study, interpolations were performed to visualize the age structure of the forest stand and the spatial distribution of recurrence intervals.

4. Results

4.1. Age structure of the forest stand

Data on the pith age at breast height indicate that the 135 sampled *L. decidua* Mill. trees are, on average, 297 years old.[3] Over the centuries, sampled trees gradually (re-)colonized the slope to build up the current forest at Täschgufer. However, we observe that 25% of the sampled trees–mostly those located in the southern sector–reached breast height between 1725 and 1759.

Fig. 6 illustrates the spatial distribution of the age structure at Täschgufer, indicating that old trees are largely concentrated on the northern part of the study area. In this sector, 78 trees were considered. The boundaries of age classes broadly correspond with the outer limits of the rockslide deposits mentioned in Section 2. The 57 trees sampled in the southern sector

are, on the other hand, considerably younger and generally started to (re-)colonize the slope in the early 18th century. The youngest trees are concentrated alongside the rockfall couloirs underneath Dam 7 and at the southeastern edge of the study area. Even so, younger trees are repeatedly located close to the forest fringes on the valley floor, where anthropogenic activity markedly influenced tree growth and succession rates (i.e., farming activities, extraction of fire- and construction wood).

The major differences in the age structure between the two sectors also appear in Table 1. While the trees sampled in this study averaged 362 years in the northern sector, they have an average age of only 212 years in the southern sector. Similarly, the oldest sample in the northern sector attained breast height in AD 1318 and the youngest tree here reached breast height in 1941. In contrast, the oldest tree from the southern sector dates to 1596 and the youngest to 1957.

4.2. Visible defects and growth reactions to rockfall impacts

Investigations permitted identification of 236 visible defects on the 135 *L. decidua* Mill. stems chosen for analysis. As illustrated in Table 2, candelabra trees (=broken crown) largely predominated among the visible defects. This growth feature occurs after the decapitation of the crown or part of the stem and could be identified in 151 cases (64%). Based on observations in the field, we believe that candelabra trees at Täschgufer were largely due to the propagation of impact energies from the lower-most part of the trunk to the apex of the stem, resulting in crown breakage between 2 and 13 m above the ground. In contrast, the decapitation of tree crowns was only rarely caused by high bounces of rockfall fragments. Recent or (partly) overgrown injuries (scars) were observed in 58 cases (25%). Finally, 27 trees (11%) were obviously tilted by rockfall impacts.

The analysis of the 564 cores allowed identification of 786 GD attributed to rockfall activity on the slope. In some cases, impacts caused GD in more than one core of the same tree, reducing the number of different rockfall events to 761. Table 2 shows the predominant occurrence of traumatic rows of

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[3] All of the numbers given below refer to age at breast height and do not indicate germination or inception dates.
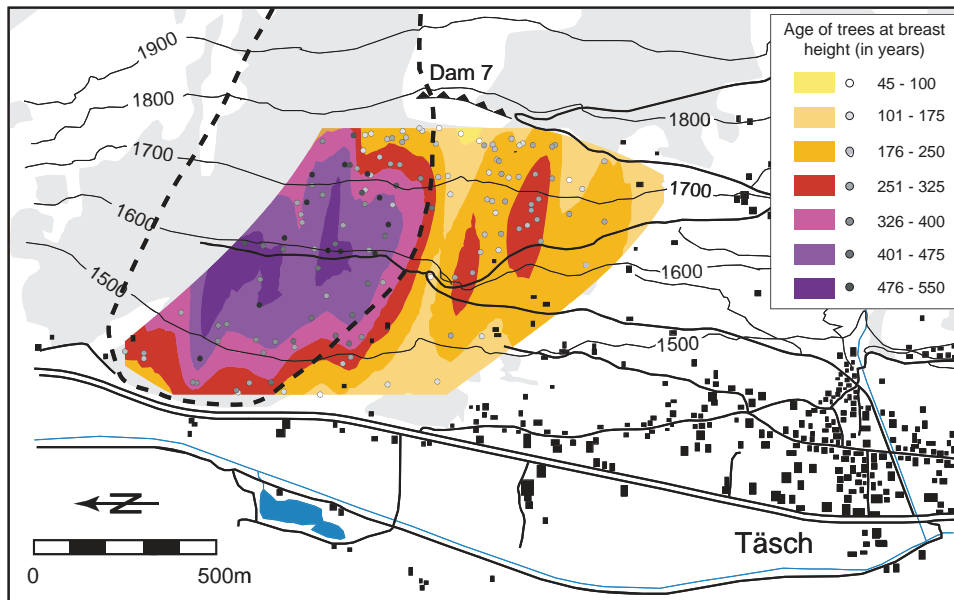
Fig. 6. Mean age of *L. decidua* Mill. trees sampled on the Täschgufer slope. The patterns have been generalized based on interpolations. Ages are for tree at breast height.

resin ducts. This feature was used in 675 cases (86%) to determine GD. Abrupt growth suppression occurred in 50 samples (6.5%), whereas abrupt growth release and reaction wood could only be found in 24 cores each (3%). Finally, callous tissue in cores proved to be rather scarce, occurring in only 13 cases (1.5%).

Characteristic increment curves of cores showing compression wood, growth suppression and missing rings after scarring are illustrated in Fig. 7: Tree A displays an abrupt growth reduction in 1908. As the indexed reference chronology–marked as REF in Fig. 7–does not show this sudden change in yearly increment, the growth suppression in Tree A was not driven by climatic variations but by stem breakage due to rockfall. The increment curves of Tree B illustrate that this tree was tilted in 1982 and started to produce reaction wood on the downhill side (core d)

thereafter, while tree-ring formation remained unaffected on the uphill side (core c). In this case, eccentric growth lasted until the core was extracted in 2002. Finally, Tree C was apparently scarred in 1970: While the callous tissue had not yet recovered the injury on the uphill side (core c), it overgrew the wound at core b–c by 1981.

4.3. Spatial distribution of growth disturbances

In the investigated forest stand at Täschgufer, reconstructed rockfall activity varied greatly across the slope. The spatial distribution of interpolated recurrence intervals are given in Fig. 8, and show that

Table 1
Pith age at breast height of the trees sampled for analysis (in years)

Pith age at breast height	Northern sector	Southern sector
Mean	362	212
Standard deviation	141.4	75.6
Maximum	684	406
Minimum	61	45

Table 2
Different types of damage observed in the field (left) and growth reactions reconstructed from increment cores (right) at Täschgufer (adapted after Schneuwly, 2003)

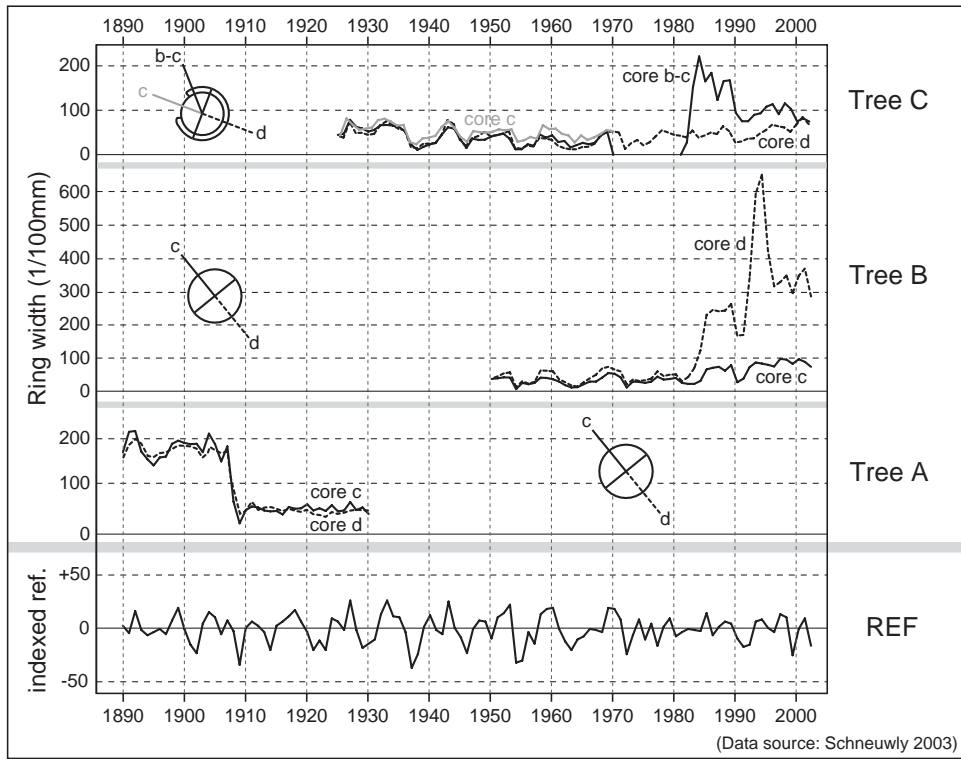| Visible defects		Growth reactions	
Broken crown	151 (64%)	Growth release	24 (3%)
Tilted stem	27 (11%)	Growth suppression	50 (6.5%)
Injuries (scars)	58 (25%)	Reaction wood	24 (3%)
		Callous tissue	13 (1.5%)
		Traumatic resin ducts	675 (86%)
Total	236 (100%)	Total	786 (100%)

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Fig. 7. Examples of growth disturbances produced by rockfall events. Tree A shows an abrupt growth reduction as a result of stem breakage in 1908. Tree B was tilted in 1982 and initiated reaction wood on the downhill side (core d) thereafter. Tree C was scarred in 1970: While the scar is not yet overgrown at core c, callous tissue overgrew the wound at core b–c by 1981. Part of the reference ring width chronology (REF) is also shown.
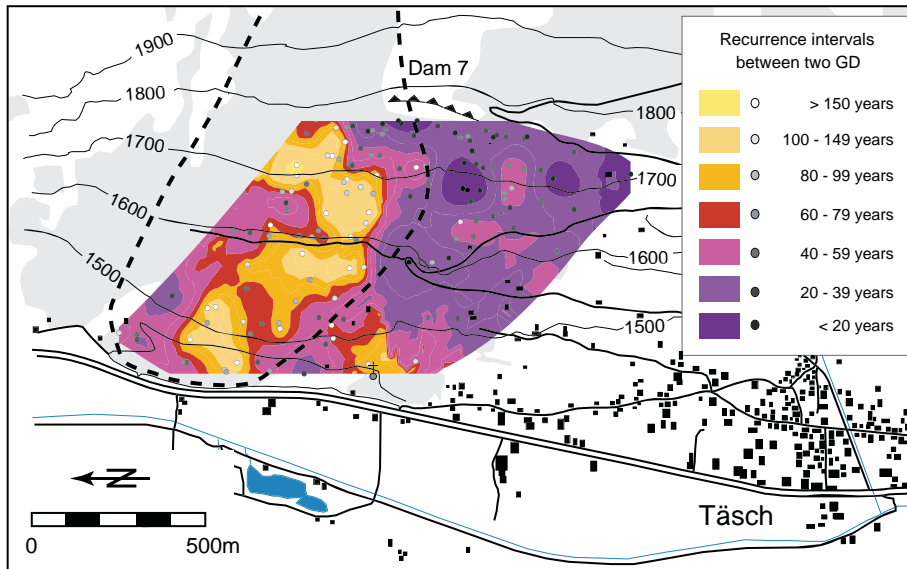

Fig. 8. Recurrence intervals of GD for the forest stand investigated. Intervals designate the number of years passing between two reconstructed growth disturbances on a single tree.

GD abundantly occurred in the trees located above 1700 m a.s.l., where surfaces gradually become more sparsely forested. Similarly, GD have repeatedly been reconstructed in trees growing in the rockfall couloirs of the southern sector below the recently built Dam 7. Here, trees were regularly disturbed by rockfall fragments and recurrence intervals were locally <10 years. In a few century-old trees growing close to the northern sector, dendrogeomorphological analysis indicates that tree growth has been disturbed almost twice a decade since the mid-19th century. In contrast, low numbers of GD can be found in trees growing in the northern sector. In this part of the slope, recurrence intervals proved to be particularly high. Here, intervals between two GD regularly exceeded 150 years and individual century-old trees even showed no GD at all. Not surprisingly, the spatial pattern of recurrence intervals largely coincides with the distribution of the age structure seen in Fig. 6 and oldest trees are commonly found in areas with relatively low numbers of GD. In contrast, youngest trees are largely concentrated in areas where rockfall repeatedly caused GD, leading to increased mortality and subsequently to higher recruitment rates by opening up sites for germination.

4.4. Rockfall magnitudes and frequencies

Throughout the last four centuries, rockfall fragments have continuously caused GD 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. In addition, 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. In the northern sector, trees sampled were disturbed considerably during the rockfalls but largely survived. Fig. 9 shows that according to the reconstructed data, 13 trees were obviously injured by abundant rockfall. Simultaneously, 11 trees reacted to the event with an abrupt growth release starting in 1721. These trees presumably benefited from the sudden elimination of neighboring trees, which improved their own growth conditions (e.g., light, nutrients, humidity). Within the northern sector, GD mainly occurred in trees located in the upper part of the slope (above 1590 m a.s.l.). Here, 16 of the existing 33 trees (48%) showed GD in 1720. In contrast, trees sampled in the lower part of
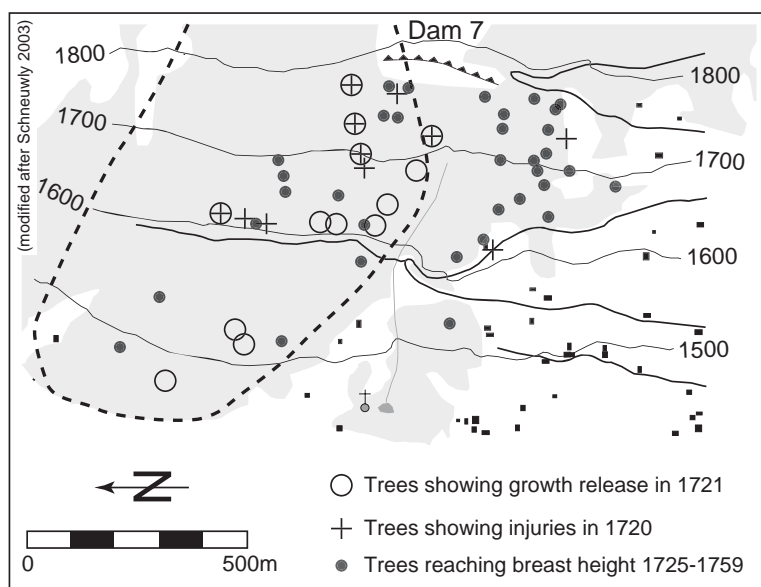

Fig. 9. Damage resulting from the 1720 rockfall. Thirteen trees have been injured (+) and 11 trees show an abrupt growth release starting in 1721 (○). The (re-)colonization of the rockfall slope (●) in the succeeding decades (1725–1759) most probably represents a reaction to the 1720 rockfall event.

the slope mostly remained unaffected by the 1720 event and scars were only present in 3 of the 21 existing trees (14%). Even so, abrupt growth releases following the event are missing here. Fig. 9 also shows that, as an indirect 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 (i.e., 34 trees). Most of the successor trees were located in the southern sector of the slope.

4.5. Decadal variations in rockfall activity

4.5.1. Northern sector (1600–1999)

Investigations of rockfall activity in the northern sector start in the year 1600, when 29 of the trees sampled were taller than breast height. We hence disregarded 12 rockfall events occurring between 1394 and 1599, since the sample depth appeared to be too low for reliable analysis and the individual trees were unevenly distributed within the sector. The number of GD was reduced to 400 events derived from 78 trees. Among all trees sampled in the sector, the DBH averaged 47.97 cm in 2002. As indicated in Table 3, the largest and smallest trees were 76.4 and 17.51 cm DBH in 2002. As a result, the decadal DBH increments varied between 0.6 and 6.29 cm, with an average increment of 1.56 cm $(10 \text{ years})^{-1} \text{ tree}^{-1}$. While the exposed diameter (ED) of the trees sampled within the northern sector only totaled 3.9 m at the beginning of the investigated period in 1600, it gradually rose to 37.8 m by 1990. Table 3 further illustrates that the decadal rockfall "rates" averaged 0.65 GD 1 m ED^{-1} $(10 \text{ years})^{-1}$.

The reconstructed rockfall "rates" of the entire population as well as the "rates" from Samples 1 and 2 are illustrated in Fig. 10A. For the period before the

Table 3
Size statistics of the trees sampled in the northern sector; DBH: diameter at breast height as measured in 2002 (in cm), 10-yr DBH: 10-year increment of the DBH (in cm), and rockfall "rates" [GD 1 m ED^{-1} $(10 \text{ years})^{-1}$]

Northern sector	DBH	10-yr DBH	Rockfall "rates"
Mean	47.97	1.56	0.65
Standard deviation	12.62	0.97	0.34
Maximum	76.40	6.29	1.53
Minimum	17.51	0.61	0.20

important rockfalls in 1720, rockfall "rates" indicate considerable fluctuations in reconstructed numbers of GD. As a result of the high-magnitude rockfalls in 1720 and the considerable damage caused to the forest fringe, the highest decadal rockfall "rate" in the last four centuries was noted in the 1720s, causing 1 GD per 0.65 m ED (i.e., a "rate" of 1.53). Since, data indicate that rockfall activity continually decreased after the 1720 event (see Fig. 10A), interrupted by decades with significantly low (1850s, 1960s, 1970s) and significantly high rockfall "rates" (1870s, 1990s).

During the 19th century, rockfall "rates" indicate rather low values during the 1850s (0.24) and, to a minor extent, the 1810s (0.36). Thereafter, rockfall caused higher "rates" during the late 19th and the early 20th century (i.e., 1870s, 1890s, 1920s, 1940s). Within the second half of the 20th century, rockfall "rates" indicate a period with low activity lasting from the 1950s until the 1970s. For the 1970s, a decadal value of 0.2 was identified, meaning that only one growth disturbance (GD) occurred every 5 m of exposed diameter (ED). This period of low activity was followed by an increase in the rockfall "rate" during the 1980s (0.54) and, even more, the 1990s (0.57). The importance of this increase as well as the influence of dam construction works on the decadal ratios of the 1980s and 1990s will be analyzed below in Section 4.6.

4.5.2. Southern sector (1740–1999)

Due to the different age structure and the large number of trees sampled that had grown after the high-magnitude rockfalls in 1720 in the southern sector, the analysis of rockfall "rates" only starts in the 1740s, when 20 of the trees sampled were greater than breast height. We disregarded 8 reconstructed GD occurring between 1657 and 1734, since the sample depth appeared to be too low for reliable analysis. In total, 341 GD were dated in the 57 trees sampled. Among the trees sampled, the DBH averaged 48.3 cm in 2002. As illustrated in Table 4, the largest tree had 79.5 cm and the smallest only 25.4 cm DBH in 2002. As a result, the decadal DBH increment greatly varied between 0.78 and 8.59 cm, with an average DBH increment of 2.70 cm $(10 \text{ years})^{-1} \text{ tree}^{-1}$. At the beginning of the investigation in 1740, the ED of all trees sampled totaled 0.9 m and gradually rose to 27.7 m by 1990.
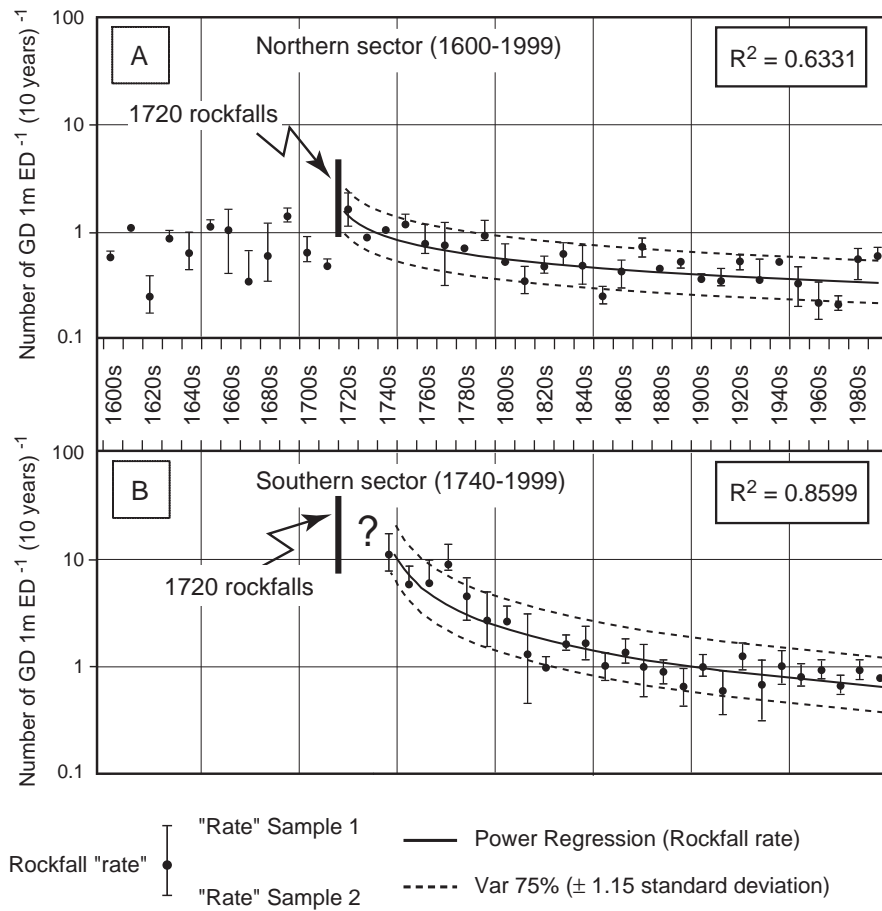
Fig. 10. Reconstructed rockfall activity. Rockfall activity is measured by the rockfall "rate" (for explanation see text). (A) In the northern sector, analyses cover the last four centuries (1600–1999), indicating that the large 1720 rockfalls temporarily reduced the protection afforded by the forest. (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.

Results on decadal rockfall "rates" in the southern sector averaged 2.36 GD 1 m ED^{-1} (10 years)$^{-1}$, which represents a value almost four times higher than

Table 4
Size statistics of the trees sampled in the southern sector; DBH: diameter at breast height as measured in 2002 (in cm), 10-yr DBH: 10-year increment of the DBH (in cm), and rockfall "rates" [GD 1 m ED^{-1} (10 years)$^{-1}$]

Southern sector	DBH	10-yr DBH	Rockfall "rates"
Mean	48.39	2.70	2.36
Standard deviation	13.89	1.58	2.70
Maximum	79.58	8.59	10.99
Minimum	25.47	0.78	0.63

that of the northern sector. Reconstructed rockfall "rates" of the entire population as well as the "rates" of Samples 1 and 2 are shown in Fig. 10B. During the early decades following the high-magnitude rockfalls of 1720, the successor trees sampled for analysis were repeatedly subject to GD. As a consequence, the highest rockfall "rate" was reconstructed for the 1740s, when almost 11 disturbances were identified per 1 m ED (i.e., a "rate" of 10.99). Similarly to the northern sector, reconstructed rockfall "rates" continually decreased in the southern sector after the high magnitude rockfalls of 1720.

Unlike the results from the northern sector with six decadal values located beyond the $Var_{75\%}$

boundaries, only two rockfall "rates" lie beyond the Var$_{75\%}$ limits here, namely, those of the 1770s and the 1820s (Fig. 10B). We note that, after a slight decrease in the 1750s and 1760s, the "rate" indicates a considerable increase in rockfall activity in the 1770s. For this period, the rockfall "rate" gives a value of 8.86 GD 1 m ED^{-1} (10 years)$^{-1}$, approaching that for the 1740s. This period of increased rockfall activity lasted until the 1780s or even 1790s. In contrast to the high magnitude rockfalls of 1720s, reconstructed data indicate that the considerable number of GD identified for the last three decades of the 18th century were not caused by one high-magnitude event, but rather by a series of years with high rockfall activity (i.e., 1772, 1774, 1779, 1783, 1792). Even though the number of GD also increased in the northern sector (see Fig. 10A), significant effects remained mostly restricted to the "rates" of the southern sector. Between the 1870s and the 1940s, comparably low numbers of GD were found in the trees sampled, resulting in a considerable decrease in rockfall "rates". During this period, the lowest rockfall "rate" of the last 260 years was derived, totaling 0.63 during the 1910s. In contrast to the northern sector, the rockfall "rate" started to increase again in the 1940s, oscillating around the calculated power regression trend line ever since. However, the changes in the rockfall "rates" seem to be less marked here. Again, the influence of the dam construction works on the decadal ratios of the 1980s and 1990s will be analyzed further down in Section 4.6.

4.6. Yearly fluctuations in rockfall activity (1950–2002)

In complement to the decadal rockfall "rates", yearly fluctuations were analyzed for the period 1950–2002. In total, we identified 172 GD, 105 in the southern (61%) and 67 in the northern sector (39%). On average, more than 3 GD year^{-1} could be identified in the 135 trees sampled.

As illustrated in Fig. 11A, the number of reconstructed GD remained on a comparably low level in the northern sector during the first three decades of investigation, when years without GD occur almost as frequently as years with GD. After 1980, rockfall repeatedly caused more GD to the trees sampled. Reconstructed data neatly reflect the period of increased rockfall activity in the 1980s and the early 1990s, as described for the Täschgufer slope by Lauber (1995). Between 1950 and 2002, yearly rockfall "rates" averaged 0.037 GD 1 m ED^{-1} year^{-1}, , indicating that approximately 1 GD was recorded for every 27 m of ED.

In the southern sector, decadal rockfall "rates" slightly increased in the 1940s and thereafter. Yearly resolved "rates" indicate that during the first three decades, (short) periods with increased numbers of GD (e.g., 1959–1964) were followed by several years with (almost) no GD (Fig. 11B). Similar to the northern sector, considerably increased rockfall "rates" can be discerned in 1980 and 1992. In contrast, the high rockfall "rate" reconstructed for 1986 (0.28) was probably restricted to the southern sector. On
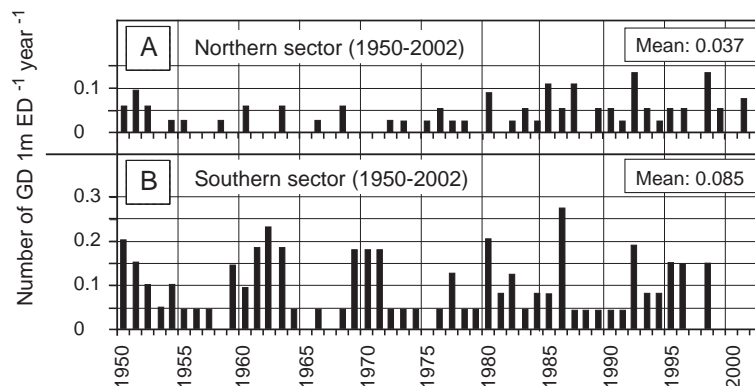

Fig. 11. Annual estimates of rockfall 1950–2002. Note the important variability in reconstructed growth disturbances and different activity in the sectors.

average, yearly "rates" totaled 0.085 GD 1 m ED^{-1} year^{-1}, indicating that more than 1 GD has been recorded per 12 m of ED.

In contrast to the results from trees located in the heavily disturbed forest stand above 1780 m a.s.l. (Stoffel et al., in press), the construction of Dams 1 to 5 (1988/89; see Fig. 1B) only slightly influenced the rockfall "rates" of the present study. In the northern sector, the two GD recorded in 1989 caused an increase in the decadal "rate" from 0.46 to 0.52. Similarly, the only GD recorded in the southern sector in 1989 influenced the "rate", resulting in a value of 0.96 instead of 0.92. In contrast, reconstructed rockfall "rates" prove to be influenced by the construction works (e.g., excavation, blastings) of the two protection dams in the late 1990s. As can be seen from Fig. 12, rockfall triggered during the

Fig. 12. Rockfall events during and after dam construction, 1996–2002. Growth disturbances have been recorded during construction works at Dam 6 in 1996 (+), Dam 7 in 1998 (▲) and in the succeeding years (●=1999; *=2001). No growth disturbances were recorded in the years 1997, 2000 and 2002.

construction of Dam 6 in 1996 (≈ 2000 m a.s.l.) caused six GD. Growth reactions were even more frequent during the construction of Dam 7 in 1998 (1780 m a.s.l.). As a result of anthropogenic intervention on the slope, six GD were caused in the northern and nine GD in the southern sector. For this reason, the rockfall "rates" of the 1990s given in Section 4.5 were clearly influenced by anthropogenic intervention on the slope, making it difficult to estimate the undisturbed rockfall frequency over this period.

As a further consequence, anthropogenic intervention on the slope hindered rockfall fragments to cause GD to the trees sampled after 1998. While no GD have been recorded since 1999 in the southern sector (Fig. 11), GD could still be identified in the northern sector. As illustrated in Fig. 12, rockfall fragments apparently passed north of the recently built dams in 1999 and 2001, causing GD to five trees in the northern sector. In the sparsely wooded areas between Dam 6 and 7, reconstructed data clearly indicate that abundant rockfall still occurs on the slope (Stoffel et al., in press). We therefore have to believe that the recently built dams efficiently stopped rockfall in the recent past and so further influenced the rockfall "rates" of the 1990s.

5. Discussion

In the study we report here, cores extracted from 135 living *L. decidua* Mill. trees allowed reconstruction of yearly and decadal rockfall activities on the Täschgufer slope. Similar to analysis used in debris flow, snow avalanche or flooding research (e.g., Schweingruber, 1996), we investigated growth disturbances (GD) in increment cores to analyze past rockfall activity. In the trees sampled, rows of traumatic resin ducts proved to be by far the most common reaction to rockfall impacts. Reaction wood, growth suppression or growth release could be identified less frequently.

We identified 741 GD covering the period 1600–2002. Impacts could be found more commonly in trees located in the southern sector of the slope, where GD rockfall recurred locally more than once per decade. According to the results, we believe that rockfall activity at Täschgufer mainly consisted of low
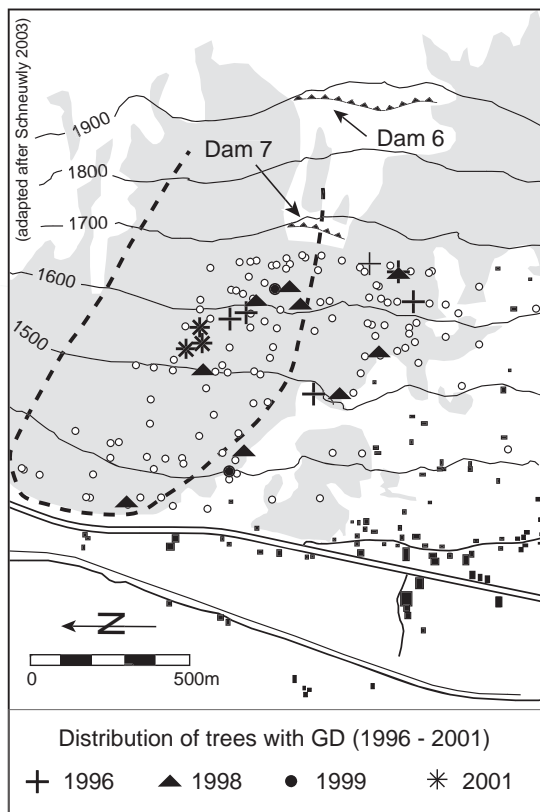
magnitude–high frequency events, considered to be typical for rockfall in alpine areas (e.g., Matsuoka and Sakai, 1999; Jomelli and Francou, 2000). The only high magnitude–low frequency event occurred in 1720, causing considerable damage to the forest in the northern sector. As a result, the forest fringe was displaced downslope. The forest stand in the southern sector was almost completely destroyed by the devastating rockfalls in 1720. Data also show that the high rockfall frequency both inhibited recolonization and caused considerable damage in the juvenile trees of the southern sector thereafter. As a result, considerable differences emerge in the reconstructed numbers of GD between the northern and the southern sector.

In contrast to the analysis of geomorphic processes involving larger volumes, such as debris flows, snow avalanches or flooding, results from dendrogeomorphological investigations of rockfalls cannot immediately be used to illustrate yearly or decadal fluctuations in rockfall activity. As rockfall consists of single falling, bouncing or rolling stones, a single event may only disturb trees along its trajectory. Furthermore, trees at Täschgufer were of uneven age and displayed abundant differences in their DBH as well as the decadal DBH increment. As a result, the number of reconstructed GD steadily increased with time, reaching maximum values for the recent past. Even so, a ratio dividing the decadal number of GD by the number of trees (Tr) existing at the beginning of a particular decade cannot concisely represent the importance of decadal rockfall activity. As illustrated in Table 5, GD–Tr ratios regularly increased in periods following major modifications in the sample depth (e.g., 1690s and after 1720 in the northern and after the 1770s in the southern sector), leading to an overestimation of past rockfall activity. Even so, it appears that the GD–Tr ratio may not correctly represent the rockfall activity during the late 20th century, when the lack of succeeding trees and an almost constant sample depth again influence the ratios.

The rockfall "rate", considering the exposed diameter (ED=DBH of all sampled trees within a sector at the beginning of a particular decade), proved, instead, to be a more reliable indicator of past rockfall activity, as it takes account of the diameter exposed to rockfall fragments as well as the

Table 5
Growth disturbance data by decades for the two sites; GD=growth disturbances; ED=exposed diameter, i.e., DBH of all trees sampled at a particular decade (in m); Tr=decadal number of existing trees, rockfall "rates"=number of GD per 1 m ED and decade; GD–Tr ratio=number of GD per tree (Tr) and decade

Decade	GD		ED (m)		Tr		Rockfall "rates"		GD–Tr ratio	
	N	S	N	S	N	S	N	S	N	S
1600s	2	–	3.9	–	29	–	0.51	–	0.07	–
1610s	4	–	4.2	–	29	–	0.95	–	0.14	–
1620s	*1*	–	4.6	–	30	–	0.22	–	***0.03***	–
1630s	4	–	5.0	–	35	–	0.79	–	0.11	–
1640s	3	–	5.5	–	38	–	0.55	–	0.08	–
1650s	6	–	5.9	–	39	–	1.01	–	0.15	–
1660s	6	–	6.4	–	40	–	0.94	–	0.15	–
1670s	2	–	6.9	–	43	–	0.29	–	0.05	–
1680s	4	–	7.5	–	45	–	0.53	–	0.09	–
1690s	10	–	8.1	–	48	–	1.24	–	0.21	–
1700s	5	–	8.6	–	49	–	0.58	–	0.10	–
1710s	4	–	9.2	–	49	–	0.43	–	0.08	–
1720s	15	–	9.8	–	50	–	**1.53**	–	0.30	–
1730s	10	–	10.5	–	51	–	0.95	–	0.20	–
1740s	13	10	11.3	0.9	58	19	1.15	**10.99**	0.22	0.53
1750s	13	8	12.1	1.4	62	22	1.07	5.93	0.21	0.36
1760s	10	11	13.0	1.8	66	25	0.77	6.01	0.15	0.44
1770s	11	21	13.9	2.4	68	28	0.79	8.86	0.16	**0.75**
1780s	11	13	14.8	2.9	69	30	0.74	4.42	0.16	0.43
1790s	14	10	15.7	3.6	69	33	0.89	2.75	0.20	0.30
1800s	9	12	16.6	4.4	70	35	0.54	2.75	0.13	0.34
1810s	6	7	17.6	5.1	70	37	0.33	1.36	0.09	0.19
1820s	8	*6*	18.5	5.9	71	38	0.43	1.02	0.11	***0.16***
1830s	12	11	19.5	6.7	71	40	0.62	1.64	0.17	0.28
1840s	10	13	20.5	7.6	71	43	0.49	1.70	0.14	0.30
1850s	5	9	21.5	8.7	74	46	0.23	1.04	0.07	0.20
1860s	9	14	22.6	9.7	74	48	0.40	1.44	0.12	0.29
1870s	16	11	23.7	10.9	75	49	0.68	1.01	0.21	0.22
1880s	11	11	24.8	12.1	76	51	0.44	0.91	0.14	0.22
1890s	13	9	25.9	13.3	76	52	0.50	0.68	0.17	0.17
1900s	9	15	27.0	14.6	76	53	0.33	1.03	0.12	0.28
1910s	9	10	28.1	15.9	76	54	0.32	*0.63*	0.12	0.18
1920s	14	22	29.3	17.3	77	55	0.48	1.28	0.18	0.40
1930s	10	13	30.5	18.6	77	55	0.33	0.70	0.13	0.24
1940s	15	21	31.7	20.0	77	55	0.47	1.05	0.19	0.38
1950s	10	18	32.9	21.5	78	57	0.30	0.84	0.13	0.32
1960s	7	22	34.1	23.1	78	57	0.21	0.95	0.09	0.39
1970s	7	17	35.4	24.6	78	57	*0.20*	0.69	0.09	0.30
1980s	19	**25**	36.6	26.2	78	57	0.52	0.96	0.24	0.44
1990s	**21**	23	37.8	27.7	78	57	0.56	0.83	**0.27**	0.40

Bold numbers indicate maximum, bold italic numbers minimum values.

gradual changes of the ED with time. As a further result, the rockfall "rates" nicely illustrate the protective function of the two selected forest stands:

After the devastating rockfalls of 1720, the recolonizing trees could not efficiently stop rockfall fragments in the southern sector, resulting in considerably high decadal ratios in the early decades of the analysis [e.g., 10.99 GD 1 m ED^{-1} (10 years)$^{-1}$ in the 1740s]. Compared to the 1740s, almost 13 times fewer GD are dated per 1 m of ED today. In the forest stand of the northern sector, rockfall "rates" persisted on a relatively low level throughout the last four centuries. Nonetheless, the high-magnitude event of 1720 also emerged from the GD–ED data, resulting in the highest decadal rockfall "rate" [1.53 GD 1 m ED^{-1} (10 years)$^{-1}$] recorded since AD 1600. As a further consequence, the efficacy of the protective forest was temporarily reduced, resulting in higher "rates" until the late 18th century. Since then, the protective function has further increased, resulting in a rockfall "rate" based on the linear regression trend of approximately 0.4.

This study represents the first attempt to analyze yearly and decadal fluctuations in rockfall activity on a forested slope. It has furthermore analyzed the age structure of the forest stands. Nevertheless, some issues remain to be resolved. In this study, we tried to select severely injured trees. However, comparisons between visible defects with reconstructed events indicate that scars and "candelabra form" trees may only reflect 28% of the GD (i.e., resin ducts, callous tissue, growth suppression) dated on the cores. We therefore stress the key role played by the sampling strategy by pleading for more random strategies when choosing trees in heavily disturbed rockfall forests. Even so, as the results presented above are from two sectors of one single slope, replicate studies are needed from a variety of similar sites to place our reconstructions as well as the general applicability of the rockfall "rate" in a wider context.

6. Conclusion

The approach outlined in this study proved to be a useful tool for analyzing fluctuations in inter-annual and inter-decadal rockfall activity on a forested slope. In contrast to former studies, this analysis was no longer limited by the restricted temporal sample available for the assessment of long-term variations in rockfall activity or by the temporal resolution of the approach (e.g., lichenometry). Although the techniques used in this investigation need further refinement and minor modifications in the sampling strategy, the results presented above clearly show that dendrogeomorphic investigations have the potential to produce results on yearly fluctuations and decadal ratios of rockfall activity over several centuries. Moreover, we have been able to determine spatial variations in rockfall activity, considerable differences in recurrence intervals and the changes in the efficacy of the protective function of the two forest stands at Täschgufer.

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