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Rolling stones and tree rings: A state of research on dendrogeomorphic reconstructions of rockfall

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Abstract

This progress report focuses on the contribution of tree-ring series to rockfall research and on recent development and challenges in the field. Dendrogeomorphic techniques have been used extensively since the early 2000s and several approaches have been developed to extract rockfall signals from tree-ring records of conifer trees. The reconstruction of rockfall chronologies has been hampered in the past by sample sizes that decrease as one goes back in time, as well as by a paucity of studies that include broadleaved tree species, which are in fact quite common in rockfall-prone environments. In this report, we propose a new approach considering impact probability and quantification of uncertainty in the reconstruction of rockfall time series as well as a quantitative estimate of presumably missed events. In addition, we outline new approaches and future perspectives for the inclusion of woody vegetation in hazard assessment procedures, and end with future thematic perspectives.

Keywords

chronology, dendrogeomorphology, frequency, hazard assessment, mass movement, rockfall, simulation, tree ring

I Introduction

Rockfall is a natural process in steep environments that threatens humans, settlements and transportation corridors. Although inherently episodic in nature, rockfall is sufficiently frequent in many mountainous localities that over even moderate time intervals it can be regarded as a continuous process. Rockfall can be defined as free-falling, bouncing or rolling rocks of different sizes (usually <5 m^3), originating from cliffs or rockwalls (Erismann and Abele, 2001; Varnes, 1978). Research from the

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last decade, in contrast to older publications (Mizuyama and Narita, 1988), has shown that on forested slopes collisions of rocks with trees dissipate a significant amount of the energy of falling rocks (Dorren and Berger, 2005; Jonsson et al., 2007; Lundström et al., 2009). In doing so, rockfall trajectories are affected and velocities or runout distances reduced compared to unforested slopes (Dorren et al., 2005, 2007; Jahn, 1988). Rockfall activity in forests also leaves characteristic imprints on the landscape as falling rocks may remove trees along their trajectory and thereby develop rockfall paths or couloirs (Dorren et al., 2005). At the same time, the interaction of rocks with trees will leave datable evidence of rockfall activity on the trunk and in the growth-ring records of injured trees (Stoffel, 2006). Forests on rockfall slopes can therefore be seen as a natural archive of past events that can be explored with so-called dendrogeomorphic techniques (Stoffel et al., 2013).

This progress report provides a review of recent trends and developments of dendrogeomorphic research of rockfalls and suggests a new approach for the reconstruction of time series of past events. Finally, this contribution outlines the potential of trees for hazard assessment and concludes with possible future research directions.

II Review of studies on tree rings and rockfall activity

A review of the pioneering dendrogeomorphic studies dealing with impacts of rocks on trees is provided in Stoffel (2006). The first reconstructions of rockfall activity in the strict sense were performed in the Swiss Alps, with a clear focus on destructive sampling (cross-sections) of a limited number of trees and the dating of visible and/or overgrown scars. Gsteiger (1989, 1993), for instance, used 25 cross-sections of *Fagus sylvatica* L. and *Picea abi*es (L.) Karst. to date rockfall events and to determine the effect of wound closure on the visibility of injuries on the stem surface. Schweingruber (1996) used cross-sections from 30 *P. abies* to develop a chronology of rockfalls beneath a road cutting. Stoffel (2005) assessed the healing of wounds and the blurring of rockfall evidence on 307 cross-sections of *Abies alba* Mill., *F. sylvatica* and *P. abies*, and noted that up to 70% of all injuries remained visible on the stem surface, even if the event had occurred several decades previously. Further work by Stoffel and Perret (2006) showed that scars remained most visible in species with soft, thin and/or non-peeling barks, whereas most scars were blurred completely in species with thick and peeling bark structures.

More recently, research started to focus on non-destructive sampling and the analysis of increment cores. Analysis of increment cores called for new analytical procedures and the consideration of additional anatomical indicators of rockfall damage in trees (i.e. growth suppression, reaction wood and tangential rows of traumatic resin ducts (TRD); for details, see below). Reconstructions based on increment cores also allowed the sampling of larger forest surfaces and more trees, as shown by Stoffel et al. (2005b) in their pioneering analysis of 135 *Larix decidua* Mill. trees in the Swiss Alps and the reconstruction of 741 rockfalls since AD 1600.

With a few exceptions, broadleaved trees did not receive much attention in dendrogeomorphic reconstructions before 2010, when Moya et al. (2010b) reconstructed rockfall frequencies in Andorra for the period 1961–2002 from 375 visible injuries in *Quercus robur* L. and *Quercus ilex* L. The largest rockfall study using broadleaved trees has been realized in the Carpathians of the Czech Republic, where Šilhán et al. (2011) dated almost 1000 rockfalls in *Acer pseudoplatanus* L., *F. sylvatica*, *P. abies*, *Sorbus aucuparia* L. and *Ulmus glabra* Huds. trees. Table 1 provides an overview of past dendrogeomorphic studies of rockfall activity.

Table 1. Overview of studies on rockfall activity using tree rings.

Authors	Year	Country	Species	Sampled trees	Number of samples	Sampling strategy	Number of events	Chronology type	Period	Reduction method
Gsteiger	1989, 1993	Switzerland	*P. abies, F. sylvatica*	7	25	stem discs	56	not applicable	unknown	not applicable
Schweingruber	1996	Switzerland	*P. abies*	30	30	stem discs	66	number of scars	1890–1987	no reduction
Stoffel et al.	2005a	Switzerland	*L. decidua*	18	270	stem discs	180	number of scars	1977–2001	no reduction
Stoffel et al.	2005b	Switzerland	*L. decidua*	135	564	increment cores	741	rockfall rate	1600 (1740)–2002	minimum SS (not precisely specified), spatial distribution
Perret et al.	2006	Switzerland	*P. abies*	33	33	stem discs	250	rockfall rate	1881–2000	minimum SS (not precisely specified)
Schneuwly and Stoffel	2008a	Switzerland	*L. decidua, P. abies, Pinus cembra*	191	937	increment cores, stem discs	745	rockfall rate	1957–2006	minimum SS (not precisely specified)
Schneuwly and Stoffel	2008b	Switzerland	*L. decidua, P. abies, Pinus cembra*	32	123	stem discs	149	number of scars	1985–2006	minimum SS (25%)
Migoń et al.	2010	Poland	*P. abies*	32	62	increment cores, stem discs	unknown	number of growth disturbances	1877–2007	unknown
Moya et al.	2010b	Andorra	*Quercus robur, Quercus ilex*	276	375	wedges, stem discs	73	number of events	1979–2002	change in rockfall frequency
Šilhán et al.	2011	Czech Republic	*Acer pseudoplatanus, F. sylvatica,P.abies, Sorbus aucuparia, Ulmus glabra*	283	1132	increment cores	989	rockfall rate	1931 (1937) (1975)–2008	minimum ED (30%)
Stoffel et al.	2011	Mexico	*Pinus hartwegii*	24	86	increment cores, stem discs	63	rockfall rate	1924–2008	minimum SS (n=10)
Šilhán et al.	2012	Ukraine	*Pinus nigra ssp. Pallasiana*	114	456	increment cores	703	rockfall rate	1780–2009	minimum SS (25%)
Trappmann and Stoffel	2013	Austria	*P. abies, F. sylvatica*	83	194	increment cores, scar count	1417	not applicable	1819–2009	not applicable

SS = sample size; ED = exposed diameter.

III Working with tree rings in rockfall research

1 Standard procedures and recent developments

Dendrogeomorphic reconstructions are based on the principle that external influences, such as the mechanical disturbance by rockfall, will cause a growth response in a tree (Alestalo, 1971; Shroder, 1978). Responses can be observed usually on the macroscopic scale in the form of a scar on the trunk, but visible evidence may become blurred with time and as a result of wound closure (Stoffel and Perret, 2006). At the microscopic scale, evidence of past impacts will be registered in the tree-ring series and can thus be used as a proxy of past rockfall activity (Stoffel and Bollschweiler, 2008; Stoffel et al., 2010). However, since different geomorphic disturbances have similar expression in the tree-ring series, likely causes of growth disturbance (*GD*) need to be identified from supplemental sources before sampling (for example, from geomorphic mapping, interpretation of aerial photos, consultation of historical archives). According to Stoffel et al. (2005b), the following *GD* are reliable indicators of past rockfall activity: (1) abrupt suppression of tree growth indicating decapitation or branch loss; (2) presence of callus tissue and TRD next to (blurred) injuries; (3) eccentric growth and the formation of reaction wood following stem tilting; and (4) abrupt growth release (suggesting that neighbouring trees were eliminated and the surviving trees benefited from improved growth conditions such as enhanced access to light, water, nutrients). The use of TRD has been proven most valuable for the detection and dating of past rockfall impacts in various conifer species (e.g. *Abies alba* Mill., *L. decidua*, *P. abies*, *Pseudotsuga menziesii* (Mirbel) Franco) over the past decade or so (Stoffel and Corona, unpublished data). The presence of TRD not only enables dating of past impacts with intra-annual resolution (Stoffel et al., 2005a), but also allows the detection of signs of scars when sampling is performed at large vertical (>1 m) and radial distances from (hidden) wounds (Bollschweiler et al., 2008; Schneuwly et al., 2009b). The interpretation of TRD as a sign of *GD* was not only key in paving the way for non-destructive sampling, but also allowed the reconstruction of more reliable time series of past rockfall activity (Schneuwly et al., 2009a; Stoffel, 2008). In addition, the position of TRD within the tree ring enabled dating with subseasonal (to monthly) accuracy, and therefore facilitated analysis of triggers (Migoń et al., 2010; Schneuwly and Stoffel, 2008a; Stoffel and Hitz, 2008; Stoffel et al., 2005a) or the coupling of rockfall activity with climatic (Perret et al., 2006; Schneuwly and Stoffel, 2008b; Šilhán et al., 2011) or seismic records (Šilhán et al., 2012).

2 Selection of suitable trees and detection of past events

Trajectories of individual rockfalls are not always clearly recognizable in the field as rocks may pass through steep forests with only few ground contacts. An assignment of injuries to specific rocks is therefore usually not possible. Trees located close or next to each other might be damaged by the same block, whereas other blocks may travel remarkable distances without impacting any trees (Dorren et al., 2006). Any reconstruction of rockfall activity and fluctuations thereof will thus depend substantially on the number and spatial distribution of trees selected for analysis. Stoffel and Perret (2006) have suggested not selecting trees based on visible damage, as this would lead to an overestimation of the more recent activity and an underestimation of events farther back in time (Mayer et al., 2010). Along the same line of thought, one should avoid sampling of multiple trees in a direct fall line, as shading effects will lead to an underestimation of activity. At the same time, multiple impacts may be generated by the same rock along its trajectory.

As a consequence, the length of the study area in the fall line of rocks should be as short as possible to avoid an overestimation of activity. As a rule of thumb, we strongly recommend restricting the length of study sites to the mean tree-free distance between trees suitable for analysis (for details, see Gsteiger, 1989, 1993; Perret et al., 2004), resulting in small lengths in dense stands and larger lengths in low-density forest stands. Recent work by Šilhán et al. (2013) has also illustrated a reduced sensitivity for certain conifer species to recording impacts with increasing age. The buffering effect of bark thickening in older trees may partly explain the apparent sensitivity decrease with increasing age. On the other hand, environmental conditions may reduce tree vigour as well (e.g. nutrient supply, water availability) and thereby significantly limit the potential of trees to react to disturbance. These considerations emphasize the great need for more research to specify the diameter sizes of trees and the optimal range of tree ages to be sampled so as to enhance the reliability of reconstructions even further in future work (Bollschweiler and Stoffel, 2010).

In a similar way, Trappmann and Stoffel (2013) demonstrated that reconstructed rockfall frequencies will depend strongly on the approach used and on the species considered for analysis. In their study, the small rockfall clasts left much less datable evidence in the tree-ring records of *P. abies* than on the stem surface of *F. sylvatica*. It is possible that hidden scars in *P. abies* were not always detected with dendrogeomorphic techniques, but it also seems likely that some of the multiple injuries observed in *F. sylvatica* were inflicted by the same rocks and during a single impact. More importantly, however, there is evidence for a preferential recording of the impact of smaller clasts on the stems of broadleaved species with smooth barks, like *F. sylvatica*, and a partial absence of the same impacts in (conifer) species with thicker bark structures, such as *P. abies*. In conclusion, the sampling strategy that will likely yield the most realistic and most complete picture of past rockfall activity at a given site includes: (1) a balanced mixture of different age classes; (2) the inclusion of broadleaves and conifers; (3) sampling independently of visual signs of past rockfall activity; and (4) sampling in a regular pattern (e.g. sampling strips) across slopes (Stoffel et al., 2013).

3 Temporal frequency of rockfall and the problem of sample size

Besides the analysis of spatial patterns of rockfall in terms of trajectory frequencies or spread and reach of rocks, the primary goal of rockfall analyses typically is the reconstruction of event chronologies and the related assessment of temporal fluctuations in activity and triggers.

In initial dendrogeomorphic work published on rockfall activity, chronologies were presented as absolute numbers of reconstructed impacts over time (Schweingruber, 1996), thereby ignoring (1) the continuous reduction of the number of trees available for analysis as one goes back in time and (2) the related decline of the number of potentially recordable *GD*. To take account of (1) the number of trees available for analysis in a given year (i.e. sample size, or *SS*) and (2) the changes of the exposed diameter (*ED*) of all living trees (i.e. increase of 'target sizes' with increasing tree age), Stoffel et al. (2005b) introduced the *rockfall rate* as a proxy of rockfall activity that remains more stable over time. The *rockfall rate* has been used in many recent studies addressing the temporal activity of rockfall and changes thereof (Perret et al., 2006; Schneuwly and Stoffel, 2008a; Šilhán et al., 2011, 2012; Stoffel et al., 2011), despite the fact that the *rockfall rate* is sensitive to artificial trends related to (1) very small *SS* in the early stages of the reconstruction and (2) the progressive increase in diameter of trees over time.

As a result of these limitations, most authors limited the time covered by the reconstruction to the period for which (1) a minimum *SS* was available (Perret et al., 2006; Schneuwly and

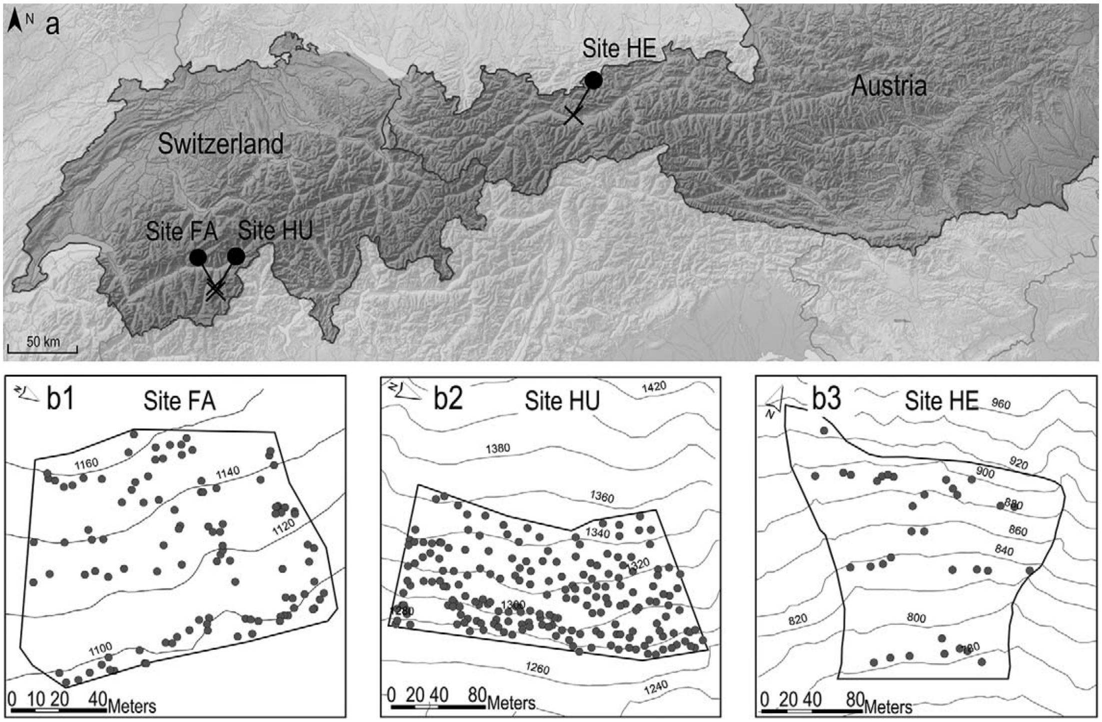

Figure 1. (a) Overview of study sites located in Switzerland (sites FA, HU) and Austria (site HE); background is a shaded relief map. (b1–3) Detailed views of the study sites and positions of sampled trees; contours represent elevation in metres.

Stoffel, 2008a, 2008b; Šilhán et al., 2012; Stoffel et al., 2011), (2) a minimum number of trees (in terms of the *SS*) was distributed evenly over the slope under investigation (Stoffel et al., 2005b), (3) at least 30% of the present *ED* was attained (Šilhán et al., 2011), or (4) a pronounced change in rockfall frequency was observed (Moya et al., 2010b). With the exception of Moya et al. (2010b), however, the criteria selected for the definition of periods for which the reconstruction had the smallest biases remained rather subjective. As a result of these shortcomings, a *range corrected impact concept* (*RCIC*) will be introduced in the following section. The *RCIC* (1) represents a more objective means to define reliable timeframes, (2) enhances accuracy, and (3) can be used to quantify uncertainties in dendrogeomorphic rockfall reconstructions.

IV Reconstructing rockfall chronologies with the range corrected impact concept (RCIC)

The *RCIC* is illustrated with three case studies from the Alps with different mean rock sizes and different lithologies. Results obtained with the *RCIC* are compared with (1) absolute numbers of past events in each year and (2) the *rockfall rate* in each year y (RR_y). The sites selected for analyses (Figure 1) are located in the Swiss Alps (Fallowina, 46°12'4"N, 7°53'28"E, site FA; Huteggen, 46°10'49"N, 7°54'16"E, site HU) and the Austrian Alps (Hechenberg, 47°16'11"N, 11°18'18"E, site HE).

Bedrock consists of tectonized gneisses at sites FA and HU and of dolomitic facies at site HE. Estimated mean block diameters are $\sim$0.3 m (site FA), $\sim$0.7 m (site HU) and $\sim$0.2 m (site HE).

Table 2. Overview of tree species, area, sample size, spatial density of sampled trees, diameter at breast height (*DBH*) and age of sampled trees at sites FA, HU, and HE (SD = standard deviation).

Site	Fallowina (FA)	Huteggen (HU)	Hechenberg (HE)
Area in ha	1.1	2.8	3
No. of sampled trees	107	198	33
Sampled trees ha^{-1}	97	71	11
Species	*L. decidua*	*P. abies, L. decidua*	*P. abies*
Mean diameter (*DBH*) in cm (SD)	36 (18)	33 (12)	48 (16)
Mean age in years (SD)	115 (50)	134 (41)	135 (53)
No. of cores	348	712	144

Table 3. Overview of growth disturbances used to determine rockfall events at sites FA, HU and HE.

Growth disturbances	Fallowina (FA)		Huteggen (HU)		Hechenberg (HE)	
	Number	%	Number	%	Number	%
Traumatic resin ducts	222	94	370	78	246	89
Injuries	4	2	24	5	16	6
Callus tissue	9	4	3	1	14	5
Growth suppression	2	<1	59	13	0	0
Growth release	0	0	1	<1	0	0
Reaction wood	0	0	15	3	1	<1
All reconstructed events	237	100	472	100	277	100

The forests consist of *L. decidua* (site FA), mixed *P. abies L. decidua* stands (site HU) and *P. abies* (site HE). Table 2 summarizes the main characteristics of the study sites. As the selected species form TRD, analysis was based on increment cores that were extracted next to visible injuries (Stoffel and Bollschweiler, 2008). One increment core was extracted between the scars if injuries were located next to each other. In trees where signs of impacts were absent on the stem surface, cores were taken from the upslope side at ~ 0.5, 1.0 and 1.5 m. One undisturbed sample was taken from the downslope side of the trunk and as low as possible to determine tree age. Table 3 summarizes the *GD* of the trees sampled.

In a first approach, chronologies represent absolute numbers of *GD* irrespective of changing sample and target sizes. In the second approach, we use the *rockfall rate* RR_y (Stoffel et al., 2005b), which takes account of changing target sizes as follows:

$$RR_y = \sum \frac{GD_y}{\sum ED_y} \tag{1}$$

where GD_y is the number of reconstructed *GD* (or rockfalls) in year y, and ED_y represents the diameter sum of all sampled trees (i.e. exposed diameter) in year y. *ED* values are calculated for each tree and each year by dividing the diameter at breast height (*DBH*) at the time of sampling by tree age, thereby assuming linear diameter increase over time.

The *range corrected impact concept* (*RCIC*) is based on the idea that the sample size (*SS*), exposed diameter (*ED*) and a mean block diameter *d* determine a range that is covered by trees in a given year (Figure 2), and that this range can be used to derive impact probabilities. The *RCIC* assumes homogeneous slope conditions and homogeneous blocks passing the forest in the fall line, and that no trees are selected in the shadow

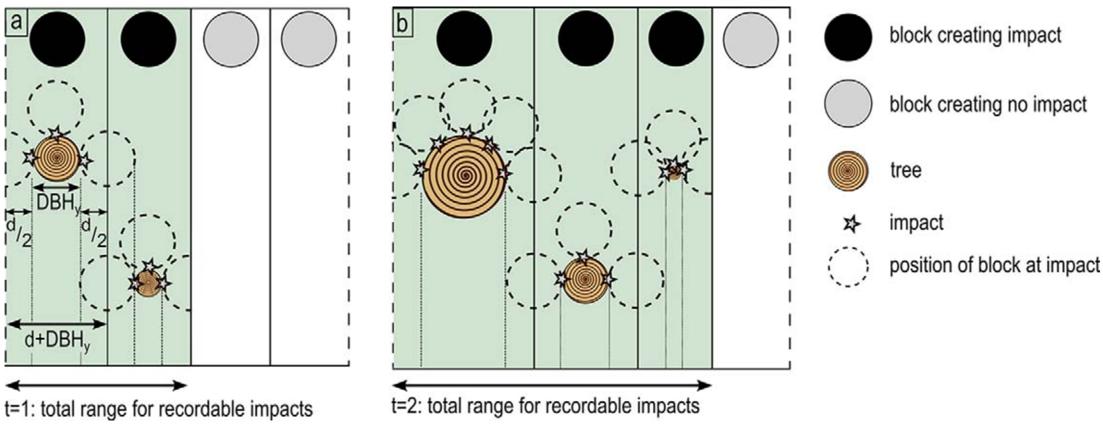

Figure 2. Range concept used for the definition of rockfall impact probability in a specific year.

of other selected trees. The total range that is covered by trees in year y (RC_y) is:

$$RC_y = \sum ED_y + SS_y \times d \qquad (2)$$

where ED_y represents the ED of all trees in year y, and SS_y expresses the SS in year y. The determination of ED_y follows the approach suggested by Stoffel et al. (2005b).

For each year, the range of the slope that is not covered by the reconstruction (RNC_y) can be calculated as:

$$RNC_y = W - RC_y \qquad (3)$$

where W is the width of the slope under investigation.

Assuming continuous rockfall activity, the number of missed events in year y (GDM_y) can be approximated by calculating the mean number of GD per RC obtained for individual years, multiplied by the range that was not covered in year y (RNC_y). In this sense, the GDM_y is a means to express uncertainties in the reconstruction:

$$GDM_y = \frac{1}{n}\sum_{i=m}^{n}\frac{GD_i}{RC_i} \times RNC_y \qquad (4)$$

where m represents the first year for which continuous rockfall activity (i.e. constant sequence of years with GD) is registered and n the last year of the records. For the period where $GD_y > GDM_y$ (i.e. where more events will be recorded than presumably missed), reconstructions and fluctuations in activity can be considered as free of sampling-related biases (primarily SS) and highly reliable. By contrast, GD observed or events missed in older portions of the reconstruction should be disregarded (Figure 3).

The decreasing number of trees available for analysis was yet another limitation of rockfall chronologies in the past, resulting in lower impact probabilities for the early periods of the time series when only very few of the sampled trees were present on the slope. Moya et al. (2010a) were the first to quantify impact probability and to correct rockfall frequencies at the stand level. A similar approach is used in the *RCIC* to normalize the number of observed GD by calculating the *range corrected impacts* RCI_y in year y as:

$$RCI_y = GD_y \times \frac{W}{RC_y} \qquad (5)$$

Results obtained with the three different approaches of chronology reconstruction described above are illustrated in Figure 4. Comparison between reconstructed chronologies shows quite clearly that the use of raw GD data (Figure 4b) will lead to an increase of rockfall

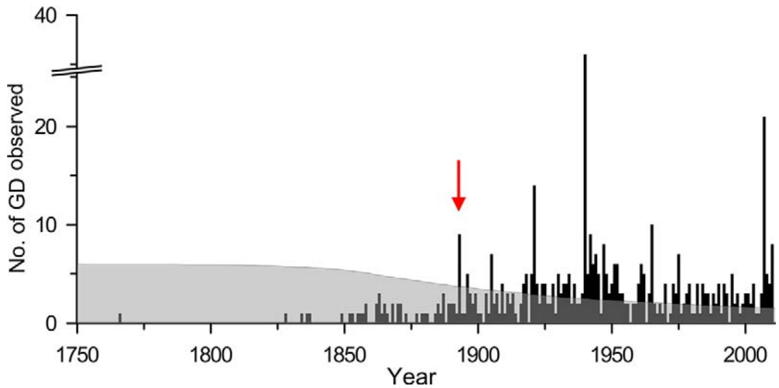

Figure 3. Raw numbers of growth disturbances (*GD*) over time for the study site HU. The presumed number of missed events is shown in light grey. The reconstruction can be assumed reliable since 1893 (arrow), when more impacts start to be registered in sampled trees than were presumably missed.

activity with time, and that the results obtained are reflective of increasing *SS* and *ED* rather than of 'real' trends in rockfall activity. Chronologies based on the *rockfall rate*, illustrated in Figure 4c, apparently overcome this drawback partly and yield more balanced reconstructions and higher *rockfall rates* for the past. At the same time, however, rates indicated in Figure 4c exhibit a negative trend with extremely high values for the early segments of the reconstruction and decreasing values for the more recent past. This artificial trend can be reduced significantly by the *RCIC* as illustrated in Figure 4d, where the rockfall activity, defined as *range corrected impacts*, remains on a comparable level. For the earliest portions of the reconstruction, sample size is critically low. To allow comparison between the *range corrected impacts* and the raw number of *GD*, both chronologies are compiled in Figure 4d. The smaller the difference between values, the higher the reliability of the reconstruction. The number of presumably missed rockfalls in each year is indicated in grey. Reconstructions become reliable after 1920 (spatial density 69 trees ha^{-1}) and 1893 (spatial density 49 trees ha^{-1}) at sites FA and HU, respectively. At site HE (maximum 11 trees ha^{-1}), the number of sampled trees is too small for the creation of a reliable chronology.

In summary, the *RCIC* represents the most suitable approach to reconstruct past rockfall activity, as it allows estimation of the 'real' number of yearly rockfalls at the study site and facilitates a direct and realistic comparison of rockfall activity at different sites, in addition to providing ranges of uncertainty, a quantitative estimate of missed events, and indications of the quality and reliability of the reconstruction and definition of an adequate *SS* (i.e. slope width = range covered, if the study is aiming for a complete record of all passing blocks).

V The potential of tree witnesses for rockfall hazard assessment

Rockfall hazards are typically assessed through an estimation of their intensity (in terms of kinetic energy), spatial extent (runout zones) and temporal probability (frequency). Practical assessments of rockfall hazards are usually based on simulation runs and focus on runout zones or impact energies. A realistic determination of rockfall frequencies and the verification of simulation results, however, is often quite difficult as archival records remain scarce and fragmentary (e.g. Dussauge-Peisser et al., 2002). The inclusion of trajectory frequencies as obtained from tree-ring records can close this gap and help the

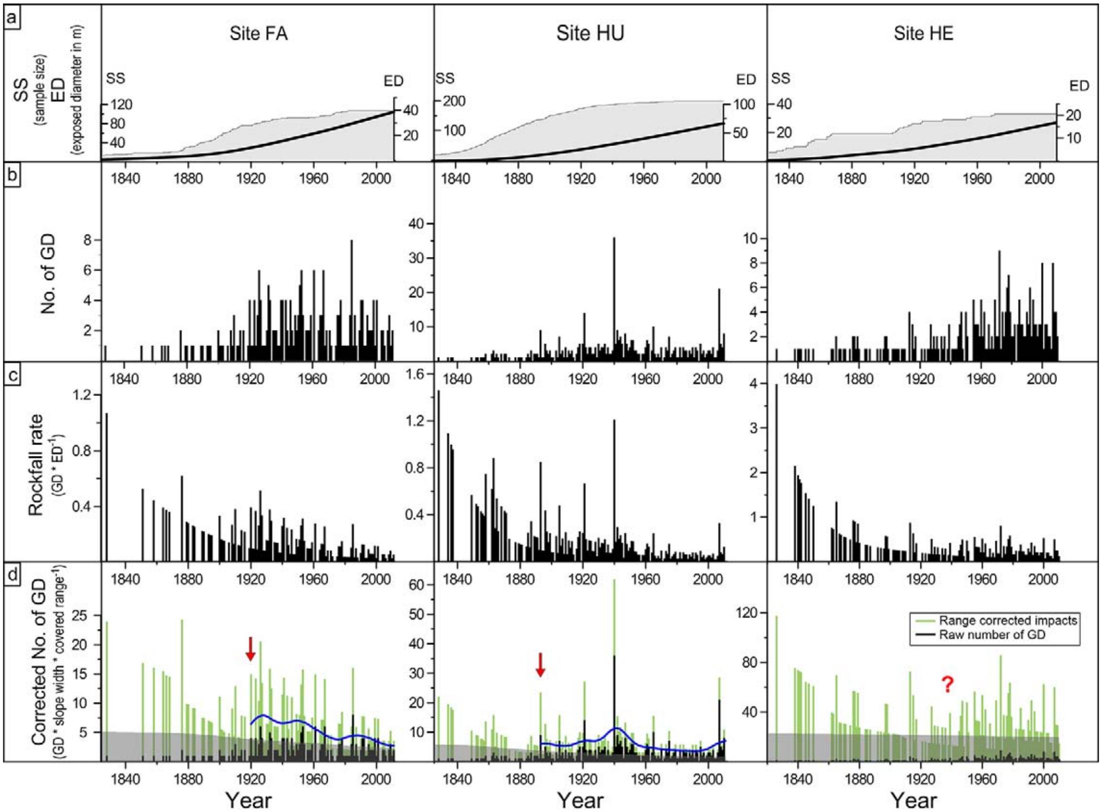

Figure 4. Rockfall reconstruction for sites FA, HU and HE. Row (a): sample size (*SS*) is shown in grey and the exposed diameter (*ED*) in black. The different types of rockfall chronologies are presented in row (b): absolute numbers of growth disturbances (*GD*). Row (c): *rockfall rate* where changes in *ED* (i.e. changing target size) are taken into account. Row (d): *range corrected impacts*. The range corrected rockfall activity is overlain by the raw number of *GD* whereas the number of presumably missed events is shown in light grey and calculated from the slope width not covered by trees in a specific year and the mean observed *GD* per year and metre of the slope covered (formula 4). Arrows indicate the year since when more *GD* are recorded than presumably missed. For the portion of the reconstruction which is considered reliable, a low-pass linear filter indicates a smoothed rockfall activity. In the case of site HE, the question mark indicates that less *GD* were recorded than presumably missed for each year of the chronology. The chronology cannot therefore be considered reliable.

validation of model output (Stoffel et al., 2006). Furthermore, recent work by Corona et al. (2013) demonstrated that impact data from trees can facilitate the definition of input parameters of rockfall models, such as the delineation of active source areas of rockfalls. The inclusion of dendrogeomorphic rockfall records also allowed transformation of modelled trajectory frequencies into real frequencies at any point on the slope under investigation. Past dendrogeomorphic work has sometimes been hampered by (1) the age of trees and (2) the occurrence of disturbances other than rockfall (e.g. various other geomorphic processes, road constructions, logging). Through the combined analysis of rockfalls with tree rings and modelling approaches, a spatial decoupling of zones where trees are analysed and zones where rockfall frequencies are needed

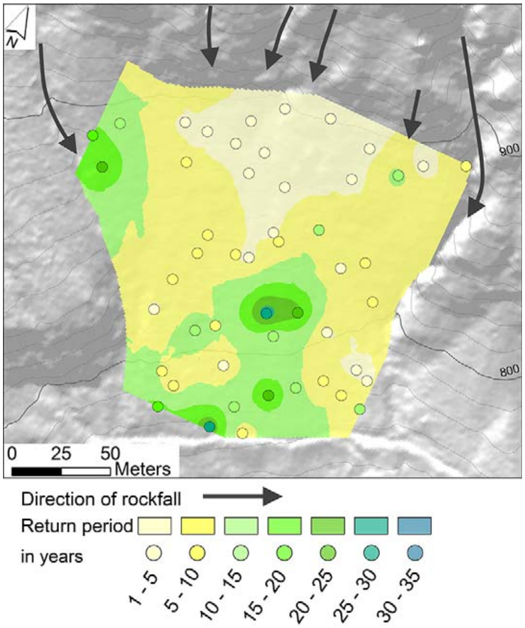

Figure 5. Return periods of rockfall based on a scar count approach on *F. sylvatica*, illustrated for individual tree locations (indicated by circles) and spatially interpolated (contour heights are in metres). *Source*: Adapted from Trappmann and Stoffel (2013).

becomes possible, and therefore helps to overcome some of the major limitations of both approaches.

Furthermore, data of passage heights derived from visible scars on trees can be used – in combination with impact traces on the ground – to reconstruct bounce parabolas and thereby serve as a basis for the back-calculation of rockfall velocities and energies (Volkwein et al., 2011). Whereas stem breakage can also be used to estimate minimum impact energies involved in rockfall events (Dorren and Berger, 2005), an estimation of impact energies based on scar characteristics (e.g. size, depth) does not seem feasible today.

For practical hazard assessment, simplified approaches to estimate rockfall frequencies and to date past events are critically needed. Trappmann and Stoffel (2013), for instance, developed a simple counting of visible scars on the stem surface of tree species with smooth bark to reconstruct reliable spatial patterns of rockfall activity (Figure 5). Along the same line of thought, a visual age estimation of rockfall scars would be desirable. The formation of ring-like structures can sometimes be found on closing wounds of *L. decidua*. Preliminary tests indicate the presence of age-dependent characteristics (e.g. bark and/or wound colour, resin) that could possibly allow a rather accurate visual estimation of wound age in the future (Figure 6).

Based on these recent achievements and the considerable additional value of tree data for hazard assessments, we recommend a systematic combination of dendrogeomorphic and modelling approaches wherever shrubs or trees cover critical rockfall slopes.

VI Thematic and methodological perspectives

1 Broadleaved trees and rockfall

Dendrogeomorphic work on rockfall scars in broadleaved tree species is still scarce, and a clear need exists for more fundamental work on wounding of non-conifer species by falling rocks. Moya et al. (2010b) were among the first to analyse visible scars in *Quercus* spp. More recently, Šilhán et al. (2011) adapted classic dendrogeomorphic approaches to broadleaved trees to reconstruct past process activity on rockfall slopes in the Czech Republic. We call for more studies that explore rockfall-growth interactions in broadleaved trees and that could eventually lead to the definition of criteria to identify and unambiguously date impacts in those species colonizing rockfall slopes quite abundantly (e.g. *F. sylvatica*, *Betula pendula*, *Quercus* spp.).

One possibility of identifying wounds in broadleaved trees is through the analysis of wood anatomical changes. Arbellay et al. (2010, 2012, 2013), Ballesteros et al. (2010) and Kames et al. (2011) have demonstrated the potential of wound-induced anatomical signatures (e.g. changes in vessel/ray number and

Figure 6. Changes in nature of injuries inflicted by rockfall on *L. decidua* with increasing age: (a) 0 years; (b) 4 years; (c) 9 years; (d) 21 years; (e) 91 years. Dotted lines indicate the border of scars on the bark for older events.

lumina) in broadleaved trees for the dating of debris flows, avalanches, flash floods or fires. Arbellay et al. (2012), for instance, showed that anatomical changes persist (radially) over several years, while most of them faded with increasing tangential distance from the injury. In addition, anatomical reactions have been shown to depend on rates of wound closure (Delvaux et al., 2010) and that the degree and persistence of reactions would vary strongly according to tree species, tree vigour and wound dimension (Neely, 1988). More research is needed on the axial extent of anatomical reactions within broadleaved tree species affected by rockfalls.

2 Rockfall activity in a changing climate

At present, the level of confidence is high that the global average temperature of the past few decades was warmer than any comparable period during the last 2000 years (Mann et al., 2008) and that further warming must be assumed during the 21st century (IPCC, 2007). Natural triggers of rockfalls comprise freeze-thaw cycles of water, melting of snow or permafrost, temperature changes and intense rainfall (for a detailed review, see Matsuoka and Sakai, 1999). In a warming atmosphere, one can speculate that the probability for rockfall activity might increase, especially at higher altitudes and as a result of more frequent freeze-thaw cycles and/or the wasting of permafrost (Allen et al., 2009; Deline et al., 2012; Ravanel et al., 2010; Stoffel and Huggel, 2012). Conversely, based on rockfall inventory data, Gruner (2004) and Sass and Oberlechner (2012) conclude that a general upward trend in the frequency of rockfalls cannot be seen in observational records. Discrepancies between these statements are mainly related to scarce historical data and a strong focus of research activities towards glaciated or permafrost areas. However, the dependency of rockfall frequency on climate variability below the permafrost line remains poorly understood even though most rockfalls threatening infrastructure indeed originate from slopes located far below permafrost. Recent dendrogeomorphic work attempted to identify dependencies of rockfall on meteorological conditions (Perret et al., 2006; Schneuwly and Stoffel, 2008a). Tree-ring data from a regional study in the Carpathians (Šilhán et al., 2011), for instance, suggests that freeze-thaw cycles would be the most relevant trigger of rockfall activity, whereas precipitation totals seem to be less important. Similarly, for a slope in the Crimean Mountains, no significant correlation was identified between rockfalls and precipitation (Šilhán et al., 2012). Whereas these studies clearly point to the potential of dendrogeomorphology to yield continuous time series of rockfall activity with seasonal to yearly resolution spanning several centuries, systematic and in-depth assessments of rockfall–climate change interactions have not so far been realized. By averaging the records over a large number of slopes, however, it should be possible to obtain rockfall series without local artifacts and therefore possibly identify climate-related trends in rockfall activity.

VII Conclusions

In this progress report we outline recent developments and challenges in the analysis of rockfall processes using tree rings. Over the course of the past few years, applications developed from the simple dating of a limited number of scars to the four-dimensional study (in terms of lateral spread, reach, bounce heights and temporal activity) of rockfall processes and the coupling of reconstructions with physically based process models. Whereas early work focused almost exclusively on European conifer species, more recent research started to analyse growth anomalies and the impacts of mechanical disturbance in broadleaved tree species. The potential of tree-ring records in the analysis of rockfall processes nowadays includes the assessment of process fundamentals in terms of climatic triggers, propagation of rocks on slopes, realistic assessments of rockfall frequencies over fairly long periods of the past, and practical applications for rockfall hazard assessment, especially in combination with three-dimensional rockfall models. The destructive sampling of rather limited numbers of trees has been replaced by non-destructive, but equally reliable, sampling techniques. In the same line of thinking, the more systematic definition of reliable rockfall signatures in tree-ring records also allows the sampling of larger numbers of trees with comparably reasonable efforts. Recent methodological considerations also indicate that the number, spatial distribution and age of selected trees, as well as the sampling strategy itself and the selected species, can have a significant influence on the quality of reconstructions. In this sense, the *range corrected impact concept* introduced in this progress report clearly represents an important contribution to the field and towards even more reliable reconstructed time series of past rockfall activity as it includes the impact probability of the forest stand in each year of the reconstruction. Several issues, however, persist and will need to be addressed in the future. Above all, future research should investigate the suitability of specific tree species and age ranges of trees as rockfall recorders to further increase the reliability of dendrogeomorphic rockfall reconstructions. Similarly, future work should take account of the influence of sample size on frequency reconstructions or interpolated return periods.

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