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Possibilities and Limitations of Dendrogeomorphic Time-Series Reconstructions on Sites Influenced by Debris Flows and Frequent Snow Avalanche Activity

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Abstract

Past debris-flow and snow avalanche activity was assessed for the Reiselehnrinne (Tyrol, Austria) using growth disturbances in growth-ring series of 372 Norway spruce (*Picea abies* (L.) Karst.) trees. Determination of events was performed by analyzing (a) the number and (b) intensity of growth disturbances within tree-ring series and (c) the spatial distribution of affected trees. Differentiation of debris flow from snow avalanche events was based on the intra-annual position of scars, callus tissues or tangential rows of traumatic resin ducts, and on the spatial distribution of trees with simultaneous reactions in the tree-ring series. We introduce a weighting factor to substantiate the dating of past process activity in a comprehensive way and to compare individual events as to their intensity and total number of tree-ring responses. The accuracy of the dendrogeomorphic assessment was then evaluated by comparing the reconstructed event frequency with chronologies available for the Reiselehnrinne. Comparison of tree-ring with historical data demonstrated clearly that the reconstructed event frequency contains the majority of past debris flow and snow avalanche events in the Reiselehnrinne, but that dating of events is not always possible, especially if they are clustered in time or have a limited spread on the cone.

Introduction

Debris flows and snow avalanches constitute major threats for human activities, settlements, and infrastructure in mountain environments. In order to avoid damage or fatalities, mitigation measures and appropriate hazard assessment are needed. Consequently, knowledge of the frequency and magnitude of snow avalanches and debris flows is vital for the delineation of hazard zones and the design of mitigation measures (Rickenmann, 1999; Gruber and Margreth, 2001; Jakob et al., 2005). Numerical and/or empirical modeling of debris flow and snow avalanches represent valuable tools for the assessment of hazards and risks, but they need to be validated and calibrated against historical data and field evidence. Historical data on past process activity, frequency or reach are, in many cases, limited to the vicinity of settlements, and most often include only those events that caused damage to infrastructures or loss of life (Jakob, 2005) resulting in monitoring series over insufficiently long periods of the past and for a minority of the endangered areas.

The analysis of trees that have been affected by past geomorphic activity represents a valuable and accurate alternative for the documentation and reconstruction of earth-surface processes over considerable periods of the past (Alestalo, 1971; Stoffel and Bollschweiler, 2008; Stoffel et al., 2010). Jakob (2010) and Luckman (2010) provided extensive reviews on where and how dendrogeomorphic techniques have been used to reconstruct debris flow and snow avalanche events.

Although debris flows and snow avalanches repeatedly occupy the same runout zones (Luckman, 1992), only very few dendrogeomorphic studies have focused simultaneously on both processes to date. Combined approaches have either been performed on sites with scarce (i.e. at least several years up to several decades between events) snow avalanche and debris flow activity (Stoffel et al., 2006) or at locations with frequent debris flows and scarce snow avalanches, but with excellent data on the intra-annual timing of impacts based on the dating of scars in cross sections (Szymczak et al., 2010).

The goal of this study is to address the possibilities and limitations of dendrogeomorphic research on a site where snow avalanches and debris flows occupy common runout zones and where vegetation is repeatedly affected by both processes. We provide (a) a high-resolution history of snow avalanche and debris flow events on the Reiselehnrinne using dendrogeomorphology and (b) differentiate between these processes by investigating the intra-annual position of growth disturbances and the spatial distribution of disturbed trees on the cone. Possibilities and limitations of the dendrogeomorphic approach are evaluated by comparing the extensive database (written records) which exists at the study site with our tree-ring record. The database contains information on exact event dates, runout zones, as well as on the flow behavior of snow avalanches (powder snow avalanche, dry or wet snow avalanche) and event magnitudes.

Study Site

The area investigated within this study is the Reiselehnrinne (46°59′N, 10°52′E.), located south of Plangeross, Sankt Leonhard im Pitztal (Tyrol, Austria; Fig. 1). The catchment covers an area

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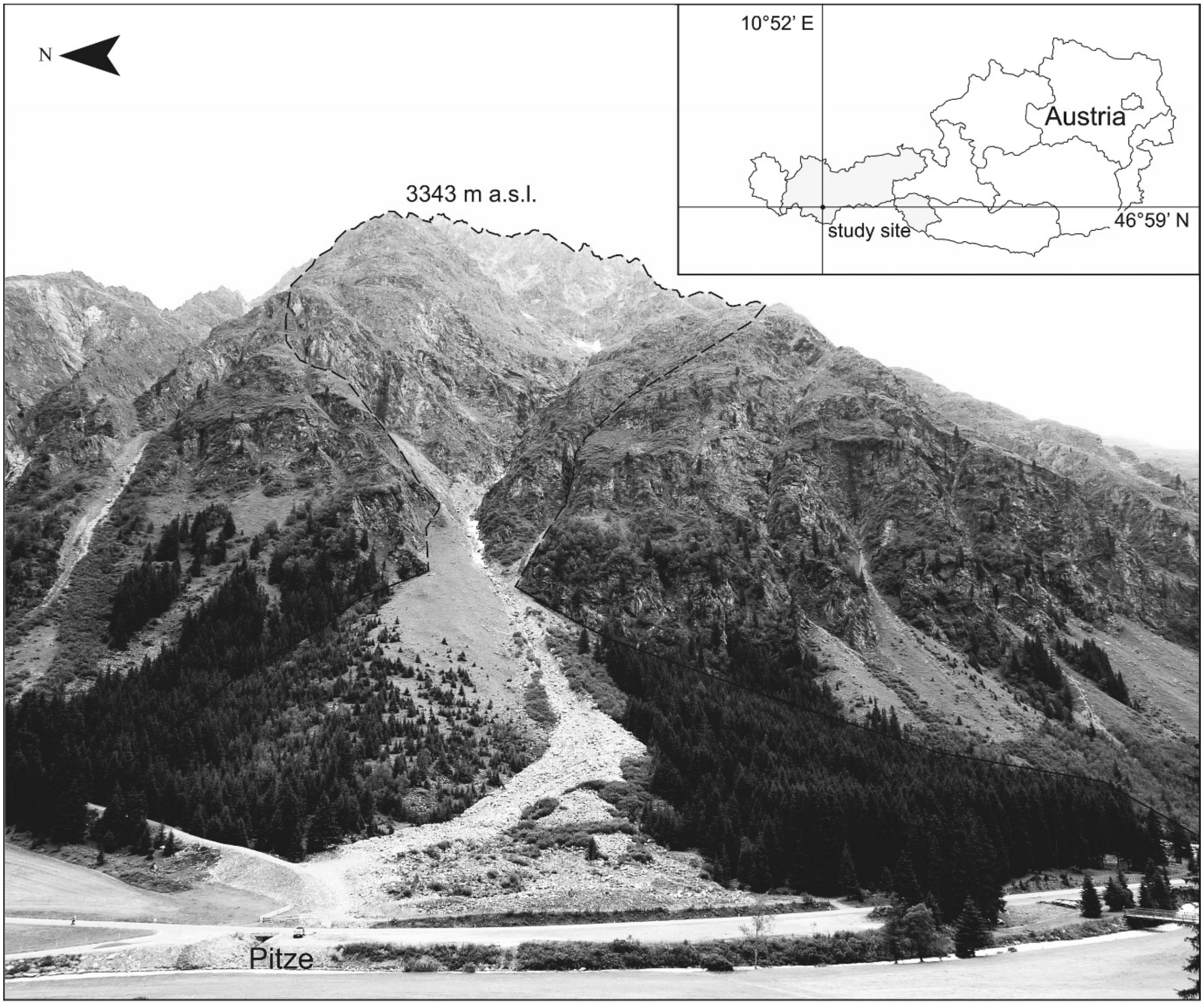

FIGURE 1. The study area is located in the Pitztal Valley in western Austria, near the village of Plangeross, Sankt Leonhard im Pitztal. The catchment area of the Reiselehnrinne torrent extends from 3343 to 1620 m a.s.l.

of 0.7 km^2 and extends from 3343 to 1620 m a.s.l. at the confluence with the Pitze river. The upper part of the catchment is dominated by gneiss and mica schists. Approximately 70% of the surface consists of bedrock and 30% of coarse talus deposits originating from the high-alpine cirque. The middle part of the catchment is dominated by a steep channel with superficial debris covering bedrock, while the cone of the Reiselehnrinne is built mainly of coarse debris flow material (Forsttechnischer Dienst für Wildbach- und Lawinenverbauung, 1998) (Fig. 2, A and B). A considerable part of the upper catchment is located above tree line and characterized by steep slopes (on average 62°) bare of any vegetation. The mixed debris flow/snow avalanche cone extends from 1810 to 1620 m a.s.l. and is vegetated by a forest composed primarily of Norway spruce (*Picea abies* (L.) Karst.). Slope gradients on the cone average 23° and deposits of past debris flows can be found predominantly south of the current channel, whereas the geomorphology and vegetation on the northern part show clear evidence of avalanche activity.

The Pitztal Valley is characterized by an inner-alpine climate with annual rainfall varying between ~600 and 1150 mm y^{-1}. Maximum daily precipitation measured at the gauging station in Plangeross (1620 m a.s.l.) was 82 mm on 10 June 1965.

An extensive database of avalanche and debris flow events exists for the Reiselehnrinne, in which snow avalanche activity is recorded in 1935, 1963, 1970, 1973, 1984, 1986, and 1991. Powder snow avalanches were recorded for the years 1935 and 1984, when the powder part of the avalanche reached the opposite side of the main valley. Archival records of former debris flow activity in the Reiselehnrinne contain information on five events, namely in 1965, 1985, 1994, 1998 and 2009 (Fig. 2, C). Records suggest that past snow avalanches have exclusively been triggered in December, January, and February and past debris flows in July and August.

Material and Methods

GEOMORPHIC AND VEGETATION MAPPING

All forms and deposits related to former debris flow activity (i.e. lobes and levees) as well as the distribution of trees and shrubs (divided into three classes: pioneer vegetation, thin forest, and dense forest) were mapped at a scale of 1:1000.

Based on an inspection of their morphology, trees obviously influenced by past debris flow and/or snow avalanche activity

FIGURE 2. The Reiselehnrinne torrent has (A) an incised channel on the upper part of the cone, and (B) no defined channel in the lower part. (C) The debris flow of August 2009 crossed the road and dammed the Pitze river. Photo courtesy of the fire department of Sankt Leonhard, used with permission).

(scars, candelabra growth, loss of apex, and buried or tilted stem base) were sampled. Trees growing on the southernmost part (Fig. 4) of the cone were disregarded for analysis, as they did not show any visible signs of disturbance. Normally two cores per tree were extracted—one in the supposed flow direction and the other on the opposite side of the stem. In total 372 *P. abies* were sampled with 41 cross sections and 731 increment cores.

TREE-RING ANALYSIS

Cross sections and increment cores were analyzed and data processed following the standard dendrogeomorphic methods described in Stoffel and Bollschweiler (2008, 2009). Tree rings were counted, ring widths measured, and ring-width series cross-dated to check for faulty tree-ring series. In a subsequent step, growth disturbances (GD) such as injuries, callus tissue, tangential rows of traumatic resin ducts (TRD), abrupt growth suppression or release, and compression wood were identified on the tree-ring series (for details see Stoffel and Bollschweiler, 2009).

For TRD, callus tissue and injuries, the exact location of the damage within the annual ring was noted and therefore allowed for an intra-annual dating of past events (Stoffel et al., 2005, 2006). As injured *Picea abies* (L.) Karst. initiate the formation of chaotic callus tissue and TRD immediately after an impact (see Stoffel, 2008, and references therein), the position of these GD inside the growth ring was used for distinction between snow avalanche and debris flow events (Stoffel et al., 2006; Szymczak et al., 2010). Figure 3 illustrates that trees showing injuries, callus tissue, or TRD at the beginning of the increment ring would have been injured by a snow avalanche during dormancy (D; October to April) or at the very beginning of the growth period. In contrast, injuries, callus tissue, and TRD located in late earlywood (LE) or within latewood (L) cell layers (see Fig. 3) were considered the result of debris flow activity, as these layers of the tree ring are formed between July and early October at the elevation of the study site under investigation.

The intra-seasonal timing of events is presented with a season index S_i:

$$S_i = \frac{\left(\sum_{i=1}^{n}(T_D + T_{EE} + T_{ME}) * 1\right) + \left(\sum_{i=1}^{n} T_{LE} * 2\right) + \left(\sum_{i=1}^{n}(T_{EL} + T_{LL}) * 3\right)}{\sum_{i=1}^{n}(T_{TRD} + T_i + T_{ct})}. \quad (1)$$

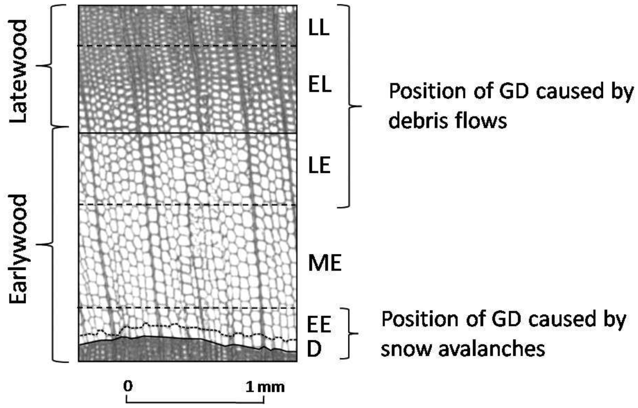

FIGURE 3. Tree ring showing earlywood and latewood cells. The earlywood is subdivided into early early (EE), middle (ME), and late (LE) earlywood and latewood into early (EL) and late (LL) latewood (adapted from Stoffel et al., 2005, 2006). D is dormancy, and GD is growth disturbances.

where T_{TRD} represents the trees showing TRD, T_i trees showing injuries, and T_{ct} trees showing callus tissue. To calculate the *Si* we assigned TRD, injuries, or callus tissue located in class D (T_D), EE (T_{EE}), or ME (T_{ME}) with a value of 1, class LE (T_{LE}) with a value of 2 and class EL (T_{EL}), and LL (T_{LL}) with a value of 3. A majority of trees was sampled with increment cores (89%), resulting in some samples being taken closer to the wounds than others. As there is an intra-annual shift of TRD with increasing tangential distance from the impact (Schneuwly et al., 2009), we attributed a value of 1 for TRD in ME and a value of 2 for TRD in LE.

In addition to the intra-seasonal dating of events, we also investigated the number and intensity of GD for each event using the criteria presented in Table 1. GD are classified after their intensity into weak (T_w), intermediate (T_m), and strong (T_s) signals as well as injuries (T_i). The classification of growth suppression or release as well as compression wood events follow the classification of Frazer (1986). TRD are weighted following Schneuwly et al. (2009).

The determination of events was based on (a) the number of trees showing GD within identical years, (b) at identical (or at least very similar) positions within the tree rings, (c) the intensity of signal within the tree-ring series, and on (d) the spatial distribution of affected trees on the cone (Stoffel et al., 2006; Bollschweiler et al., 2008a).

In order to substantiate the dating of snow avalanches and/or debris flows we calculated the W_{it} (weighted index factor), as two major factors for the assessment of events (i.e. number of trees, intensity of reactions) are taken into account with one value:

$$W_{it}=\left(\left(\sum_{i=1}^{n} T_i * 7\right)+\left(\sum_{i=1}^{n} T_s * 5\right)+\left(\sum_{i=1}^{n} T_m * 3\right)+\left(\sum_{i=1}^{n} T_w\right)\right) * \frac{\sum_{i=1}^{n} R_t}{\sum_{i=1}^{n} A_t} \quad (2)$$

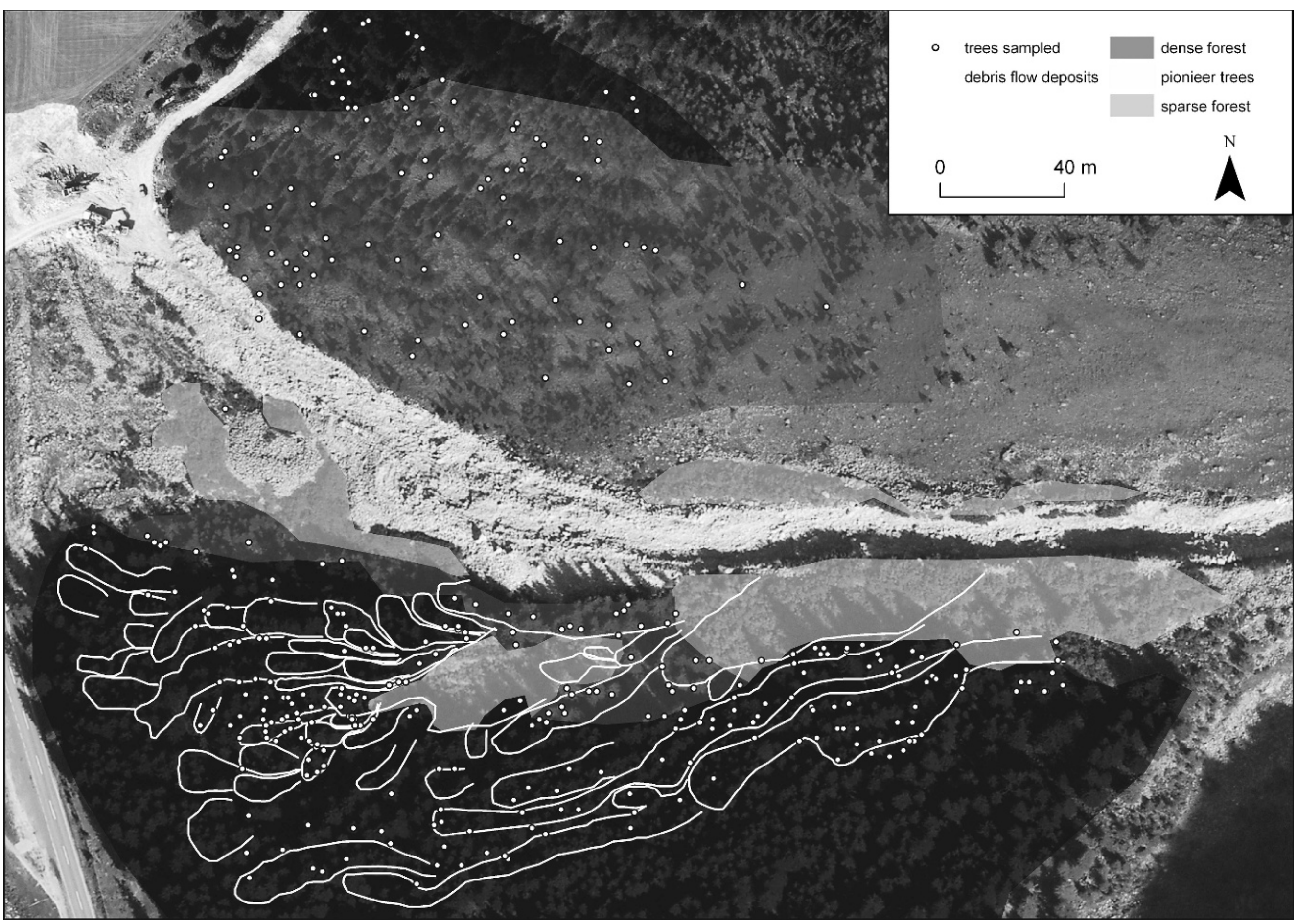

FIGURE 4. Detailed map (original scale 1:1000) of all debris flow forms and deposits (paleochannels, levees, and lobes) and of the vegetation covering (parts of) the cone (i.e. dense forest, sparse forest, and pioneer trees and shrubs).

TABLE 1

Classification of GD (growth suppression, growth release, compression wood, TRD, injuries, and callus tissue) after the intensity of the signal. TRD are traumatic resin ducts. Growth disturbances are classified after their intensity into weak (T_w), intermediate (T_m), and strong (T_s) signals as well as injuries (T_i).

		T_w	T_m	T_s	T_i
Growth suppression/Release	change in tree-ring width (%)	<60%	≥60%	≥60%	
	Duration	≥2 yrs	<5 yrs but ≥2 yrs	≥5 yrs	
Compression wood	≥50% of ring width consists of compression wood cells				
	Duration	≥2 yrs	3–5 yrs	≥5 yrs	
TRD		Tangentially aligned, with clearly observable gaps between ducts	Compact, but not completely continuous rows	Extremely compact and contiguous rows	
Injuries, callus tissue					Presence of callus tissue or injury

where the sum of trees with injuries (T_i) was multiplied by a factor 7, the sum of trees with strong GD (T_s) by a factor 5, and the sum of trees with intermediate GD (T_m) by a factor 3. R represents the number of trees showing a GD as a response to a debris flow or snow avalanche in year t, and A the total number of trees alive in year t.

The W_{it} we present here complements the index value proposed by Shroder (1978) or Butler and Malanson (1985) by adding an intensity to GD observed in individual tree-ring series. The calculation of W_{it} considerably helps to substantiate dating of snow avalanche and/or debris flow events in a comprehensive way, as the two major factors for the assessment of events (i.e. number of trees, intensity of reactions) are taken into account with one value. As trees may show multiple GD to the same disturbing event, only the strongest reaction per tree ($T_i > T_s > T_m > T_w$) was taken into consideration. The spatial distribution of the affected trees on the cone is not, in contrast, included in the W_{it} as it represents an exclusion rather than a weighting factor.

Results

IDENTIFICATION OF GEOMORPHIC FORMS AND MAPPING OF VEGETATION

Geomorphic mapping (Fig. 4) of the Reiselehnrinne cone (5.2 ha) at a scale of 1:1000 allowed for identification of 62 forms relating to past debris flow activity (lobes and levees). All deposits are located south of the currently active channel. Vegetation mapping (Fig. 4) clearly indicates that a light forest of rather small *P. abies* trees covers the northern part, whereas a dense forest is found in the southern part of the cone. Next to the channel and on a large lobate deposit in the central southern part of the cone vegetation is dominated by pioneer shrubs (mainly A*lnus viridis* (Chaix) DC.) and juvenile *P. abies*, indicating frequent disturbance by snow avalanches and debris flows.

AGE STRUCTURE OF THE FOREST STAND

Figure 5 shows the age structure of the forest stand at Reiselehnrinne. The oldest tree cored shows 188 increment rings at sampling height (A.D. 1821); the youngest sampled tree had 17 growth rings (A.D. 1992).

EVENT FREQUENCY AND SEASONAL TIMING OF EVENTS

Analysis of GD occurring simultaneously in different trees allowed us to reconstruct 13 previously unknown events and to confirm 7 events, known from archival data; the identification of 12 events was only based on archival records as tree-ring data alone did not provide sufficient evidence for these events to be reconstructed (Table 2). Based on the intra-annual position of injuries, TRD and/or callus tissue (i.e. S_i), the spatial distribution of affected trees, the nature of response in the tree-ring data (W_{it}), and/or the archival records, 17 snow avalanches and 8 debris flows could be identified.

Table 3 summarizes the events (differentiated between events previously known from archival data and previously unknown events), W_{it} and S_i and the process responsible for the GD for any of the reconstructed years. The W_{it} values obtained for 2009 represent the minimum values for the present study. In contrast, the highest values for W_{it} were seen during the avalanche event in 1986. In general, results illustrate that W_{it} values are considerably higher for snow avalanches (mean W_{it} = 9.5) than for debris flows (mean W_{it} = 5.4). The S_i values of snow avalanches were found to be between 0 and 1.7 and those for debris flows between 1.8 and 2.4.

GROWTH DISTURBANCES

The 372 *P. abies* trees sampled allowed identification of 735 GD relating to past debris flows and/or snow avalanches. Most frequently, signs of past activity were preserved in the tree-ring series in the form of TRD (63%), followed by growth reductions (15%), compression wood (13%), injuries (5%), and growth increases (4%).

SPATIAL EXTENT OF PAST EVENTS

The spatial extent of past events was assessed by investigating the position of all trees showing GD during a particular event. In general, more events could be reconstructed for the southern part of the Reiselehnrinne cone reflecting the higher tree age in this sector. North of the currently active channel, in contrast, reconstruction was limited by sparser vegetation and younger tree age.

Trees showing GD within their tree-ring series following debris flows were, in general, restricted to the southern part of the cone. The debris flow events of 1899 (Fig. 6, A) and 1964 affected trees along the present-day channel as well as in the southwestern part of the cone. In contrast, the reconstructed debris flow activity for the more recent years shows that only trees growing close to the currently active channel were affected. This is especially true for the events in 2002, 2005, and 2009 when GD following debris flow events could only be found in a comparably small number of trees growing on or near the present-day channel.

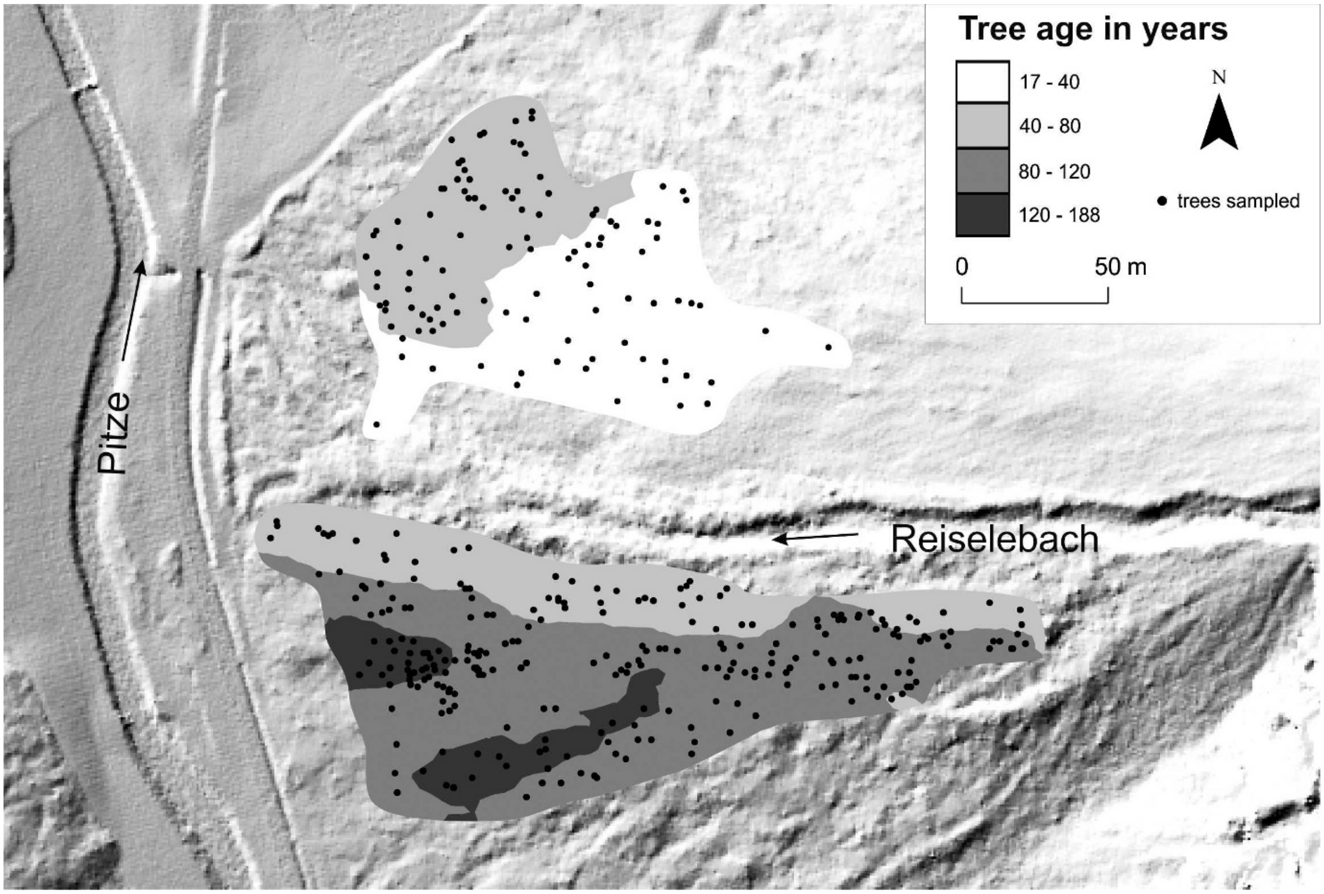

FIGURE 5. Age structure of the forest stand on the Reiselehnrinne cone. The oldest trees are located in the southern part of the cone whereas the trees north of the currently active channel are rarely older than 40 years.

TABLE 2

Index values (I_t), weighting factor (W_{it}), season index (S_i), and process type for the events reconstructed on the Reiselehnrinne cone.

Year	W_{it}	S_i	Process type	Archival data	Confirmed with tree rings
1868	7.1	0.0	Snow avalanche	no	yes
1884	7.7	1.0	Snow avalanche	no	yes
1899	2.0	2.4	Debris flow	no	yes
1905	3.7	1.0	Snow avalanche	no	yes
1921	2.0	1.0	Snow avalanche	no	yes
1935	4.8	1.3	Snow avalanche	yes	yes
1945	9.9	1.1	Snow avalanche	no	yes
1947	4.6	1.3	Snow avalanche	no	yes
1951	6.8	1.5	Snow avalanche	no	yes
1963	1.2	1.1	Snow avalanche	yes	no
1964	3.4	2.0	Debris flow	yes	yes
1970	7.4	1.0	Snow avalanche	yes	yes
1973	10.7	1.1	Snow avalanche	yes	yes
1982	6.0	1.1	Snow avalanche	no	yes
1984	3.9	1.1	Snow avalanche	yes	no
1985	3.2	1.9	Debris flow	yes	no
1986	26.8	1.3	Snow avalanche	yes	yes
1990	25.4	1.2	Snow avalanche	no	yes
1992	24.5	1.7	Snow avalanche	yes	yes
1994	16.0	1.8	Debris flow	yes	yes
1998	4.0	1.8	Debris flow	yes	no
1999	8.9	1.4	Snow avalanche	no	yes
2002	7.2	2.1	Debris flow	no	yes
2005	5.1	2.0	Debris flow	no	yes
2009	1.1	2.0	Debris flow	yes	no
Average	8.1	1.4			

TABLE 3

Growth disturbances (GD) identified in the 372 *Picea abies* (L.) Karst. trees. TRD are traumatic resin ducts.

	All events		Avalanches		Debris flows	
	total	%	total	%	Total	%
TRD	462	63	311	57	151	80
Injuries	33	5	22	4	11	6
Growth reduction	111	15	94	17	17	9
Growth increase	32	4	28	5	4	2
Compression wood	97	13	92	17	5	3
GD	**735**		**547**		**188**	

The spatial reconstruction of snow avalanche activity shows that a major part of the cone was likely affected by avalanche snow during the 1992 event and that a considerable number of trees were disturbed (Fig. 6, B). A similar pattern could be observed for 1964, 1970, 1973, 1986, and 1991. In contrast, the spatial distribution of trees showing GD after the snow avalanche event in 1999 was more limited to the uppermost part of the cone. However, the spatial extent of previous snow avalanche events could only be dated for the southern part of the cone, as tree-ring data on the northern part extends back only to the 1960s.

Discussion and Conclusion

In this study, dendrogeomorphology was used to assess debris flow and snow avalanche activity on a forested cone frequently influenced by either of the processes sharing similar runout zones. The tree-ring reconstruction was successful in confirming and complementing the existing chronologies back to A.D. 1868, and added 10 snow avalanches and 3 debris flows to the local database of past events. The differentiation of debris flow from snow avalanche events was based on the intra-annual position of injuries, callus tissue, and/or tangential rows of traumatic resin ducts (TRD) within the tree-ring series, the spatial position of trees showing reactions to a specific event and archival data.

North of the currently active channel tree age is homogeneous (mean age of trees at sampling height: 43 yr), forms of past debris flow activity are clearly missing, and the present-day surface is covered with a sparse forest composed predominantly of small trees. As a result of the homogeneous tree age, there is scope and reason to believe that the 1935 powder snow avalanche would have caused widespread tree elimination and subsequent recolonization.

Remarkable differences exist in the relative importance and nature of GD induced by snow avalanches and debris flows. Table 3 shows that W_{it} values are in general much lower for debris flows as compared to snow avalanches. This is at least partially due to the fact that debris flows were concentrated to the southern part (i.e. 56% of the study area). In addition, the spread of debris flows on cones tends to be more limited and therefore results in a smaller overall amount of affected trees (Moya et al., 2010).

Noteworthy, for previously known events, we also observe that debris flows were causing primarily injuries (6%) and TRD (80%), whereas trees affected by snow avalanches caused a much higher percentage of compression wood (17%), growth reduction (17%), and growth increase (5%) within their tree-ring series (Table 3). These differences were of great help to further improve confidence in differentiating debris flows from snow avalanches at Reiselehnrinne, especially for event years where trees showing injuries, TRD, and/or callus tissue were comparably rare (e.g., 1868).

In general, a clear differentiation of snow avalanches from debris flows was possible based on the position of TRD, callus tissue, and injuries within the growth rings of affected trees and the spatial distribution of disturbed trees on the cone. For previously unknown events the maximum value of S_i was 1.5 for snow avalanches (1951), and the minimum value for debris flows (2005) was 2.0. Higher (snow avalanches) or lower (debris flows) values were observed in the years 1985, 1992, 1994, and 1998, where the type of process was known from archives. For these years, a differentiation of processes based on the intra-annual position of damage alone would not have been possible.

The weighted index value W_{it} is illustrated in Figure 7 for each year between 1830 and 2010. W_{it} includes the number of trees showing a response to process activity and the total number

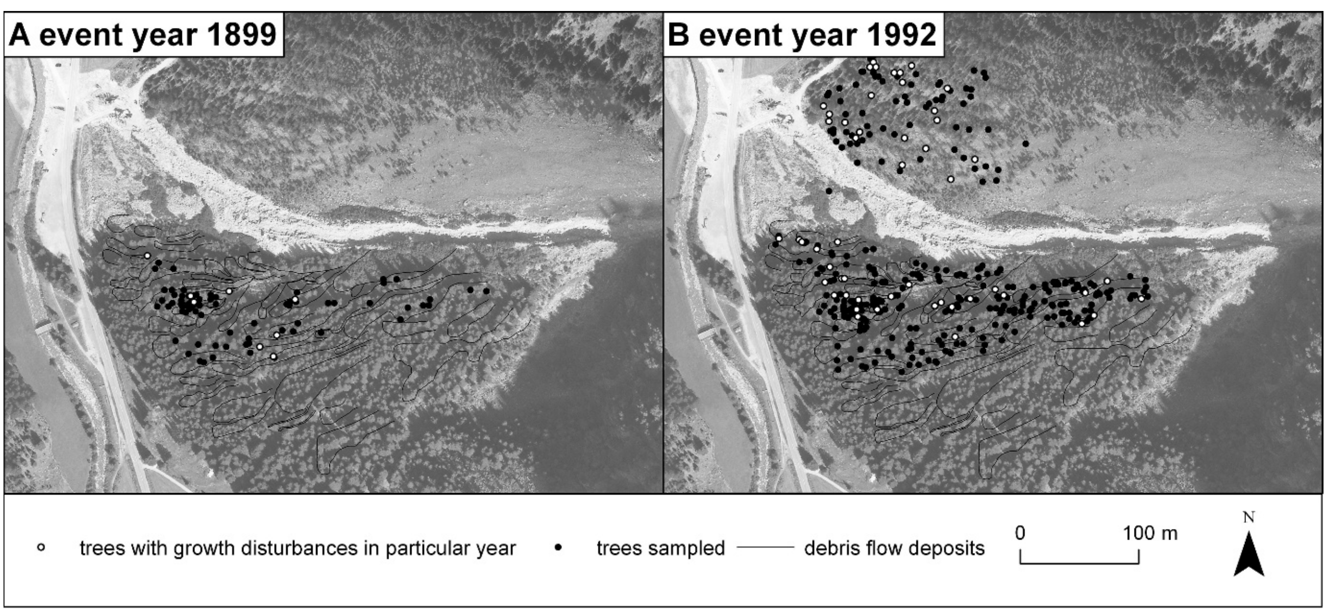

FIGURE 6. Spatial extent of a (A) debris flow (1899) and a (B) snow avalanche (1992) event, the position of trees with GD, as well as all trees available for analysis in these particular years.

of available trees (as defined by Shroder, 1978; or Butler and Malanson, 1985), but also takes account of the intensity of GD. Reconstructed events between the early 19th and the mid-20th century show significantly higher W_{it} values during years with snow avalanches or debris flows (mean W_{it} 5.5) as compared to years with no process activity (mean W_{it} for year with no process activity 0.3). For the period 1980–2009, in contrast, a large concentration of years with unusually high W_{it} (mean W_{it} for years with no process activity 2.1; mean W_{it} for event years 11) can be observed (Fig. 7). This increase in W_{it} values presumably reflects the sampling strategy where trees with visible growth defects were preferentially sampled. However, *P. abies* has been shown to heal over and mask damage quite rapidly after events (Stoffel and Perret, 2006) so that the preferential selection of visibly affected trees may have led to an oversampling of trees with more recent activity in the present case.

On the other hand, it also seems as if *P. abies* would have reacted more and in a more sensitive way to debris flow and/or snow avalanche disturbances in the recent past. This increase of reactions might be a result of the superimposed effect of very frequent geomorphic and other environmental disturbances (e.g. such as changing climatic conditions and/or air pollution; Ceulemans et al., 2002; Dulamsuren et al., 2010). We therefore speculate that the combined effect of different mass-movement processes and enhanced environmental stress renders an accurate differentiation of signal from noise rather difficult for the most recent segment (i.e. last 30 years) of the reconstruction. The impact of this limitation on the frequency series is, however, minor as this period coincides with the time segment covered best with written records.

For the reasons listed above, we used a minimum $W_{it} \geq 2$ to date past debris flows and snow avalanches. This threshold may appear small, but we are confident that it can be used for the dating of past process activity with a high degree of confidence for the older periods (i.e. pre-1980) of the tree-ring record because of the high deviation of W_{it} between years with and without process activity and as a result of the spatial distribution of tree showing simultaneous GD. Two events noted in archival records show a $W_{it} < 2$ (i.e. 1963, 2009) and would not therefore have been dated if the assessment was only based on tree-ring data.

The repeated clustering of debris flow and/or snow avalanche events in consecutive years represents a much bigger issue. The dating of individual events (i.e. 1963, 1984, 1985, and 1998) would not have been possible based on the weighted tree-ring response alone either. In addition, in the case of compression wood, growth decrease, or growth increase, reactions might be delayed (Stoffel et al., 2010) and GD only visible in the year(s) following an event (Timell, 1986). An association of GD to a specific debris flow and/or snow avalanche event would therefore not have been possible in these cases.

We therefore realize that the presence of TRD reduces uncertainty and doubtlessly improves dating accuracy on sites with scarce process activity (Stoffel et al., 2006), but will likely fail to allow differentiation of multiple events within individual or in subsequent growth rings if reconstructions are based exclusively on increment cores. This is because resin and related ducts will be produced in *P. abies* as long as hormonal stimuli continue to be emitted by the wound. As a consequence, TRD will be formed over several years after the initial impact (e.g., Bollschweiler et al., 2008b; Stoffel and Hitz, 2008; Schneuwly et al., 2009), thus preventing differentiation of TRD caused by new damage from those stemming from the initial impact. In this case, dendrogeomorphology will not yield a complete record of past activity and at least one cross section or a wedge would need to be taken per scar (Arbellay et al., 2010b; Szymczak et al., 2010) to overcome this problem.

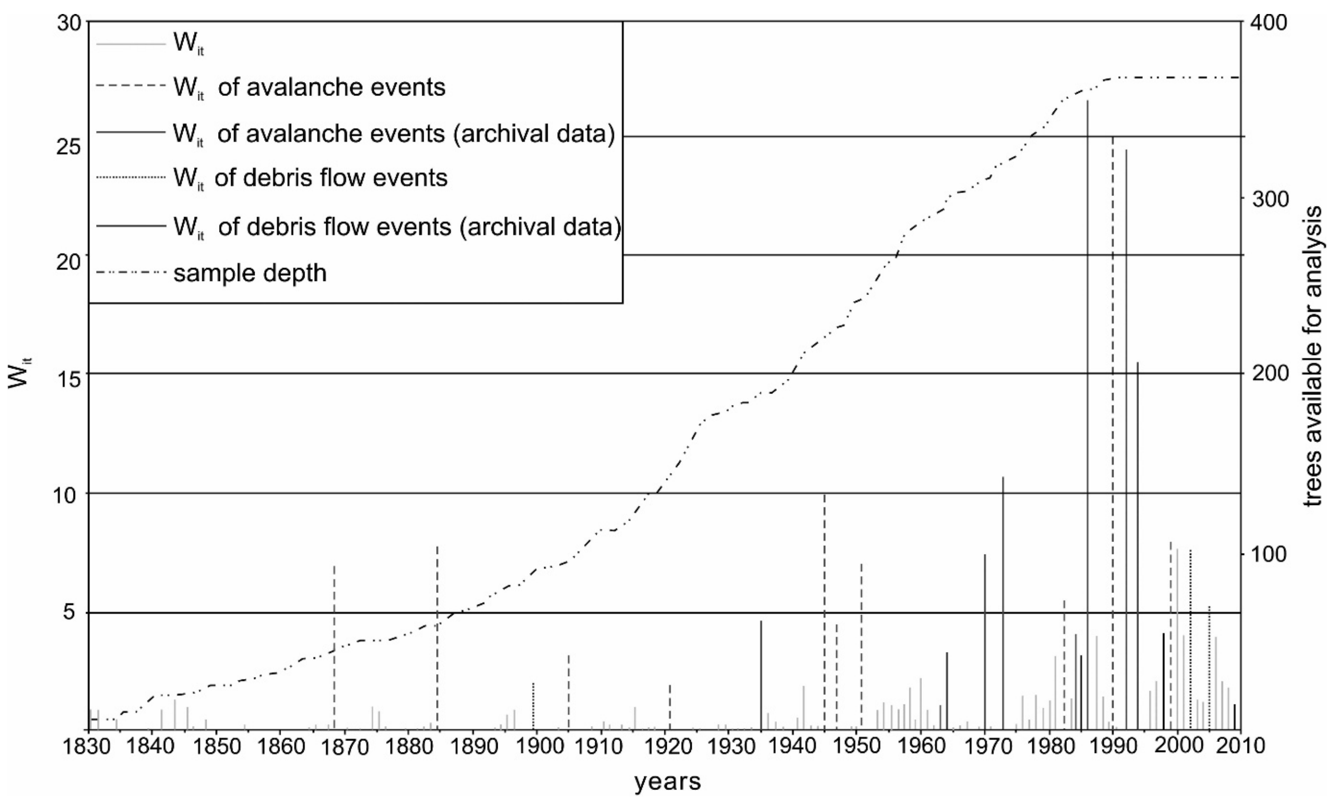

FIGURE 7. Values of W_{it} (weighted index factor) between 1830 and 2010, with a minimum value of 1.1 following the debris flow event in 2009 and a maximum value of 26.9 caused by an avalanche in 1986.

The extensive database on past events of the Reiselehnrinne cone allowed evaluation of the accuracy of reconstruction of debris flows and snow avalanches based on dendrogeomorphic techniques. The comparison of documented with reconstructed event histories (see Table 2) indicates that dendrogeomorphic reconstructions were successful in confirming 59% of the archival records (i.e. 71% of known snow avalanche and 40% of debris flows). In addition, tree-ring analysis allowed addition of 13 previously undocumented events (i.e. 10 snow avalanche and three debris flow events) to the existing chronology.

The dendrogeomorphic reconstruction of past debris flows (and snow avalanches to a minor degree as well) was clearly limited to outbreak events; flows which have been limited to the non-forested active channel could not, in contrast, be reconstructed with dendrogeomorphology. The approach also has limitations concerning data on event magnitude or run-out distance. Trees are not usually present in run-out zones and a determination of magnitudes is only exceptionally possible for debris flows (e.g., Stoffel, 2010) and hardly ever feasible for snow avalanches. The study at Reiselehnrinne also showed that dendrogeomorphic methods have clear limitations in the reconstruction of temporally clustered events, as delayed GD (e.g., growth increases and decreases or compression wood) and prolonged production of TRD following impact would not allow us to identify single event years. This limitation could possibly be minimized through the inclusion of shrubs (Arbellay et al., 2010a).

A differentiation of debris flow from snow avalanche events based on the position of TRD, injury, and callus tissue was, in contrast, possible for snow avalanche events between October and April and for debris flow events between July and late September. An approach based exclusively on S_i will fail to differentiate late spring avalanches and debris flows occurring in late fall or early spring. In this case, the spatial distribution of affected trees on the cone and the analysis of cross sections (rather than increment cores) can clearly help to overcome this problem. The approach furthermore demands a sufficient number of tree-ring series showing injuries, callus tissue, and TRDs.

Despite the many limitations listed above, we believe that the results presented in this study show clearly that dendrogeomorphology has a considerable potential to add substantially to event chronologies of past debris flow and snow avalanche activity over periods beyond written records. In addition, the approach also allows differentiation between these processes by investigating the intra-annual position of the GD and thus considerably improves understanding of process activity in complex situations. Even though run-out distance and magnitude can only exceptionally be reconstructed based on tree-ring data, an assessment of breakout locations and an approximation of the spatial extent of past events on forested cones is usually possible. We are therefore convinced that the reconstructed frequency series as well as the data obtained on the lateral spread and reach of past events will serve as a very accurate and valuable basis for hazard analyses and risk assessment and as an excellent basis for the calibration and accuracy assessment of process-based simulation models.

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