Landslides (2009) 6:225–230
DOI 10.1007/s10346-009-0165-4
Received: 13 December 2008
Accepted: 21 July 2009
Published online: 12 August 2009
© Springer-Verlag 2009

Markus Stoffel · Michelle Bollschweiler

Tree-ring reconstruction of past debris flows based on a small number of samples—possibilities and limitations

Abstract Tree-ring analyses have often been used in the past for the reconstruction of spatiotemporal patterns of previous debris-flow activity, often yielding very precise and extensive data for torrents where information on former activity was largely missing. Unless dendrogeomorphology is slated for multimillion Euro developments, the large sets of tree-ring series that are usually used in these studies render analysis time-consuming and not necessarily very cost-effective. In this study, we present results on past debris flows obtained with 35 *Larix decidua* Mill. trees growing on the cone of the Torrent de Pétérey (Zinal, Valais, Swiss Alps). It is concluded that studies based on a limited number of samples may yield valuable data on past events, but that the reconstructed frequency remains widely incomplete and indications on the spatial aspects of past events are only fragmentary.

Keywords Debris flow · Dendrogeomorphology · Tree-rings · Frequency · Valais Alps · Switzerland

Introduction

Detailed knowledge on the temporal and spatial incidence of debris flows is of crucial importance as soon as anthropogenic activity interferes with potentially hazardous processes (Bloetzer et al. 1998). In this sense, data on the previous occurrence of events are of crucial importance for the assessment of hazards and risks as well as for the design of, e.g., torrent control works or retention basins (Rickenmann 1999). As a consequence, attention has been directed toward the analysis and documentation of process dynamics in the aftermath of the widespread flooding and debris-flow events in July and August 1987 (Rickenmann and Zimmermann 1993), September 1993 (Röthlisberger 1994), October 2000 (BWG 2002), or August 2005 (Bezzola and Hegg 2007), affecting large parts of the Swiss Alps and each of them causing damage of several hundred million Euros.

Only a few torrents and gullies have been monitored over sufficiently long periods of the past, and archival records on events remain incomplete, despite recognition that debris flows are more erosive and have a higher hazard potential than floods of comparable return periods (Pierson 1980; de Scally and Owens 2005). Due to the general lack of documented events, tree-ring records have repeatedly been used in the past to obtain information on previous events (i.e., Strunk 1997; Baumann and Kaiser 1999; Bollschweiler and Stoffel 2007), gain knowledge on spatiotemporal patterns of former debris-flow activity on cones (Bollschweiler et al. 2007, 2008a), investigate meteorological conditions triggering debris flows (Stoffel et al. 2005a; Pelfini and Santilli 2008), or predict the impact of changing climatic conditions on past as well as potential future events (Stoffel and Beniston 2006; Stoffel et al. 2008). In all these studies, several hundreds to up to more than a thousand trees have been analyzed and very extensive and complete information was obtained on the local debris-flow history of the past few centuries.

While yielding important and large amounts of data on previous events, the large sets of tree-ring series used in these studies also render analysis time-consuming and not very cost-effective for some applications. In this paper, we present results on spatiotemporal patterns of past debris flows obtained from 35 *Larix decidua* Mill. growing on the cone of the Torrent de Pétérey (Zinal, Valais, Swiss Alps) and highlight possibilities and limitations of the approach.

Study area

The area investigated in this study is the cone of the Torrent de Pétérey, located in the southern part of the village of Zinal (Valais, Swiss Alps, 46°08′ N/7°38′ E; Figs. 1 and 2). The catchment area of the Pétérey torrent covers 1.6 km^2, and the length of the primary channel totals 1.8 km. The cone itself extends from approximately 1,680 to 1,800 m a.s.l., has a cone area of 4.2 ha, and is covered with a forest composed of European larch (*L. decidua* Mill.) around the currently active channel. The distal portions of the cone are not forested and have served as pasture land over centuries, before increased economic and touristic demands have led to the construction of residential and vacation homes since the 1960s.

Debris-flow sediment predominantly originates from the "Glacier Bonnard" rock glacier below the Diablons des Dames (3,609 m a.s.l.; Fig. 1). Contemporary horizontal movements of the rock-glacier body vary between 0.3 and 1 m year^{-1} (Delaloye et al. 2007), thus providing the Pétérey as well as the neighboring Tracuit torrents with sediments belonging to the Cretaceous schists of the "Tsaté nappe" (Penninic units; Labhart 2004). The high elevation of the departure zone (>2,400 m a.s.l.) and the presence of contemporary permafrost restrict the release of debris flows to a few months during the summer and early autumn. Debris-flow material also originates from an active landslide located SSW of the torrent between 1,800 and 2,000 m a.s.l. (Fig. 1).

Evidence for past debris-flow activity is scarce for the Torrent de Pétérey and archives yield data on only five events between 1929 and today (1929, 1932, 5 July 1987, 20 June 1998, 4 August 2003). Data are also largely missing for the neighboring Torrent de Tracuit (3 July 1987). Only two major flood episodes are noted for La Naviscence (24 September 1993, 14/15 October 2000), which is the main river of the Val de Zinal valley (see Fig. 1). After a reaction to the recent debris-flow activity, a dam and a retention basin (Fig. 1) have been constructed on the lower part of the cone.

With respect to federal regulation, all Swiss communities need to complete debris-flow and flooding hazard maps by 2011. Hazard zoning will have important consequences on land-use planning and on the determination of priorities for (non-)constructive countermeasures, and consequently, hazard maps need to be based

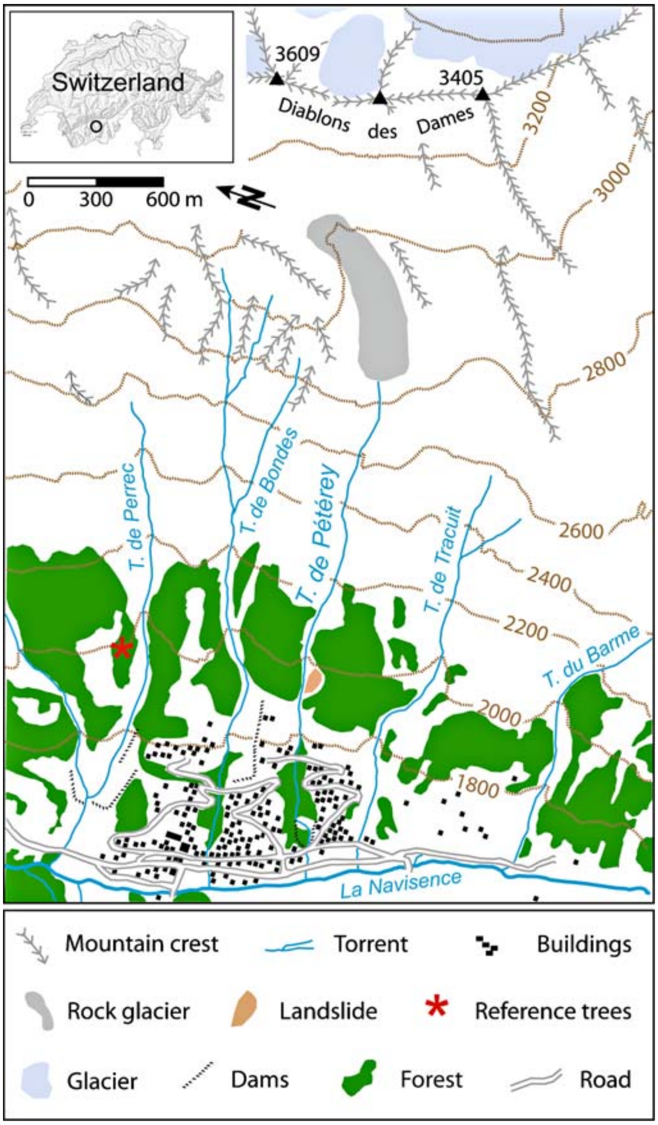


Fig. 1 The Torrent de Pétérey (Zinal, Valais Alps, Switzerland) rises from its source at ~2,600 m a.s.l. and passes through a forested cone, before converging with the La Navisence river (1,660 m a.s.l.). The *asterisk* indicates the forest stand where reference trees have been selected

on reliable input data. In regions where archival data are nonexisting or incomplete, the history of past incidences can be reconstructed with tree-ring analysis and through the use of debris-flow models.

Materials and methods

Geomorphic mapping of debris-flow features

Analysis of past debris-flow activity begins with detailed mapping of all features associated with past events, such as lobes, levées, or abandoned flow paths in a scale of 1:1,000. Features and deposits originating from other geomorphic processes or anthropogenic activity are also mapped to avoid erroneous dating of debris-flow events. Due to the presence of a relatively dense forest cover, global positioning system cannot normally be used on the cone, which is why geomorphic mapping is executed with a tape, compass, and inclinometer.

Fig. 2 Debris-flow cone of the Torrent de Pétérey (1,660–1,800 m a.s.l.; 4.2 ha) as seen from the departure zone

Sampling design

On the Pétérey cone covering approximately 4 ha, only a small minority of the predominant European larch trees show visible growth defects (GD) related to past debris-flow activity (e.g., corrasion scars, tilted stems, partially buried trunks, decapitation, partial destruction of root mass; see Stoffel and Bollschweiler 2008, 2009 for details). Based on the detailed geomorphic map and on an outer inspection of the stem surface, we extracted at least two cores per disturbed tree using Suunto increment borers, one in the flow direction of past debris flows and the other on the opposite side of the trunk (maximum core length, 40 cm×6 mm). Cores were preferably sampled at the height of the visible damage or within the segment of the stem tilted during past events.

In addition to the disturbed trees sampled on the cone, we selected undisturbed reference trees from a forest stand located northeast of the cone, indicated with an asterisk in Fig. 1. For every single reference tree, two cores per tree were extracted parallel to the slope direction. In total, 64 trees were sampled (128 increment cores): 35 trees (70 cores) from the debris-flow cone and 29 trees (58 cores) from undisturbed reference sites. In contrast to the disturbed trees, increment cores of the reference trees were extracted at breast height (≈130 cm).

Data recorded for each tree sampled included (a) determination of its position within levées, flow channels, or on deposits, (b) sketch and position of visible GD, (c) sampling position of cores with respect to the stem surface, (d) tree diameter at breast height (≈130 cm), and (e) data on neighboring trees.

Reconstruction of past debris-flow activity

Samples were analyzed and data processed following the standard procedures described in 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 2008). Growth curves of the disturbed samples were then crossdated with the corresponding reference chronology constructed from undisturbed *L. decidua* trees, in order to separate insect attacks or climatically driven fluctuations in tree growth from GD caused by debris flows (Cook and Kairiukstis 1990).

Increment curves were then used to determine the initiation of abrupt growth reduction or recovery (McAuliffe et al. 2006). In the case of tilted stems, both the appearance of the cells (i.e., structure of the reaction wood cells) and the growth curve data were analyzed (Fantucci and Sorriso-Valvo 1999; Stoffel et al. 2006). Finally, the cores were visually inspected to identify further signs of past debris-flow activity in the form of callus tissue overgrowing abrasion scars or tangential rows of traumatic resin ducts formed following cambium damage (Bollschweiler et al. 2008b; Stoffel 2008). Figure 3 gives an overview on the visible GD that we were looking for in the field and on how they influence yearly increment rates and wood anatomy of *L. decidua* (i.e., both visibly on the cross sections as well as in the growth curves).

Due to the small number of trees available for analysis, we distinguish between certain and possible events. In the results section, these two types of events are given with solid and dashed lines, respectively. A reconstructed debris-flow event is considered sure if (a) at least two trees show severe GD at the same time of the year and (b) if the position of affected trees in the field makes sense. In contrast, an event was only considered possible if only one tree showed severe and several others exhibited simultaneous yet less traumatic reactions.

Results

Geomorphology of the forested cone

The features and deposits inventoried in the study area covering 4.2 ha included 18 lobes, seven levées, and the currently used channel. In contrast, there were no signs of well-developed, but currently abandoned, channels observable in the field. In the lowest part of the cone, signs of former debris-flow activity are inexistent and the terrain completely remodeled through the dam

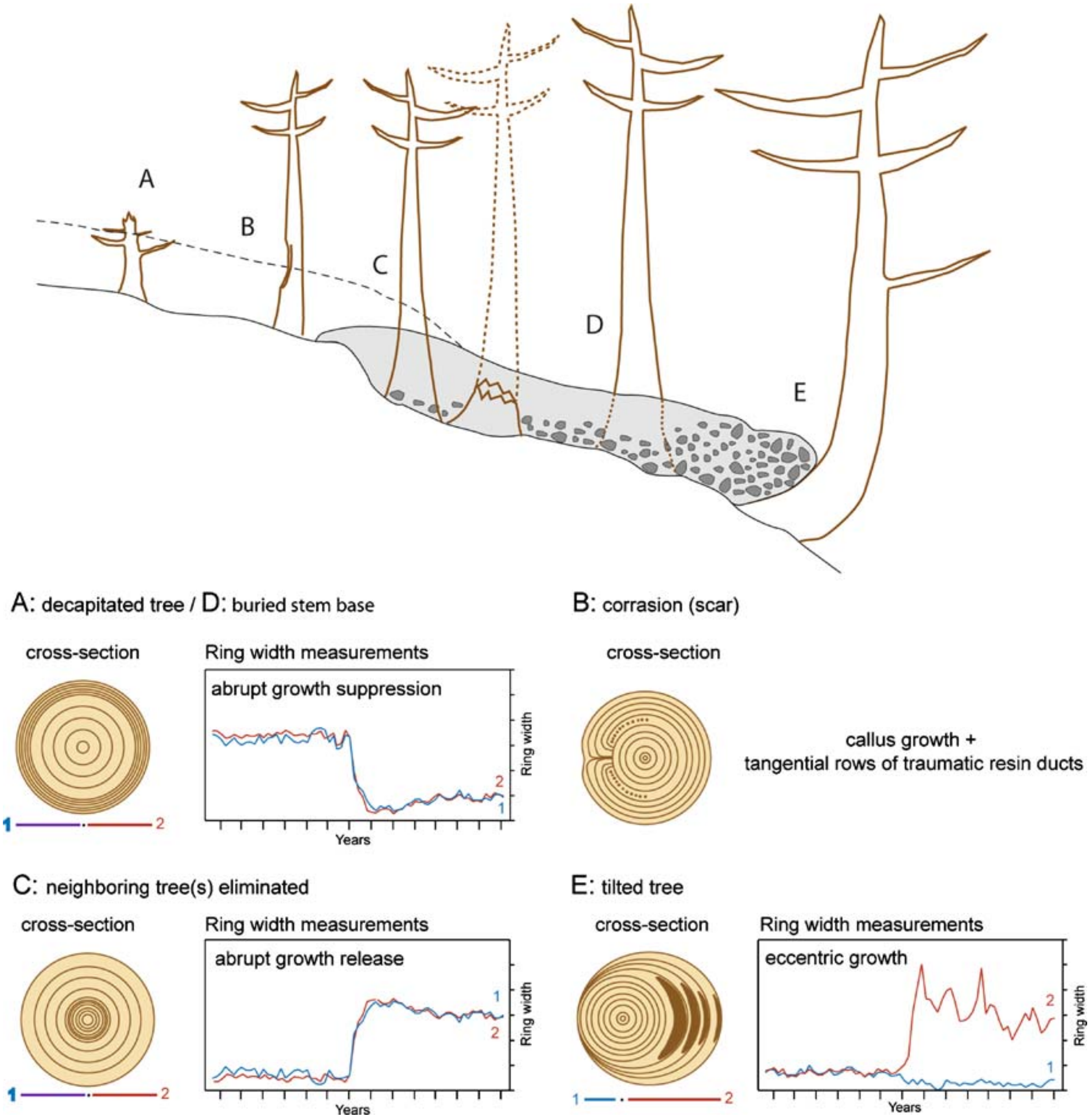


Fig. 3 Detailed map of the study site with debris-flow lobes and deposits, the position of sampled trees as well as human constructions (roads, tracks buildings, and dams)

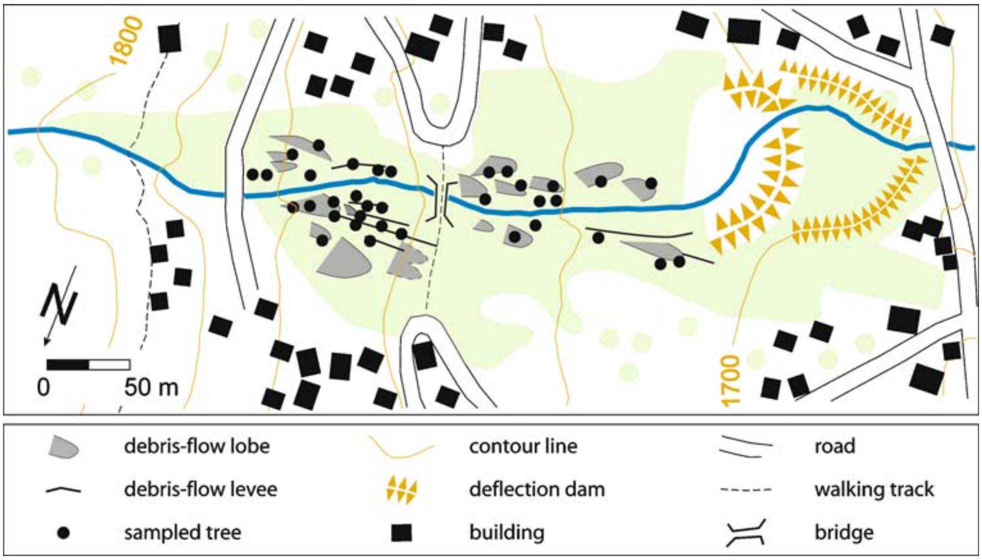


Fig. 4 Evidence used to infer debris-flow events from growth anomalies in tree-ring records (adapted from Stoffel et al. 2005b; Bollschweiler and Stoffel 2007)

construction works. Figure 4 illustrates the different features identified on the cone and provides indications on the extent of the forest stand as well as the position of the trees sampled.

Growth disturbances in trees and reconstructed debris-flow activity

Analysis of the disturbed trees allowed reconstruction of 97 characteristic GD caused by passing debris-flow surges or the deposition of material on the cone (Table 1). Signatures of past incidences were mainly identified on the increment cores via tangential rows of traumatic resin ducts (63%), reaction wood (18%), or abrupt growth reductions (15%). Growth recovery or injuries were, in contrast, only occasionally found in the tree-ring series. In total, the analysis of signatures occurring simultaneously in different trees on the cone allowed the reconstruction of 22 debris-flow events covering the last 145 years, with nine being considered possible and 13 defined as sure events. Figure 5 provides the reconstructed frequency of debris flows between AD 1862 and today.

Based on the spatial distribution of trees showing GD to the same event, it was also possible to characterize the spatial spread of surges during individual events, as shown with two examples in Fig. 6. Figure 6a illustrates the GD associated with a debris flow that occurred in 1959, when debris-flow material apparently left the main channel at the level of the bridge and deposited several debris lobes in the forest. In 1896 (Fig. 6b), only 11 trees were present for analysis. Two of them are located in a debris-flow levée and show tangential rows of traumatic resin ducts as a result of debris-flow activity.

Discussion and conclusions

In the study we report here, 70 increment cores extracted from 35 living *L. decidua* Mill. trees allowed reconstruction of 97 growth defects belonging to 22 debris-flow events since AD 1862. In comparison to the five previously documented events, we were able to extent the history of incidences in the Torrent de Pétérey (Zinal, Valais, Swiss Alps) by more than 60 years back to AD 1862 and to augment the number of documented events.

This information is valuable to the local and regional authorities (i.e., natural hazards and land-use planning authorities) and the civil and hydraulic engineers being in charge of the planning of passive debris-flow mitigation. In addition, the small number of samples allowed reconstruction of previous activity and a rough estimation on how often the torrent produced debris flows within reasonable time and with limited effort.

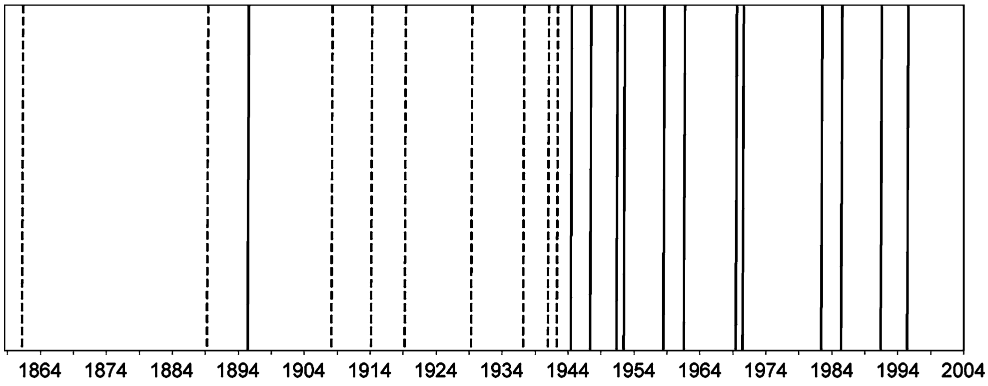
Nonetheless, it is worthwhile to note that the reconstructed frequency may only represent a minimum frequency of events for the Pétérey torrent. All those surges having remained in the main channel did not (necessarily) affect trees growing on the cone. As a consequence, these events will not be identified in the tree-ring series, unless the flowing material was denudating parts of the root mass or tilting the stem axis of trees growing along the channel's edges. In addition and as a result of the comparably small number of trees sampled on the Pétérey cone, it is also probable that even some events that actually left the channel and flew over some parts of the cone may have passed between the selected trees and did not, therefore, disturb the 35 trees selected within this study. This limitation may, however, not be significant for hazard and risk

Table 1 Debris-flow signatures identified in the 70 increment cores analyzed

Signature	Number	Percent
TRD	61	63
Wound	2	2
Reaction wood	17	18
Growth reduction	15	15
Growth increase	2	2
Total	97	100

TRD tangential rows of traumatic resin ducts

Fig. 5 Debris-flow frequency showing 22 events reconstructed since AD 1862 from the tree-ring series. *Solid lines* indicate sure events where at least two trees showed severe growth disturbances. If only one tree showed severe and several others exhibited simultaneous yet less traumatic growth disturbances, reactions were considered the result of a possible event (*dashed lines*)



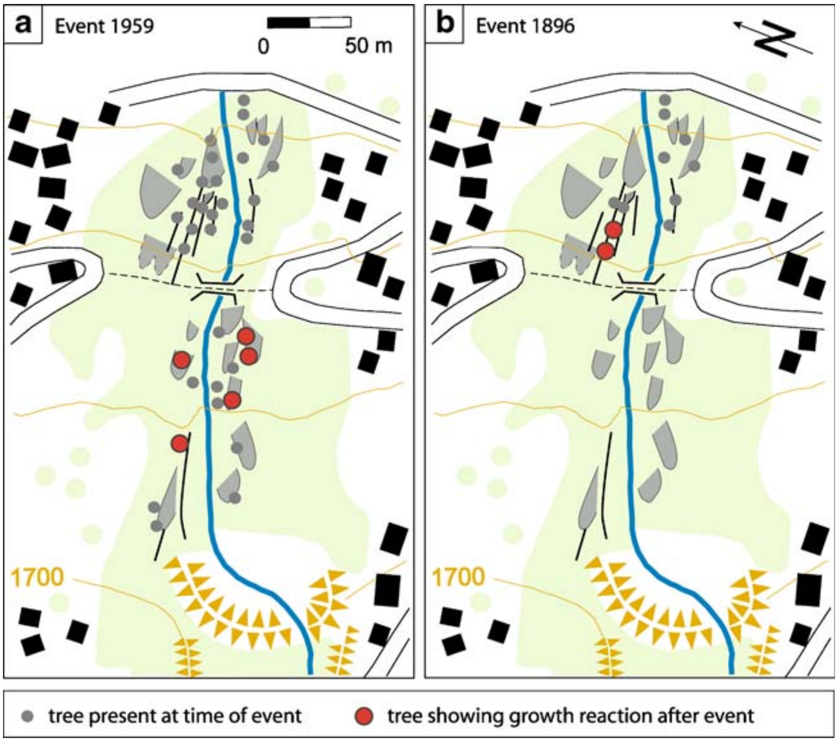
studies as it truncates the debris-flow frequency for the lower magnitude events. Most prudent debris-flow mitigation measures will rely on a high return period event, whose frequency is more important that often occurring smaller events.

In addition, tree-ring-based dating of past debris-flow activity is not normally based on one reaction in one single tree, but determined through a quantitative (= minimum number of trees; threshold exceedance; Butler et al. 1987) or semiquantitative analysis (= number and spatial distribution of trees; Bollschweiler et al. 2007; Stoffel et al. 2008) of trees showing GD in a particular year. Hence, it will be more difficult to reduce uncertainty and to accurately identify past debris-flow events when only a limited number of trees are selected on the cone in general and in individual sectors in particular.

Similarly, the validity of results obtained with a limited number of samples is also reduced as soon as studies are focusing on the spatial extent of debris-flow events or on the activity in currently abandoned channels. Due to the limited sample depth, the number of trees showing simultaneous reactions is often too small to track the paths of previous events or to attribute lobate deposits to specific events. Exceptions are always possible, as shown with the two examples in Fig. 6. As a further consequence of lacking information on the spread of debris-flow material on the cone or on the deposition of lobes, it seems illusory to estimate the volume of past events. Therefore, reliable frequency–magnitude relationships are almost impossible to achieve even on sites where extensive datasets have been created through the tree-ring-based analysis of important numbers of trees and the subsequent dating of deposits on the current-day surface (Strunk 1986; Stoffel et al. 2005a, 2008).

Based on the results and the above considerations, it appears possible to characterize past debris-flow activity in and to provide a minimum frequency for the Torrent de Pétérey with a very limited number of trees sampled. The limited amount of time invested renders analysis more cost-effective but may, as a consequence, only provide a rather incomplete dataset and exclusively data on the past existence of debris flows. Data on the spread of material on the cone, the activity in currently abandoned channels, the age of deposits, or the magnitude of past events cannot be obtained with this approach.

Fig. 6 Spatial representation of trees affected during debris-flow activity in **a** 1959 and **b** 1896 (*red dots*). Trees living at the time of the event but remaining unaffected by the event are represented with *gray dots*



Acknowledgments

This paper is dedicated to our friend Grégoire Devaud (1974–2006), who passed away while climbing in his beloved mountains. Work has been undertaken in the context of the RUFINE project financed by the Swiss Federal Office for Environment as well as the Service Forêt et Paysage and the Service des Routes et Cours d'Eau (both canton of Valais). We offer our sincere thanks to the anonymous reviewers for their insightful comments.

References

Baumann F, Kaiser KF (1999) The Multetta debris fan, Eastern Swiss Alps: a 500-year debris flow chronology. Arct Antarct Alp Res 31:128–134

Bezzola GR, Hegg C (eds) (2007) Ereignisanalyse Hochwasser 2005. Teil 1—Prozesse, Schäden und erste Einordnung. Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL. Umweltwissen 0707, Bern

Bloetzer W, Egli T, Petrascheck A, Sauter J, Stoffel M (1998) Klimaänderungen und Naturgefahren in der Raumplanung—Methodische Ansätze und Fallbeispiele. Synthesebericht NFP31. vdf Hochschulverlag, Zürich

Bollschweiler M, Stoffel M (2007) Debris flows on forested cones—reconstruction and comparison of frequencies in two catchments in Val Ferret, Switzerland. Nat Hazards Earth Syst Sci 7:207–218

Bollschweiler M, Stoffel M, Ehmisch M, Monbaron M (2007) Reconstructing spatio-temporal patterns of debris-flow activity using dendrogeomorphological methods. Geomorphology 87(4):337–351

Bollschweiler M, Stoffel M, Schneuwly DM (2008a) Dynamics in debris-flow activity on a forested cone—a case study using different dendrochronological approaches. Catena 72(1):67–78

Bollschweiler M, Stoffel M, Schneuwly DM, Bourqui K (2008b) Where do traumatic resin ducts occur in *Larix decidua* trees that have been impacted by debris flows? Tree Physiol 28:255–263

Bräker OU (2002) Measuring and data processing in tree-ring research—a methodological introduction. Dendrochronologia 20(1–2):203–216

Butler DR, Malanson GP, Oelfke JG (1987) Tree-ring analysis and natural hazard chronologies: minimum sample size and index values. Prof Geogr 39:41–47

BWG (Bundesamt für Wasser und Geologie) (ed) (2002) Hochwasser 2000—Les crues 2000. Berichte des Bundesamtes für Wasser und Geologie, Serie Wasser 2:1–248

Cook ER, Kairiukstis LA (1990) Methods of dendrochronology—applications in the environmental sciences. Kluwer, London

Delaloye R, Bardou E, Hagin C (2007) Glacier Bonnard. Mouvements du glacier rocheux. Troisième campagne de mesure. Unpublished intermediate report. University of Fribourg, Idéalp Sàrl and Geosat AG, Fribourg and Sion

de Scally FA, Owens IF (2005) Depositional processes and particle characteristics on fans in the Southern Alps, New Zealand. Geomorphology 69:46–56

Fantucci R, Sorriso-Valvo M (1999) Dendrogeomorphological analysis of a slope near Lago, Calabria (Italy). Geomorphology 30:165–174

Labhart TP (2004) Geologie der Schweiz, 6th edn. Ott, Thun

McAuliffe JR, Scuderi LA, McFadden LD (2006) Tree-ring record of hillslope erosion and valley floor dynamics: landscape responses to climate variation during the last 400 yr in the Colorado Plateau, northeastern Arizona. Glob Planet Change 50(3–4):184–201

Pelfini M, Santilli M (2008) Frequency of debris flows and their relation with precipitation: a case study in the central Alps, Italy. Geomorphology 101:721–730

Pierson TC (1980) Erosion and deposition by debris flows at Mt. Thomas, north Canterbury, New Zealand. Earth Surf Processes Landf 6:227–247

Rickenmann D (1999) Empirical relationships for debris flows. Nat Hazards 19:47–77

Rickenmann D, Zimmermann M (1993) The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology 8:175–189

Rinntech 2008. LINTAB—precision ring by ring. http://www.rinntech.com/Products/Lintab.htm.

Röthlisberger G (1994) Unwetterschäden in der Schweiz im Jahre 1993. Wasser Energie Luft 86(1–2):1–8

Stoffel M (2008) Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26:53–60

Stoffel M, Beniston M (2006) On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophysical Research Letters 33:L16404

Stoffel M, Bollschweiler M (2008) Tree-ring analysis in natural hazards research—an overview. Nat Hazards Earth Syst Sci 8:187–202

Stoffel M, Bollschweiler M (2009) What tree rings can tell about earth-surface processes. Teaching the principles of dendrogeomorphology. Geography Compass 3:1013–1037

Stoffel M, Bollschweiler M, Hassler GR (2006) Differentiating events on a cone influenced by debris-flow and snow avalanche activity—a dendrogeomorphological approach. Earth Surf Processes Landf 31(11):1424–1437

Stoffel M, Conus D, Grichting MA, Lièvre I, Maître G (2008) Unraveling the patterns of late Holocene debris-flow activity on a cone in the central Swiss Alps: chronology, environment and implications for the future. Glob Planet Change 60:222–234

Stoffel M, Lièvre I, Conus D, Grichting MA, Raetzo H, Gärtner HW, Monbaron M (2005a) 400 years of debris-flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arct Antarct Alp Res 37(3):387–395

Stoffel M, Schneuwly D, Bollschweiler M, Lièvre I, Delaloye R, Myint M, Monbaron M (2005b) Analyzing rockfall activity (1600–2002) in a protection forest—a case study using dendrogeomorphology. Geomorphology 68(3–4):224–241

Strunk H (1997) Dating of geomorphological processes using dendrogeomorphological methods. Catena 31:137–151

Strunk H (1986) Episodische Materialverlagerungen und die Fragwürdigkeit von Bilanzierungen. Darmstädter Geographische Studien 7:45–57

M. Stoffel (✉) · M. Bollschweiler
Laboratory of Dendrogeomorphology, Institute of Geological Sciences,
University of Berne,
Baltzerstrasse 1+3,
3012 Berne, Switzerland
e-mail: markus.stoffel@dendrolab.ch

M. Stoffel · M. Bollschweiler
Climatic Change and Climate Impacts Group, Environmental Sciences,
University of Geneva,
chemin de Drize 7,
1227 Carouge, Switzerland

M. Stoffel · M. Bollschweiler
Department of Geosciences, Geography, University of Fribourg,
chemin du Musée 4,
1700 Fribourg, Switzerland