Geomorphology 116 (2010) 107–114

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Debris-flow activity and snow avalanches in a steep watershed of the Valais Alps (Switzerland): Dendrogeomorphic event reconstruction and identification of triggers

Sonja Szymczak [a], Michelle Bollschweiler [b,c], Markus Stoffel [b,c,*], Richard Dikau [a]

[a] Institute of Geography, University of Bonn, Meckenheimer Allee 166, D-53115 Bonn, Germany
[b] Laboratory of Dendrogeomorphology (dendrolab.ch), Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland
[c] Climatic Change and Climate Impacts Group (C^3i), Environmental Sciences (ISE), University of Geneva, 7 chemin de Drize, CH-1227 Carouge-Geneva, Switzerland

ARTICLE INFO

Article history:
Received 26 August 2009
Received in revised form 12 October 2009
Accepted 15 October 2009
Available online 24 October 2009

Keywords:
Debris flow
Snow avalanche
Dendrogeomorphology
Seasonality
Conifers
Broad-leaved trees
Triggering

ABSTRACT

Debris flows and snow avalanches are common processes in the headwaters of steep watersheds worldwide. In forested areas, dendrogeomorphic analyses of trees affected by debris flows and snow avalanches have regularly been used to date past events. Previous studies have, however, almost never focused on both processes at once, as snow avalanche impacts cannot easily be distinguished from debris-flow scars. In a similar way, tree-ring studies have often been limited to conifers, and sites colonized with broad-leaved forests have been widely disregarded. We report on a case from the Valais Alps (Switzerland) where past debris-flow and snow avalanche activity was dated with intraseasonal precision using different broad-leaved and conifer trees. In total, the analysis of 171 cores, 34 wedges, and 11 crosssections from 93 trees allowed identification of 20 debris-flow and 3 snow avalanche events between A.D. 1930 and 2008. Results also indicate that some of the events would have been missed without the sampling of broad-leaved trees.

1. Introduction

Debris-flow and snow avalanche activity can frequently be observed in the headwaters of steep watersheds where their repeated occurrence usually results in characteristic landforms, such as cone-shaped debris accumulations at the mouth of gullies or torrent valleys. In mountain areas, debris flows are triggered either by intense rainfall, prolonged periods of precipitation, extreme and rapid snowmelt, the outbreak of lakes, or a combination of those triggers (Corominas et al., 1996). Snow avalanches occur in winter and early spring in any location where sufficient snow is deposited and a weak layer formed on inclined surfaces steeper than 30° (Schweizer et al., 2003). Many watersheds are vulnerable to both processes leading to a high damage potential for buildings and infrastructure or even to the loss of lives along their trajectories and on their cones (i.e., Jakob and Hungr, 2005). As a consequence, protection measures are essential for vulnerable areas and facilities, and knowledge about the spatial and temporal behavior of past events is of fundamental importance for the planning of control works and mitigation strategies.

However, for most torrents and avalanche tracks in the Swiss Alps, data exist only for catastrophic or recent events (Rickenmann and Zimmermann, 1993; Zimmermann et al., 1997; SLF, 2000; Gruber and Margreth, 2001). Reliable chronologies spanning several decades or even centuries are, in contrast, often missing, especially for debris flows.

The most accurate technique to reconstruct long-term chronologies of past debris flows or snow avalanches is dendrogeomorphology (e.g., Alestalo, 1971; Stoffel and Bollschweiler, 2008). The method is based on the facts that (i) trees form one increment ring per year in temperate climates and that (ii) trees affected by geomorphic processes will record the event in the form of characteristic growth disturbances (GD) in their tree-ring series (Shroder, 1980; Schweingruber, 1996). Through the determination of the position of the GD within a tree ring, a geomorphic process cannot only be dated to the year, but sometimes even with intraseasonal resolution (Stoffel and Beniston, 2006; Stoffel et al., 2006).

Previous dendrogeomorphic analyses of debris flows focused on the reconstruction of frequencies (Strunk, 1997; Wilkerson and Schmid, 2003) or magnitudes (Stoffel, in press), spatial patterns of past activity on cones (Bollschweiler et al., 2007), minimum ages of abandoned channels (Bollschweiler et al., 2008) or the synchronicity of incidences in neighbouring torrents with different lithologies (Bollschweiler and Stoffel, 2007). Other studies focused on the comparison of reconstructed debris-flow data with archival records on flooding (Stoffel et al., 2005a), or on changes in the seasonality of debris-flow activity (Stoffel et al., 2008a).

Over the last three decades, dendrogeomorphology has been used frequently to create snow avalanche chronologies (Butler and Sawyer,

* Corresponding author. Laboratory of Dendrogeomorphology (dendrolab.ch), Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland. Tel.: +41 316318743; fax: +41 3163148 43.
E-mail address: markus.stoffel@dendrolab.ch (M. Stoffel).

0169-555X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2009.10.012

2008, and references therein). While most studies have been performed in North America, only a limited number of studies exist for Europe to date (Muntán et al., 2004; Casteller et al., 2007). Studies have primarily addressed the frequency and spatial distribution of past activity (Patten and Knight, 1994; Hebertson and Jenkins, 2003) or focused on the identification of high-magnitude events (Boucher et al., 2003; Dubé et al., 2004).

Most previous tree-ring studies focused on one of the two processes at a time, although it is not unusual that debris flows and snow avalanches occupy common starting and runout zones. A distinction of geomorphic processes based on dendrogeomorphic methods is possible, either through the intraseasonal position of GD in the growth rings of trees standing on cones affected by debris flows and snow avalanches (Stoffel et al., 2006) or through wood anatomical analyses in the case of snow avalanche and rockfall events occurring at the same time of the year and at the same site (Stoffel and Hitz, 2008).

Notably, most of the aforementioned studies have been performed in crystalline environments (gneiss or granite), and dendrogeomorphic reconstructions did not often focus on regions dominated by limestone and dolomite lithologies (e.g., Strunk, 1997; Butler and Sawyer, 2008; Pelfini and Santilli, 2008; Stoffel et al., 2008b). In addition, most of the studies were performed with conifers and broad-leaved trees have been used only exceptionally for dendrogeomorphic investigations to date (Bryant et al., 1989; Mundo et al., 2007; Casteller et al., 2008; Arbellay et al., in press).

The reconstruction of past process activity normally aims at understanding current and potential future evolutions including possible impacts of a future greenhouse climate (Stoffel et al., 2008a) or the identification of triggers of past events (Bacchini and Zannoni, 2003). Rainfall intensity–duration thresholds for debris flows were first introduced by Caine (1980) and have since undergone continuous application and development, summarized by Guzzetti et al. (2008) using rainfall data of known and well-documented events. Pelfini and Santilli (2008) identified precipitation thresholds for debris-flow events that have been previously reconstructed with dendrogeomorphic methods.

Avalanches are triggered either naturally (e.g., rapid loading from special precipitation conditions) or through artificial triggers (e.g. skiers, gas injection, helicopter bombing or artillery; Schweizer et al., 2003). Meteorological factors measured by automatic weather stations are often applied to forecast avalanche probability, but the formation process is too complex to corrrelate events with data from nearby snowgauge stations (National Research Council, 1990). Studies on avalanche triggers therefore concentrate on the physical processes in the snow layer and the interaction between snow layer and terrain (e.g., McClung and Schweizer, 1999).

This study presents a coupled debris-flow and snow avalanche reconstruction based on dendrogeomorphic methods. We investigate the headwaters of a steep watershed in a calcareous environment where (i) debris-flow and snow avalanche activity is reconstructed with intraseasonal resolution using conifer and broad-leaved trees, (ii) the utility of injured broad-leaved trees for dendrogeomorphic studies is analyzed, and where (iii) debris-flow triggering rainfall events are identifed.

2. Study area

The watershed investigated is the Meretschibach located on the north-facing slope of the Rhone valley in southern Switzerland (Valais, 46° 18′ N./7° 40′ E.; Fig. 1). From its source at Untere Meretschialp (1920 masl), the torrent flows mostly in a northern direction along the border of the two municipalities Agarn and Leuk-Susten to its confluence with the Rhone River at about 620 masl. The mean slope angle of the torrent averages 21.5° and ranges from 8° on the cone to 33.7° in the upper part of the torrent. Debris flows and snow avalanches develop outside the main channel at the northern slope of the Meretschihorn (2567 masl). In the upper catchment (average slope angle 33°), large amounts of extensively fractured calcareous material is stored in talus slopes. The debris-flow system at Meretschibach is transport-limited (supply-unlimited) and material is therefore readily available for entrainment by debris flows. Three active debris-flow channels enter the Meretschibach between 1160 and 860 masl. Snow avalanches can either follow the debris-flow channels and affect the upper part of the torrent or fall west of the main channel.

Located in one of the driest regions in Switzerland, mean annual rainfall at the nearby climate station Sierre amounts to 612 mm (mean annual value for the period 1901–2007; MeteoSwiss, 2008). Maxima occur in winter (December and January) as well as in August when heavy thunderstorms (convective precipitation) are common. From the climate data and based on archival evidence from neighbouring catchments, we can assume that avalanche activity is restricted to a period between November and early April. Debris flows occur between late-April and mid-October, which roughly corresponds with the local growth period of trees. Local trees form light earlywood cells between early May and mid-July, and the darker latewood cells are produced from mid-July through late October.

The vast majority of the watershed is covered with a dense forest consisting mainly of Norway spruce (*Picea abies* (L.) Karst.) and broad-leaved trees, including Grey alder (*Alnus incana* DC), European Mountain ash (*Sorbus aucuparia* L.), Pubescent birch (*Betula pubescens* Erh.), and Great maple (*Acer pseudoplatanus* L.). In the uppermost reaches of the catchment (1900 masl) and close to timberline, a limited number of European larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.) trees can be found. The surface of the cone is used as pasture and occupied by the village of Agarn.

Data on past debris-flow events is scarce and includes information on six events since 2000: October 2000 (2 events), 31 July 2002, 21 May 2003, 19 August 2003, and 29 July 2008 (Municipality of Agarn, 2008; personal observation). As a result of the large debris-flow events in October 2000, two retention basins and deflection dams were constructed on both sides of the torrent at the level of the cone in 2007. Snow avalanches are less common at Meretschibach, with the most recent event on record in 2001 (Kanton Wallis, 2008).

3. Material and methods

3.1. Field methods

An accurate identification of forms and deposits related to past debris-flow and snow avalanche activity is crucial, as a basis for the selection of trees to be sampled. The first analytical step, therefore, consists of in a geomorphic mapping of forms and deposits at a scale of 1:500. Geographical position system (GPS) devices could not be used in the steep channel because of the topography of the terrain and the forest cover; this is why mapping was conducted using compass, tape measure, and inclinometer.

Based on the detailed geomorphic map and an inspection of their morphology, trees showing visible growth disturbances (GD) resulting from past geomorphic activity were preferably sampled. The sampling was conducted either with an increment borer, a hand saw, or a chain saw. Sampling focused on the debris-flow transportation zone between 760 m and 860 m to avoid areas disturbed by humans.

Conifers were sampled with increment borers, allowing for an extraction of ~5.5-mm-thick cores with a maximum length of 40 cm. At least two cores were taken per tree, one in the flow direction, the other one from the opposite side. In the case of visible wounds, additional cores were taken from the overgrowing callus. Sampling height and position were chosen depending on the type of disturbance and following the recommendations provided by Stoffel and Bollschweiler (2008, 2009). Sampling of broad-leaved trees focused on stems with visible scars. A wedge was extracted from the wound and the

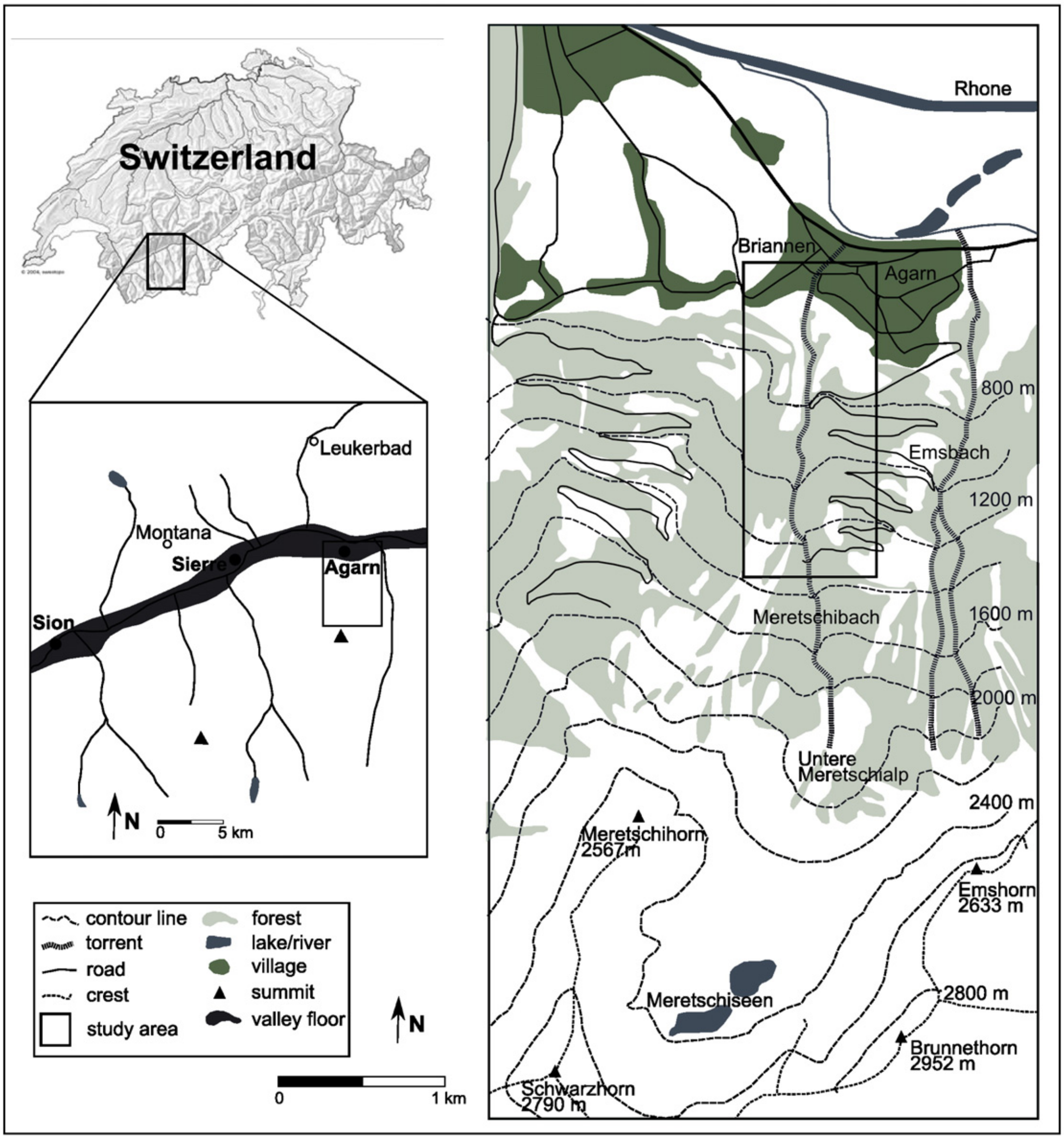

Fig. 1. Location map of the study site. The map on the left side indicates the location of the climate stations Sion and Sierre on the valley floor of the Rhone valley.

overgrowing callus tissue using a hand saw. In case of large scars, a crosssection was taken with a chain saw.

In total, 171 cores, 34 wedges, and 11 crosssections were extracted from 61 conifers and 32 broad-leaved trees: 57 *P. abies*, two *L. decidua*, two *Abies alba*, 12 *A. incana*, nine *S. aucuparia*, four *B. pubescens*, two *A. pseudoplatanus*, one *Laburnum alpinum*, one *Corylus colurna*, one *Ulmus glabra*, one *Fraxinus excelsior*, one *Buddleja davidii* (also see Table 1).

3.2. Laboratory methods

Analysis of the samples followed the standard procedures described by Bräker (2002) and included surface preparation, counting of tree rings, as well as measuring of tree-ring widths using a digital LINTAB positioning table connected to a Leica stereomicroscope and TSAP 5.0 software (Time Series Analysis and Presentation, Rinntech, 2008). In addition to the disturbed debris-flow and snow avalanche trees, we used 10 undisturbed and old *P. abies* trees to build a reference chronology representing normal growth at the stand (Cook and Kairiukstis, 1990).

Each sample from the disturbed trees was then analyzed visually for GD caused by past debris-flow and snow avalanche activity (Stoffel and Bollschweiler, 2008). GD included tangential rows of traumatic resin ducts (TRD; Stoffel, 2008; Schneuwly et al., 2009a,b), callus tissue, injuries, onset of compression wood, and abrupt growth changes, i.e. increases as well as reductions. For TRD, callus tissue, and injuries, the exact location of the damage within the annual ring was noted and therefore allowed for an intraseasonal dating of past events (Stoffel et al., 2005b, 2006; see Fig. 2). As injured trees start immediately with the compartmentalization of the wound and callus tissue formation, one can use the position of these growth features inside the growth ring (i) to assess the timing of events with intraseasonal resolution and (ii) for a distinction between different processes. In the years where injuries, callus tissue and TRD were identified outside the vegetation period or at the very beginning of the new increment ring (i.e., in dormancy D or early earlywood EE), they were interpreted the result of snow avalanche impact. In contrast,

Table 1
Overview of the sample size.

	Trees sampled	Cores	Wedges	Crosssections
Conifers	61	148	0	1
Broad-leaves	32	23	34	10
Total	93	171	34	11

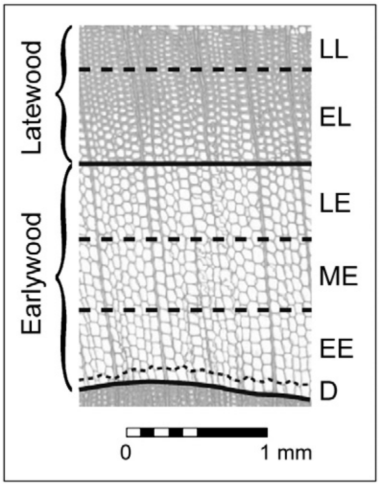

Fig. 2. Detail of a tree ring with earlywood and latewood cells. Earlywood (E) is further subdivided into early (EE), middle (ME) and late (LE) earlywood, and latewood (L) into early (EL) and late (LL) latewood. D represents dormancy, the time outside the vegetation period (source: Stoffel et al., 2005b).

injuries, callus tissue and TRD located in later portions of the tree ring (i.e., in middle earlywood ME, late earlywood LE and early EL or late latewood LL) were interpreted as a consequence of debris-flow activity. An intraseasonal dating was not possible for the onset of reaction wood, abrupt growth increases and decreases.

In a subsequent step, GD were classified after their intensity into strong, intermediate, and weak reactions (for details see Schneuwly et al., 2009a,b). Events were reconstructed from the tree-ring series if GD occurred simultaneously in different trees and based on the following criteria: (i) at least one tree must show a GD of strong intensity; and (ii) the GD of strong intensity must be supported by GD of all intensities in other trees. Broad-leaved trees were regarded as highly reliable indicators for past events as their sampling strategy minimized the risk for errors.

3.3. Identification of triggering precipitation events

Rainfall events that may have triggered debris flows where analyzed. Following Cannon and Ellen (1985), triggering thresholds differ with mean annual precipitation of the area under investigation. Heavy rainfall events were defined as events with daily sums of at least 20 mm (this equals half of the mean monthly rainfall sum) and/or an intensity of at least 5 mm/h (intensity of a moderate rain shower). Data with hourly resolution was only available for the period 1981–2008 at the climate station of Sion, located about 25 km west of the study site (46° 14′ N./7° 22′ E., 482 masl; MeteoSwiss, 2008; see Fig. 1). Precipitation data with daily resolution was used from the station at Sierre (1960–2008; 10 km west of the torrent, 46° 18′ N./7° 32′ E., 542 masl), for older events.

In the case of snow avalanches, rainfall data was only used to determine precipitation during late autumn and winter to exclude the possibility of GD being the result of debris flows very late in autumn and after the end of the vegetation period.

4. Results

4.1. Geomorphic mapping

Geomorphic mapping concentrated on the landforms related to past debris-flow and snow avalanche activity. Debris flows are the process doing most geomorphic work at Meretschibach, this is why geomorphic forms related to past snow avalanche activity are completely missing in the field. In total, an area of 3.3 ha was mapped and 23 segments of levees identified. As a consequence of the recent construction of deflection dams on both sides of the channel, levees are inexistent along the channel reaches through the debris-flow cone. The majority of the mapped levees are located between 860 and 800 masl. They can be further classified by their relative age. The youngest levees are located inside or adjacent to the active channel and consist of unvegetated large boulders. Older levees are covered with moss and are located up to 3 m above the present channel bed. Several trees are growing either in or on these forms.

4.2. Age structure of the trees

The average age of the 93 sampled trees (171 samples) is 54 years, with the oldest tree showing 95 (A.D. 1913) and the youngest one only 4 increment rings (A.D. 2004) at sampling height. Broad-leaved trees are significantly younger than conifers (average 32 and 63 years, respectively). The age structure of the trees sampled is heterogeneous but shows a regular pattern. Younger trees are concentrated along or inside the active channel bed, while the oldest trees grow on or close to the oldest debris-flow forms and along the debris-flow channels. Reconstruction of past debris-flow and snow avalanche activity is limited to the time period A.D. 1930–2008 as < 10 of the trees sampled are older than 78 years (A.D. 1930).

4.3. Growth disturbances and event years

Analysis of the 148 increment cores allowed for an identification of 340 GD relating to past geomorphic processes along the channel (Table 2). TRD were the GD most frequently observed (35%), followed by growth reductions (24%) resulting from a partial stem burial or decapitation and the presence of compression wood (19%) after tilting. In contrast, injuries and adjacent callus tissue were only rarely observed on the increment cores (2% and 6%, respectively).

In addition, 45 injuries were identified on the 34 wedges and 10 crosssections. As destructive sampling focused on injuries remaining visible on the stem surface of young broad-leaved trees, the time span covered extends back to only 1987.

In total, analysis of GD occurring simultaneously in different trees enabled reconstruction of 20 event years between A.D. 1930 and 2008, with 1937 representing the oldest and 2008 the most recent year with signs of process activity (Fig. 3). The number of trees affected per event ranges from 3 to 17. A slight increase in the reconstructed frequency is observable since the 1990s, with a clustering of incidences between 2000 and 2003.

4.4. Seasonality of events: separating debris flows from snow avalanches

As can be seen in Table 3, a total of 20 debris flows and 3 snow avalanches can be identified from the tree-ring records between 1930 and 2008. An intraseasonal dating of the GD was not possible for events in 1974 and 1937, when trees reacted to geomorphic activity with abrupt changes in growth and the formation of compression wood.

Snow avalanches were identified based on the location of injuries within the tree ring. In 1994, 1977, and 1951, injuries were inflicted

Table 2
Growth disturbances (GD) and their intensities assessed in the 148 increment cores of 57 *P. abies* (L.) Karst, 2 *L. decidua* Mill. and 2 *Abies alba* Mill. trees.

Growth disturbance	TRD	Growth reduction	Reaction wood	Growth increase	Callus tissue	Injury
Total (number)	120	81	65	46	21	7
Total (%)	35	24	19	14	6	2
Weak signal (%)	46	28	22	39	0	0
Intermediate signal (%)	34	52	46	52	0	0
Strong signal (%)	20	20	32	9	100	100

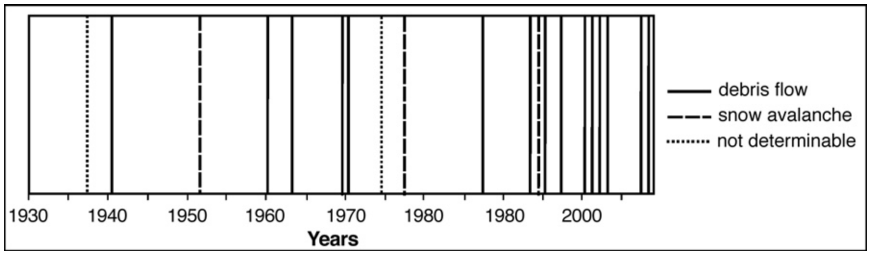

Fig. 3. Reconstructed debris-flow and snow avalanche events at Meretschibach between 1930 and 2008.

during the dormant season or at the very beginning of the new growing period, i.e., sometimes between November and April. The winter months in these years were characterized by intense snowfall and an absence of heavy rainfall events in late autumn (i.e., October and early November). Based on the intraseasonal position of the injuries, the spatial distribution of affected trees, and the meteorological records, we are confident that the observed GD have to be the result of snow avalanche activity. Interestingly, the snow avalanche event in March 2001, known from archival data, did not leave any datable signs in the selected trees.

GD in all the other years result from debris-flow activity, as damage was inflicted during the growing season of trees. They are predominantly located in earlywood, meaning that debris flows were repeatedly triggered between May and mid-July. The intraseasonal dating of events not only allowed for a separation of debris flows from snow avalanches, but also for the detection of repeated debris-flow activity within the same year, namely in 2008, 2007, 2003, and 2001. A distinction was, in contrast, not possible for the two debris-flow events in October 2000 as they occurred within only a few days and at the very end of the growing season.

Based on the spatial location of trees showing GD after an event, determining the source area for some of the events was also possible. The western debris-flow channel was active during seven events and the central channel during at least three and possibly even five events (Table 3). Fig. 4 presents an example of a debris-flow event occurring in the western debris-flow channel. Trees with GD are concentrated along the western debris-flow channel as well as on both sides of the torrent, mainly in the upper part directly after the confluence of the debris-flow channel with the torrent. A total of 17 trees pinpoint this event.

4.5. Event-triggering precipitation

Table 3 lists rainfall events that have possibly triggered the reconstructed debris flows. The focus of this analysis was on single events, and the accumulating effect of multiple small rainfall events was neglected deliberately. As GD relating to past debris flows are usually observed in earlywood, the triggering rainfall events occurred predominantly in June and July and are rare in August and September. The event with the highest daily rainfall sum was recorded on 11 October 1987 at Sierre (48 mm). A similar daily rainfall total was measured on 14 October 2000 with 47.9 mm at Sierre and 45.1 mm at Sion. The highest intensity (12 mm/h) was recorded during an event on 16–17 June 2008. Based on the intraseasonal position of GD in the trees and the meteorological records, identifying triggering precipitation events was possible for all events except 2003 (one out of the two events), 2002, 1993 and 1970.

The winter months with reconstructed snow avalanche activity are characterized by large amounts of snowfall and some single events with high daily snowfall sums, i.e., 19 December 1993 (daily sum 33.5 mm at Sierre and 23.5 mm at Sion) or the period 18–21 January 1951 with 55.6 mm precipitation recorded at Sion.

Table 3
Source area of past debris flows and triggering rainfall events.[a]

Event	Source area	Seasonality	Process	Archival data	Possible triggering rainfall events
2008a	Western channel	E	Debris flow	Before 6 July	16/17 June
2008b	Eastern channel		Debris flow	29 July	29 July*
2007a	Unknown	E	Debris flow		27/28 May; 15–25 June
2007b	Unknown	L	Debris flow		3 July; 8/9 July; 8 August; 29 August
2003a	Unknown	LE	Debris flow	21 May	Not determinable
2003b	Unknown	L	Debris flow	19 August	14–18 August*
2002	Western channel	L	Debris flow	31 July	Not determinable
2001a	Western channel	ME	Debris flow		9 June; 15 June; 27/28 June
2001b	Central channel	L	Debris flow		7 July; 15/16 July
2000	Western channel	L	Debris flow	15/23 October	Extensive precipitation 8–15 October
1997	Central and/or Eastern channel	E	Debris flow		21 June
1995	Western channel	E	Debris flow		30 May
1994	Unknown	D	Snow avalanche		Not determinable
1993	Central channel?	E	Debris flow		Not determinable
1987	Unknown	L	Debris flow		15 July; 17 August; 1 September; 26 September; 11 October
1977	Unknown	D	Snow avalanche		Not determinable
1974	Unknown	Not determinable	unknown		Not determinable
1970	Central channel	LE	Debris flow		Not determinable
1969	Western channel	ME	Debris flow		23 June
1963	Unknown	LE	Debris flow		Wet June
1960	Unknown	ME	Debris flow		19 May
1951	Western channel	EE	Snow avalanche		Not determinable
1940	Unknown	ME	Debris flow		25 June
1937	Central channel	Not determinable	unknown		Not determinable

*These events do not fulfill the above-mentioned criteria for intensity and/or daily sum. They were detected because of the known date of a debris flow.
[a] The listed events are either of high intensity (at least 5 mm/h), large daily sum (at least 20 mm/h), or a combination of both. Abbreviations used for seasonality are based on the location of growth disturbances within the tree ring: D = dormancy; E = earlywood; L = latewood; EE = early earlywood; ME = middle earlywood; LE = late earlywood.

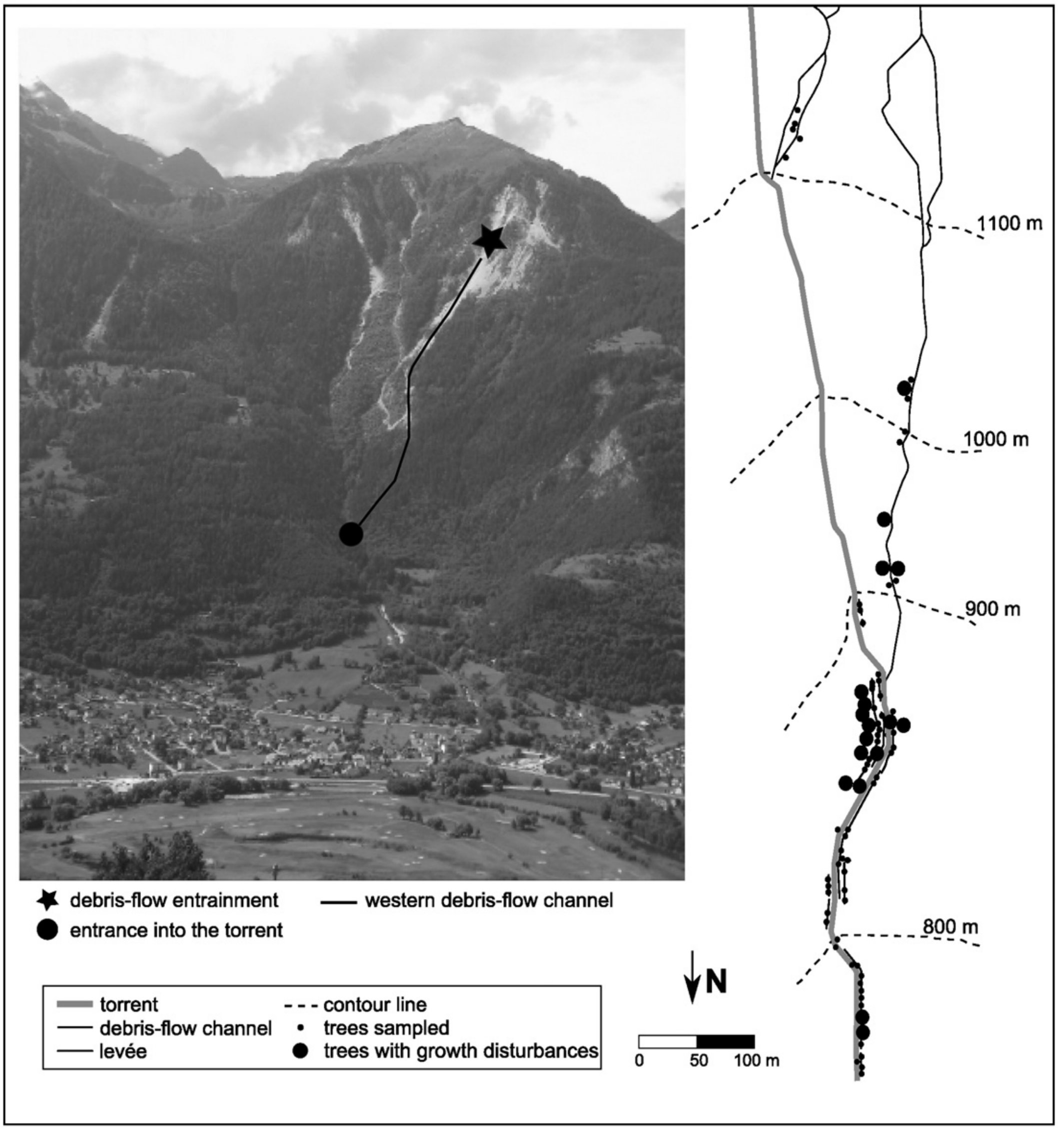

Fig. 4. Map illustrating the distribution of trees with growth disturbances and the source area of the debris-flow event in 1995.

5. Discussion

The analysis of 171 increment cores, 34 wedges and 11 crosssections extracted from 93 trees (conifers and broad-leaved trees) provided information on 25 debris-flow and snow avalanche events between A.D. 1930 and 2008. The differentiation of debris-flow incidences from snow avalanches was based on the intraannual position of GD (scars and tangential rows of traumatic resin ducts) inside the tree ring, the spatial arrangement of trees showing reactions, and on meteorological records.

The dating of visible scars from broad-leaved trees improved the reconstruction of debris-flow and snow avalanche activity considerably for the second half of the period covered by this study. Fig. 5 points out that broad-leaved trees played an essential role in the identification of younger events and that all but three events have been dated with the additional information conserved in the tree-ring record of the broad-leaved trees. For the events of 2008a, 2007a, 2007b, and 2001b, an identification of the event would not have been possible without the inclusion of broad-leaved trees. Moreover, they have served as an essential basis for the distinction of multiple events in one year.

The number of trees affected by a debris flow or a snow avalanche does not directly provide indications on the magnitude of the event. A high-magnitude debris flow can be highly erosive and thus cause an incision of the channel rather than a deposition of material along and outside the channel. Such an event would affect only a limited number of trees. In a similar way, small magnitude events or debris flows stalling inside an incised channel probably will not affect trees, this is why the frequency presented in this paper has to be considered a minimum frequency.

Similarly, the observed frequency increase since the 1990s has to been seen as an artifact resulting from the sampling strategy rather than a climate signal. We believe that the large presence of young broad-leaved trees in the data set has allowed for a reconstruction of small in-channel debris flows for the most recent decades, a class size of events that remained unidentified for most of the older times covered by our study.

Rainfall data was only available from climate stations located several kilometers away from the study site, and ca. 1400 m below the source area of debris flows. In this sense, debris-flow triggering rainfall events could not be identified for all events. In 2002, for instance, the exact date of the event is known (31 July). However, only the climate station of Sion recorded an insignificant amount of precipitation on 30 July (1.4 mm). For a more reliable reconstruction of triggering rainfall events we call for other proxies, if available, to be analyzed in future studies, such as distant lightning or radar data.

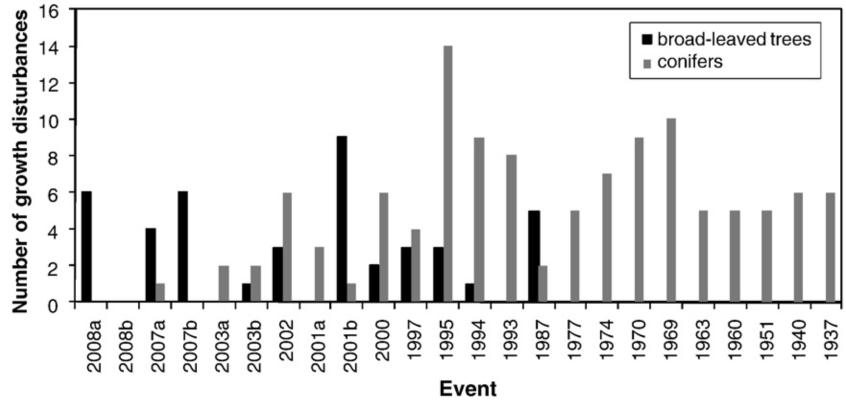

Fig. 5. Conifers vs. broad-leaved trees for the reconstruction of event years.

At Meretschibach, snow avalanches could less commonly be reconstructed than debris flows. This is possibly why forms of past snow avalanches are largely missing in the lower parts of the catchment and along the debris-flow channel and why no archival data exist on catastrophic events. Surprisingly, the known snow avalanche event of March 2001 was not recorded by the trees sampled in this study, but they allowed (in contrast) for an identification of three other avalanche events. Snow avalanches can take various paths downslope in watersheds, whereas debris flows are more restricted to predefined channels. The sampling strategy of this study focused on trees standing close to the torrent and along the debris-flow channels. Therefore, snow avalanches taking paths other than the one defined by the torrent were not reconstructed in this study.

The Meretschibach is flanked by two other torrents affected by debris flows, the Emsbach to the east and the Illgraben to the west. A comparison of the debris-flow frequencies of these three torrents is presented in Fig. 6. The most obvious differences in frequency are due to data availability. While only a few events are known for the Emsbach (Kolenko, 2004), debris-flow records are complete at Illgraben since the installation of an automated debris-flow observation station in 2000 (Graf et al., 2007). Although topographic settings and catchment size are very different, all three torrents show debris-flow activity in October 2000 because of the special rainfall conditions,

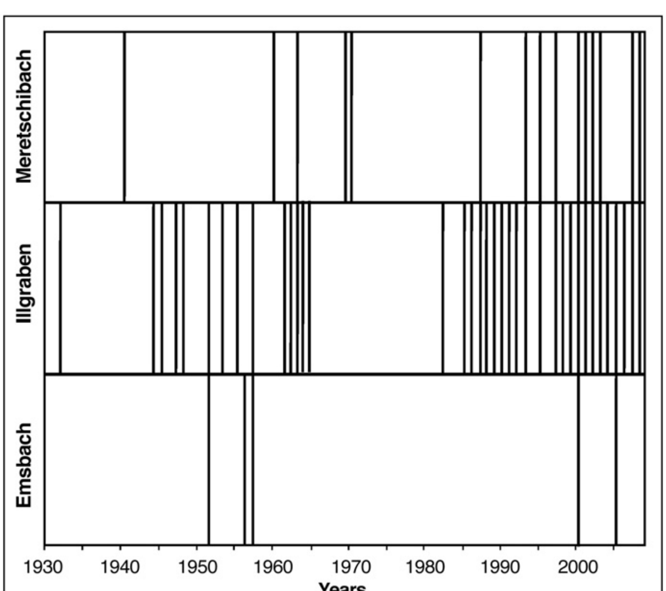

Fig. 6. Comparison of the reconstructed debris-flow frequency at Meretschibach with the neighbouring torrents Emsbach and Illgraben (data source: Kolenko, 2004 (Emsbach); T&C and WSL, 2005; Stoffel et al., 2008b (Illgraben)).

with 110.5 and 94.2 mm precipitation recorded between 8 and 15 October in Sion and Sierre respectively (BWG, 2002; MeteoSwiss, 2008). In 11 years, debris flows occurred simultaneously in Meretschibach and Illgraben: in 2000 and 2002 on the same date, and in 2003 at least in the same month. This accordance between the reconstructed debris flows in the Meretschibach and the ones occurring in neighbouring torrents shows that data obtained from dendrogeomorphology allows a reliable reconstruction of past process activity with high resolution.

6. Conclusions

The analysis of 216 samples extracted from 93 trees of various species allowed for a reconstruction of 20 debris-flow and 3 snow avalanche events between A.D. 1930 and 2008 with intraseasonal resolution. The potential of broad-leaved trees for dendrogeomorphic studies should not be neglected as the dating of injuries allowed for an intraannual dating of past events and a separation of different processes. As many slopes and torrents in alpine regions are affected by more than one mass-movement process at a time, multiprocess studies are necessary especially in the scope of hazard analysis. We therefore conclude that dendrogeomorphology is a very valuable tool to unravel the spatial and temporal patterns of different processes that have been active in the past.

Identification of debris-flow triggering rainfall events with precipitation records from neighbouring climate stations was possible for most of the 20 reconstructed debris-flow events although rainfall data does not reflect the conditions in the catchment area. The relationship between process and triggering factors is important to better understand the responses of geomorphic processes to climate change. We therefore stress the importance of further studies with other proxies such as, e.g., radar data and records on distant lightning.

Acknowledgements

This publication has been supported by the FOEN-SFP-SRCE project RUFINE (Project No. 0931030100RA0000008253) and the EU-FP7 “ACQWA” project (www.acqwa.ch) under “Contract Nr 212250”. It benefited considerably from insightful comments of David R. Butler, Matthias Jakob and Forrest D. Wilkerson.

References

Alestalo, J., 1971. Dendrochronological interpretation of geomorphic processes. Fennia 105, 1–140.
Arbellay, E., Stoffel, M., Bollschweiler, M., in press. Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees. Earth Surface Processes and Landforms.
Bacchini, M., Zannoni, A., 2003. Relations between rainfall and triggering of debris-flow: case study of Cancia (Dolomites, northeastern Italy). Natural Hazards and Earth System Sciences 3, 71–79.

Bollschweiler, M., Stoffel, M., 2007. Debris-flows on forested cones — reconstruction and comparison of frequencies in two catchments in Val Ferret, Switzerland. Natural Hazards and Earth System Sciences 7, 207–218.

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

Bollschweiler, M., Stoffel, M., Schneuwly, D., 2008. Dynamics in debris-flow activity on a forested cone — A case study using different dendroecological approaches. Catena 72, 67–78.

Boucher, D., Filion, L., Hétu, B., 2003. Reconstitution dendrochronologique et fréquence des grosses avalanches de neige dans un couloir subalpin du mont Hog's Back, en Gaspésie centrale (Québec). Géographie Physique et Quaternaire 57, 159–168 (in French).

Bräker, O.U., 2002. Measuring and data processing in tree-ring research — a methodological introduction. Dendrochronologia 20, 203–216.

Bryant, C.L., Butler, D.R., Vitek, J.D., 1989. A statistical analysis of tree-ring dating in conjunction with snow avalanches: comparison of on-path versus off-path responses. Environmental Geology and Water Sciences 14 (1), 53–59.

Butler, D.R., Sawyer, C.F., 2008. Dendrogeomorphology and high-magnitude snow avalanches: a review and case study. Natural Hazards and Earth System Sciences 8, 303–309.

Bundesamt für Wasser und Geologie (BWG), 2002. Hochwasser 2000 — Les crues 2000. Serie Wasser 2. Berichte des Bundesamtes für Wasser und Geologie, Berne, Switzerland. 248 pp. (in German).

Caine, N., 1980. The rainfall intensity–duration control of shallow landslides and debris flows. Geografiska Annaler 62A (1–2), 23–27.

Cannon, S.H., Ellen, S.D., 1985. Rainfall conditions for abundant debris avalanches in the San Francisco Bay region, California. California Geology 38 (12), 267–272.

Casteller, A., Stöckli, V., Villalba, R., Mayer, A.C., 2007. An evaluation of dendroecological indicators of snow avalanches in the Swiss Alps. Arctic, Antarctic, and Alpine Research 39 (2), 218–228.

Casteller, A., Christen, M., Villalba, R., Martínez, H., Stöckli, V., Leiva, J.C., Bartelt, P., 2008. Validating numerical simulations of snow avalanches using dendrochronology: the Cerro Ventana event in northern Patagonia, Argentina. Natural Hazards and Earth System Sciences 8, 433–443.

Cook, E.R., Kairiukstis, L.A., 1990. Methods of Dendrochronology — Applications in the Environmental Sciences. Kluwer, London.

Corominas, J., Remondo, J., Farias, P., Estevao, M., Zézere, J., Díaz, de Terán, J., Dikau, R., Schrott, L., Moya, J., González, A., 1996. Debris flow. In: Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.-L. (Eds.), Landslide Recognition: Identification, Movement and Causes. Wiley, Chichester, UK, pp. 161–180.

Dubé, S., Filion, L., Hétu, B., 2004. Tree-ring reconstruction of high-magnitude snow avalanches in the northern Gaspé Peninsula, Québec, Canada. Arctic, Antarctic, and Alpine Research 36, 555–564.

Graf, C., Badoux, A., Dufour, F., Fritschi, B., McArdell, B.W., Rhyner, J., Kuntner, R., Teysseire, P., Nigg, U., 2007. Alarmsysteme für murgangfähige Wildbäche–Beispiel Illgraben in German Wasser, Energie, Luft 99 (2), 119–128.

Gruber, U., Margreth, S., 2001. Winter 1999: a valuable test of the avalanche–hazard mapping procedure in Switzerland. Annals of Glaciology 32 (1), 328–332.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5, 3–17.

Hebertson, E.G., Jenkins, M.J., 2003. Historic climate factors associated with major avalanche years on the Wasatch Plateau, Utah. Cold Regions Science and Technology 37, 315–332.

Jakob, M., Hungr, O., 2005. Debris-Flow Hazards and Related Phenomena. Springer, Berlin, Heidelberg, New York.

Kanton Wallis, 2008. Internetseite des Kantons Wallis. http://www.vs-wallis.ch/unwetter/main3.html (site accessed 14 November 2008).

Kolenko, A., 2004. Prozessorientierte Analyse eines Wildbaches unter Berücksichtigung von Murgängen. In: Schleis, A. (Ed.), Collection des articles des travaux de diplôme. Communication 17 du Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Fédérale de Lausanne, Lausanne, pp. 133–143. in German.

McClung, D.M., Schweizer, J., 1999. Skier triggering, snow temperatures and the stability index for dry slab avalanche initiation. Journal of Glaciology 45 (150), 190–200.

MeteoSwiss, 2008. Precipitation records of the Swiss Meteorological Institute weather stations Sierre and Sion. http://www.meteoschweiz.admin.ch/web/de/weather.html (site accessed 14 November 2008).

Mundo, I.A., Barrera, M.D., Roig, F.A., 2007. Testing the utility of *Nothofagus pumilio* for dating snow avalanche in Tierra del Fuego, Argentinia. Dendrochronologia 25, 19–28.

Municipality of Agarn, 2008. Homepage of the municipality of Agarn. www.agarn.ch (site accessed 14 November 2008).

Muntán, E., Andreu, L., Oller, P., Gutiérrez, E., Martínez, P., 2004. Dendrochronological study of the Canal del Roc Roig avalanche path: first results of the Aludex project in the Pyrenees. Annals of Glaciology 38 (1), 173–179.

National Research Council, 1990. Snow avalanche hazards and mitigation in the United States. National Academy Press, Washington, DC.

Patten, R.S., Knight, D.H., 1994. Snow avalanches and vegetation pattern in Cascade Canyon, Grand Teton National Park, Wyoming, USA. Arctic and Alpine Research 26, 35–41.

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.

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.rintech.com/Products/Lintab.htm (site accessed 16 October 2008).

Schneuwly, D.M., Stoffel, M., Bollschweiler, M., 2009a. Formation and spread of callus tissue and tangential rows of resin ducts in *Larix decidua* and *Picea abies* following rockfall impacts. Tree Physiology 29, 281–289.

Schneuwly, D.M., Stoffel, M., Dorren, L.K.A., Berger, F., 2009b. Three-dimensional analysis of the anatomical growth response of European conifers to mechanical disturbance. Tree Physiology 29, 1247–1257.

Schweingruber, F.H., 1996. Tree Rings and Environment. Dendroecology. Paul Haupt Verlag, Bern, Stuttgart, Wien.

Schweizer, J., Jamieson, J.B., Schneebeli, M., 2003. Snow avalanche formation. Reviews of Geophysics 41 (4), 1016.

Shroder, J.F., 1980. Dendrogeomorphology: review and new techniques of tree-ring dating. Progress in Physical Geography 4, 161–188.

Schnee und Lawinenforschung Davos (SLF), 2000. Der Lawinenwinter 1999. Ereignisanalyse. Switzerland Eidg. Institut für Schnee und Lawinenforschung, Davos. (in German).

Stoffel, M., 2008. Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26 (1), 53–60.

Stoffel, M., in press, Magnitude–frequency relationships of debris flows — a case study based on field surveys and tree-ring records. Geomorphology. doi:10.1016/j.geomorph.2009.10.009.

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. Natural Hazards and Earth System Sciences 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., Hitz, O.M., 2008. Snow avalanche and rockfall impacts leave different anatomical signatures in tree rings of *Larix decidua*. Tree Physiology 28 (11), 1713–1720.

Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gärtner, H.W., Monbaron, M., 2005a. 400 years of debris flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arctic, Antarctic and Alpine Research 37, 387–395.

Stoffel, M., Lièvre, I., Monbaron, M., Perret, S., 2005b. Seasonal timing of rockfall activity on a forested slope at Täschgufer (Swiss Alps) — a dendrochonological approach. Zeitschrift für Geomorphologie 49 (1), 89–106.

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

Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Gilles, M., 2008a. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. Global and Planetary Change 60, 222–234.

Stoffel, M., Bollschweiler, M., Leutwiler, A., Aeby, P., 2008b. Tree-ring reconstruction of debris-flow events leading to overbank sedimentation on the Illgraben cone (Valais Alps, Switzerland). The Open Geology Journal 2, 18–29.

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

Wilkerson, F.D., Schmid, G.L., 2003. Debris flows in Glacier National Park, Montana: geomorphology and hazards. Geomorphology 55, 317–328.

Zimmermann, M., Mani, P., Romang, H., 1997. Magnitude–frequency aspects of alpine debris flows. Eclogae Geologicae Helveticae 90, 415–420.