# DEBRIS-FLOOD RECONSTRUCTION IN A PRE-ALPINE CATCHMENT IN SWITZERLAND BASED ON TREE-RING RECORDS OF CONIFEROUS AND BROADLEAVED TREES

BY

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ABSTRACT. Past debris-flood activity on the forested fan of Torrent de la Greffe located in the Swiss Prealps was assessed from growth disturbances in coniferous and broadleaved tree species. The study of 186 tree-ring sequences sampled from 44 Norway spruce (*Picea abies* (L.) Karst.) and 55 broadleaved trees from various species affected by past activity and the sampling of an additional 49 trees for the reference chronology allowed the reconstruction of 17 debris-flood events since AD 1900. The spatial analysis of trees affected during particular events on the geomorphic map helped the identification of five breakout locations in the torrent and affected sectors on the fan. The coupling of tree-ring analysis of coniferous and broadleaved tree species proved to be a valuable tool for the reconstruction of past events. Debris-flood frequency in the investigated torrent (0.16 event $yr^{-1}$) is considerably lower than the frequencies reconstructed in most other catchments in the Swiss Alps. As material for the entrainment of debris floods is not always readily available, the torrent has to be seen as supply-limited.

*Key words:* broadleaves, debris flood, supply-limited, Swiss Prealps, tree ring

## 1. Introduction

In the Swiss Alps – as in most mountainous regions in the world – mass-movement processes occur repeatedly and, therefore, represent a major agent in landscape formation (Ballantyne 1995, 2002; Butler 2001). Hydrogeomorphic activity such as debris-flow or debris-flood events results in the formation of characteristic cone-shaped landforms (Costa 1984; Blair and McPherson 1998, 2008). In order to understand the formation history of such cones and fans, past events can be reconstructed using various types of dating methods such as radiocarbon dating (Kovanen and Slaymaker 2008; Jakob and Friele 2010), cosmogenic nuclides (Stock *et al*. 2005; Dühnforth *et al*. 2007), lichenometry (Winchester and Harrison 1994; Winchester and Chaujar 2002; Jomelli *et al*. 2003), vegetation analysis (Baroni *et al*. 2000) or dendrogeomorphology (Hupp 1984; Stoffel *et al*. 2008; Bollschweiler and Stoffel 2010b). In addition to this natural information, written archives may constitute an important source of knowledge on past activity on fans. However, archival data of past torrential events often lacks spatial and temporal information, satisfying resolution or precision, and is (i) biased toward events that caused damage to structures or loss of life on one hand and (ii) undersampled in unpopulated areas on the other hand. Additional bias is introduced when interviewing residents because human memory is short-lived and highly selective, and the record will be biased toward more frequent events in the recent past (D'Agostino and Marchi 2001).

Where the current-day fan surface is covered with forest, dendrogeomorphology provides the most accurate dating method with annual resolution for the reconstruction of past torrential processes having occurred over the past decades to

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centuries. The basic principles of tree-ring dating have been outlined extensively by Alestalo (1971), Shroder (1980), Butler (1987) and Stoffel and Bollschweiler (2008, 2009). Dendrogeomorphology is based on the fact 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. Through the determination of the position of the GD within a tree ring, it is not only possible to date a geomorphic process to the year, but sometimes even to the season (i.e. monthly resolution; Stoffel and Beniston (2006)). Past dendrogeomorphic work related to water-induced hazards focused primarily on the reconstruction of past frequencies (May and Gresswell 2004; Stoffel *et al*. 2008) and magnitudes (Stoffel 2010), on the spatial behaviours of past events (Bollschweiler *et al*. 2007; 2008a), the synchronicity of debris-flow activity in neighbouring watersheds (Pelfini and Santilli 2008; Bollschweiler and Stoffel 2010a) or on the coupling of past events with data on flooding in neighbouring catchments (Stoffel *et al*. 2005). Most often, these studies focused on debris flows which are defined as a process occurring in steep channels with a rapid flow of saturated, non-plastic material (Hungr 2005). As compared to classical debris flows, debris floods normally contain a smaller proportion of solid material and reach significantly lower discharge peaks. Nevertheless, debris floods possess a high destruction potential and, therefore, represent a major risk in many mountain regions (Wilford *et al*. 2004; Hungr 2005). Debris-flood activity has, in contrast to debris flows and apart from a case study in the Austrian Alps (Mayer *et al*. 2010), not been reconstructed with dendrogeomorphic methods so far.

Tree-ring reconstructions of past debris-flow activity in the Swiss Alps were mainly applied in high-elevation permafrost environments with unlimited sediment supply through the activity of glacial and periglacial processes (Bollschweiler and Stoffel 2010c; Stoffel 2010). Similarly, past reconstructions mainly focused on conifers for the definition of past event years. Only recently, some authors (Arbellay *et al*. 2010; Szymczak *et al*. 2010) started to use broadleaved tree species for the reconstruction of debris-flow processes.

In this paper, we present a case study of a debris-flood fan covered with coniferous and broadleaved tree species affected by past torrential activity in a pre-alpine catchment with limited sediment supply. The reconstruction is based on the sampling of 148 trees on the fan of the Torrent de la Greffe, Valais, Switzerland. Through the analysis of the trees sampled and their spatial distribution on the fan surface we analyse the debris-flood frequency of the torrent and the spatial imprint of past events.

## 2. Study site

The study was conducted on the fan of the Torrent de la Greffe located on the east-facing slope of the Rhone Valley (Valais, Switzerland, 46°18′ N, 6°54′ E; Fig. 1). The catchment area of the Torrent de la Greffe totals 11.8 $km^2$ and extends from the Tour de Don (1998 m a.s.l.) to the valley floor at 380 m a.s.l. The study area is located in the Western Swiss Prealps in the middle-penninic sediment nappes (Pfiffner 2009) and geology is mainly composed of limestone and schist of Cretaceous and Eocene ages (Badoux *et al*. 1960). Material transported during debris-flood events originates primarily from scree slopes in the upper part of the catchment with average gradients of approximately 40°. These scree slopes only cover a small portion of the catchment area (Fig. 2) and are partly vegetation covered. The reminder of the catchment only offers limited and insignificant sediment sources and debris-flood material is usually scoured from the channel. Overall, however, the assessment of geomorphic properties of, and sediment sources in, the catchment suggest a rather limited availability of sediments for entrainment by debris floods. At 540 m a.s.l. a tributary torrent draining the northern part of the catchment and supplying only very limited sediments coalesces with Torrent de la Greffe.

The depositional fan extends from 480 m a.s.l. to the valley floor at 380 m a.s.l., has an approximate size of 40 ha and was formed through repeated torrential activity since the last glacial maximum (approx. 12 000 BP; (Pfiffner 2009)). On the current-day fan surface, deposits of past debris-flood events are clearly visible and the absence of geomorphic forms related to debris-flow activity, such as well-defined levees or lobes, underlines the fact that debris floods represent the predominant process at the study site. Figure 3 shows images of the cone, the torrent and trees growing on the cone surface. Currently, the torrent describes a dogleg at the fan apex and then follows the southern-most part of the fan. Only the sector adjacent to the torrent is covered by a forest com-


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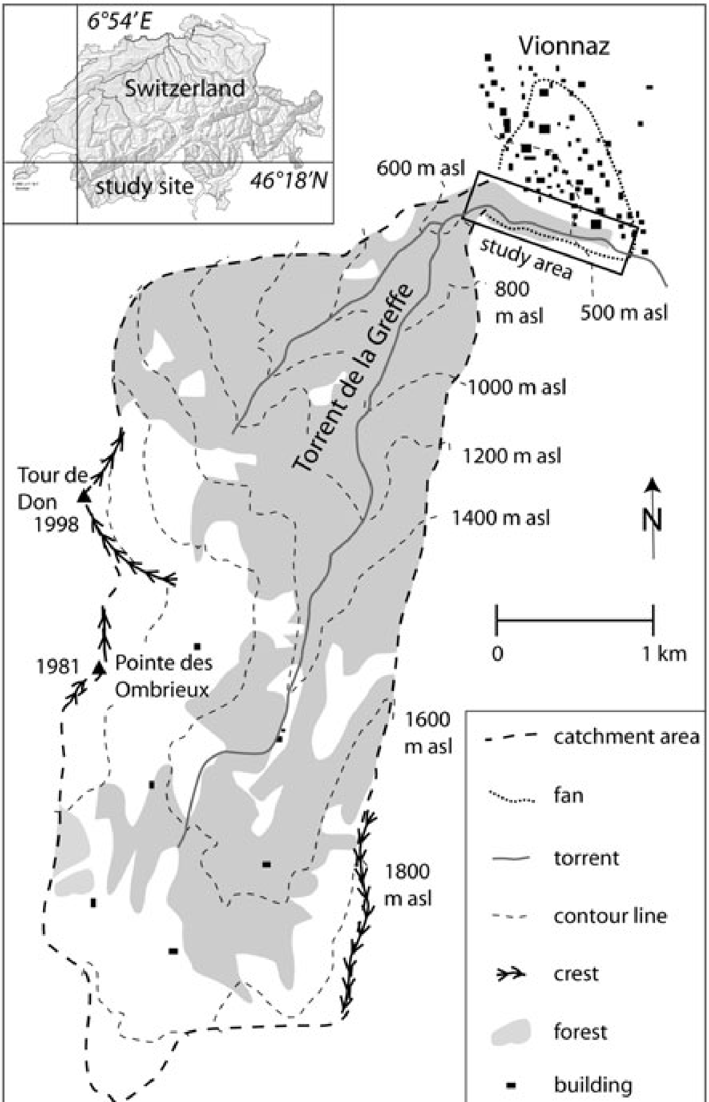


Fig. 1. This study has been conducted on the fan of Torrent de la Greffe, Valais, Switzerland. The catchment area totals 11.8 km$^2$ and extends from the Tour de Don (1998 m a.s.l.) to the valley floor at 380 m a.s.l. For this study, an area of approximately 6 ha on the southern part of the fan has been investigated.

posed of Norway spruce (*Picea abies* (L.) Karst.) and various broadleaved species such as *Fraxinus excelsior* L., *Fagus sylvatica* L., *Acer* sp., *Ulmus glabra* L., *Salix caprea* L., *Alnus incana* (L.) Moench and others. The growth season of trees in the study region starts approximately in mid-March and last on average 250 days until mid-November (Kirchhofer 1987). Climatically, the region lies between the continental climate of central Valais and the Atlantic climate of western Switzerland and is therefore dominated by regular rainstorm activity. Average yearly precipitation amounts to 1100 mm yr$^{-1}$ and the mean annual temperature is 10°C (SMI, 2008). Anthropogenic influence is most pronounced in the northern sector of the fan where the village of Vionnaz is located and where the land is used for vineyards. To protect the village, a deflection dam was built in 1742 and

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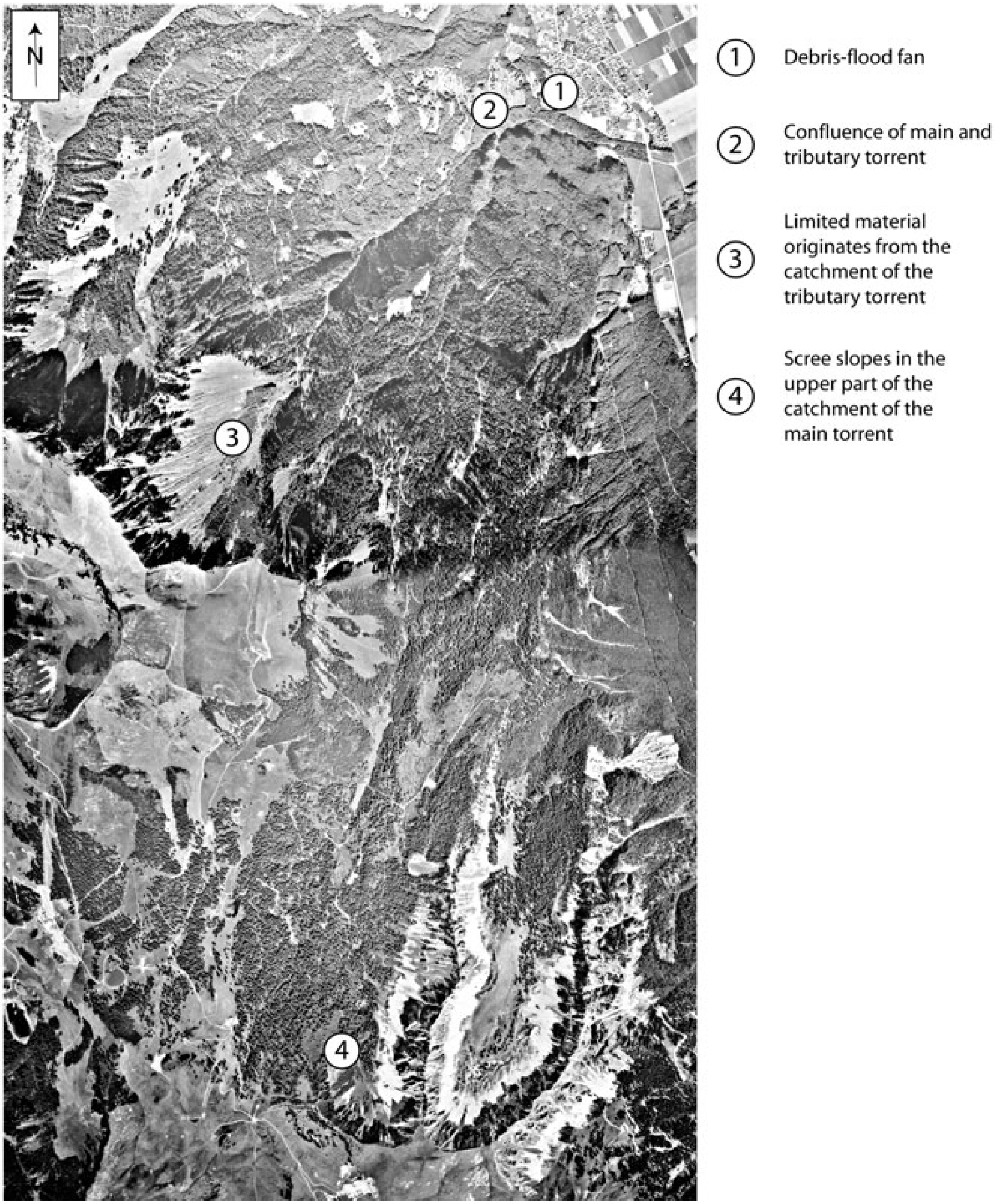


Fig. 2. Aerial view of the debris-flood fan, its catchment area and the sediment sources. Aerial photograph reproduced with courtesy of swisstopo (BA100577).

extended in 2005 (GILAT-ETEC-Alberti 2004), with a total current length of approximately 500 m. At the fan apex, the northern levee of the channel was reinforced in 2005 to prevent future events from leaving the channel. Data on past debris-flood events at Torrent de la Greffe reaches back to the eighteenth century with events noted in 1792, 1878, 1891, 1944, 1992 and 2004 (GILAT-ETEC-


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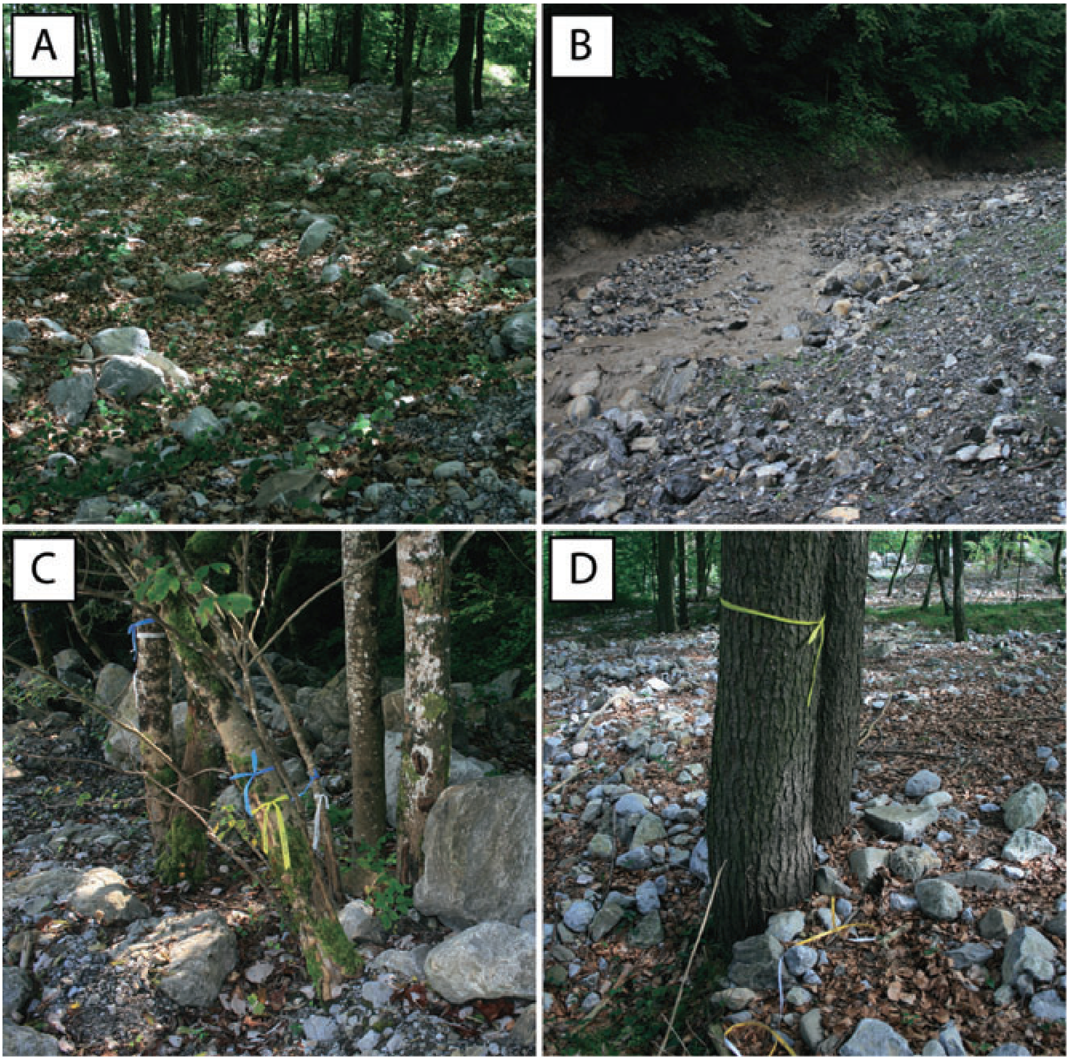


Fig. 3. A. Characteristic debris-flood deposit with clast sizes normally remaining below 30 cm. B. The channel of torrent de la Greffe during a rainfall event. C. Affected broadleaved trees in the uppermost reaches of the fan. D. Conifers located in the lower sectors of the fan buried in debris-flood deposits.

Alberti 2004). Detailed documentation is only available for the events in 1992 and 2004. In July 1992, a thunderstorm with intense convective rainfall triggered a debris-flood event depositing approximately 10 000 $m^3$ on the cone surface. After this event, the channel banks have been reinforced. In July 2004, intense regional thunderstorms in the region caused yet another debris flood comparable to that of 1992. As only devastating events are generally noted in archives, there is good reason to believe that additional events would have occurred in the torrent over the past decades and centuries.

## 3. Material and methods

### *3.1 Geomorphic mapping and sampling strategy*

Fieldwork started with the mapping of all features associated with previous debris-flood activity such as levees, lobes or abandoned channels in a scale of 1:1000. As a result of the dense forest cover, GPS did not allow for reasonable precision on the fan of

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Table 1. External morphologic disturbance of sampled trees.

| External morphologic disturbance | Number of trees | Percentage |
|---|---|---|
| Injury | 43 | 43.4 |
| Burial of stem base | 28 | 28.3 |
| Inclination | 26 | 26.3 |
| No external signs | 2 | 2.0 |
| Total | 99 | 100 |

Table 2. Sampled tree species.

| Tree species | Number of trees sampled |
|---|---|
| *Picea abies* | 44 |
| *Fraxinus excelsior* | 16 |
| *Fagus sylvatica* | 15 |
| *Acer sp.* | 10 |
| *Ulmus glabra* | 4 |
| *Robinia pseudoacacia* | 2 |
| *Viburnum lantana* | 2 |
| *Salix caprea* | 2 |
| *Alnus incana* | 1 |
| *Populus tremula* | 1 |
| *Sorbus aria* | 1 |
| *unidentified* | 3 |

Torrent de la Greffe and therefore geomorphic mapping utilized a tape, inclinometer and compass.

Based on this geomorphic map, trees showing obvious signs of influence by debris floods were sampled. Selected trees showed evidence of former activity in the form of injuries, burial of the stem base, inclination of the trunk or decapitation (Stoffel and Bollschweiler 2008, 2009). At least two cores were extracted per tree using increment borers, one in the flow direction of past debris floods and the other on the opposite side of the trunk (max. length of cores: 40 cm by 6 mm). In order to gather the greatest amount of information on growth disturbances (GD) caused by past events, increment cores were preferably taken at the height of the visible damage or within the segment of the stem tilted during past events. In the case of visible scars in coniferous trees, further increment cores were extracted from the callus overgrowing the wound (Schneuwly *et al.* 2009a, 2009b). Scars in broadleaved trees were sampled with wedges taken from the injury and the bordering callus tissue (Arbellay *et al.* 2010; Ballesteros *et al.* 2010; Szymczak *et al.* 2010). A summary on the external morphological disturbances is presented in Table 1. The position of sampled trees was precisely marked on the geomorphic map. In total, 99 trees obviously affected by past debris-flood activity were sampled with 159 increment cores, 16 cross sections, and 31 stem wedges. We primarily sampled *P. abies* (44 trees) and complemented the dataset with 55 broadleaved trees belonging to various species (see Table 2 for details).

In addition to the disturbed trees sampled on the fan, we collected samples from 49 undisturbed reference trees growing in the vicinity of the area affected by debris flood. For each reference tree, two cores were extracted parallel to the slope direction. In contrast to the disturbed trees, increment cores of the reference trees were extracted at breast height (≈ 130 cm).

### 3.2 Tree-ring analysis

In the laboratory, samples were prepared and analysed using standard dendrogeomorphic methods (Bräker 2002; Stoffel and Bollschweiler 2008, 2009). Individual preparation steps included mounting of the samples on woody support, drying and sanding. Afterwards, tree rings were counted and ring widths measured. Individual growth curves were then compared to the reference chronology established from the undisturbed trees sampled in order to identify missing or false rings and to separate insect attacks or climatically driven fluctuations in tree growth from GD caused by debris floods (Cook and Kairiukstis 1990; Vaganov *et al.* 2006). Growth curves were then used to determine the initiation of abrupt growth suppression or release (Schweingruber 2001; McAuliffe *et al.* 2006). In the case of tilted stems, both the appearance of the cells (i.e. geometry of the reaction wood cells) and the growth curve data for the determination of eccentric growth were analysed (e.g., Braam *et al.* 1987; Fantucci and Sorriso-Valvo 1999).

Finally, cores were visually inspected so as to identify further signs of past debris-flood activity. The corrasion of tree stems causes cambium damage (cambium = wood-producing tissue) and results in the formation of callus tissue overgrowing these scars (Hupp 1984). Another typical feature in *P. abies* trees are tangential rows of traumatic resin ducts (TRD; Bannan 1936; Bollschweiler *et al.* 2008b; Stoffel 2008), which are formed as a means of protection against insect and pathogen attacks following cambium damage (Bannan 1936; Hudgins and Franceschi 2004; Luchi *et al.* 2005).


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### *3.3 Debris-flood frequency reconstruction and definition of spatial behaviour of events*

After the dating of GD on the samples, the identification of events was based (i) on the number of samples simultaneously showing a growth disturbance as well as (ii) on the distribution of affected trees on the fan. GD occurring simultaneously in different trees were grouped and criteria defined for the determination of events. In this study, we distinguish between well replicated events and events which are only present in a limited number of tree-ring series. In addition, we positioned all trees with GD resulting from the same event on the geomorphic map so as to reconstruct the minimum spatial extent of events on the fan and to assess activity in currently abandoned channels.

## 4. Results

### *4.1 Geomorphic map and tree ages*

Geomorphic mapping permitted identification of 62 features related to past debris-flood activity on the fan of the Torrent de la Greffe. The features and deposits inventoried in the study area covering 6 ha are illustrated in Fig. 3 and included 52 elongated lobate-type deposits, 8 formerly active flow paths and 2 levees. Forms on the cone surface are composed of small rocks generally not exceeding 30 cm and deposits are not well pronounced as is typical for debris-flood environments. Isolated blocks featuring sizes of up to 1 m can be recognized in the vicinity of the channel. In contrast, sectors located at greater distances from the current channel are completely covered by vegetation (grass, different types of shrubs) and seem to have been unaffected by debris floods for some time. Trees growing in the outermost parts of the cone support this assumption as they do not show any signs of past debris-flood activity at all. In contrast, the areas located on both sides of the current channel show clear and multiple signs of recent torrential activity and are only sparsely covered with vegetation.

Affected trees sampled for this study are located south of the torrent for the upper part of the fan and north of the channel in its lower segments (see Fig. 4). Trees for the reference chronology were sampled in the outer part of the fan on the southern side. The average age of reference trees is 106 years ($\sigma = 34$ yr). In contrast, trees sampled for the event reconstruction average 69 yr ($\sigma = 28$ yr) at sampling height. Counted tree rings ranged from 15 (AD 1982) to 154 (AD 1853). Differences in the age distribution between conifers and broadleaved trees are pronounced. While conifers show a mean age of 96 years ($\sigma = 29$ yr), ages of broadleaved trees sampled for this study average out at only 50 years ($\sigma = 16$ yr).

### *4.2 Growth disturbances and event years*

Dendrogeomorphic analyses of the 159 increment cores, 16 cross sections, and 31 stem wedges sampled from affected trees permitted the detection of 618 GD related to past debris floods. Table 3 illustrates that signatures of past events are mainly preserved on the samples via TRD (62.5%) resulting from cambium damage. However, TRD can only be identified in the conifer trees as this feature is not formed in broadleaves. Sudden growth release following an elimination of neighbouring trees represent 17.8% of the growth reactions and suppression following tree topping, root exposure or stem burial amounts to 14.1%. These two growth reactions were especially important in broadleaved trees with 52.8% and 37.7% respectively of all reactions. Injuries were a common reaction in the broadleaved trees as well with nearly 10% of all growth reactions. Compression wood, only formed in conifers, represents 2.7% of the GD. In this study, we neglected the presence of tension wood in broadleaved trees, as the trees sampled did not exhibit strong tension wood reactions and as the formation of light tension wood might also be formed in trees competing for light.

The analysis of GD occurring simultaneously in different trees allowed the reconstruction of 17 debris-flood events between AD 1900 and 2007. Figure 5 illustrates the reconstructed frequency series, indicating that the dating of 9 events was based on a large number of GD (represented with black lines). In contrast, for the 8 events represented with grey lines, there is good evidence for the existence of events in these years as well, but the reduced number of GD did not allow for them being considered events with equal confidence. Table 4 gives the number, type and intensity of GD, as well as the spatial distribution of trees affected during particular events. Three of the six events recorded in archives could be reconstructed with tree-ring records as well (1944, 1992 and 2004). The more recent events are very well replicated with 29 and 75 GD, respectively, with a large number of injuries and related TRD and a

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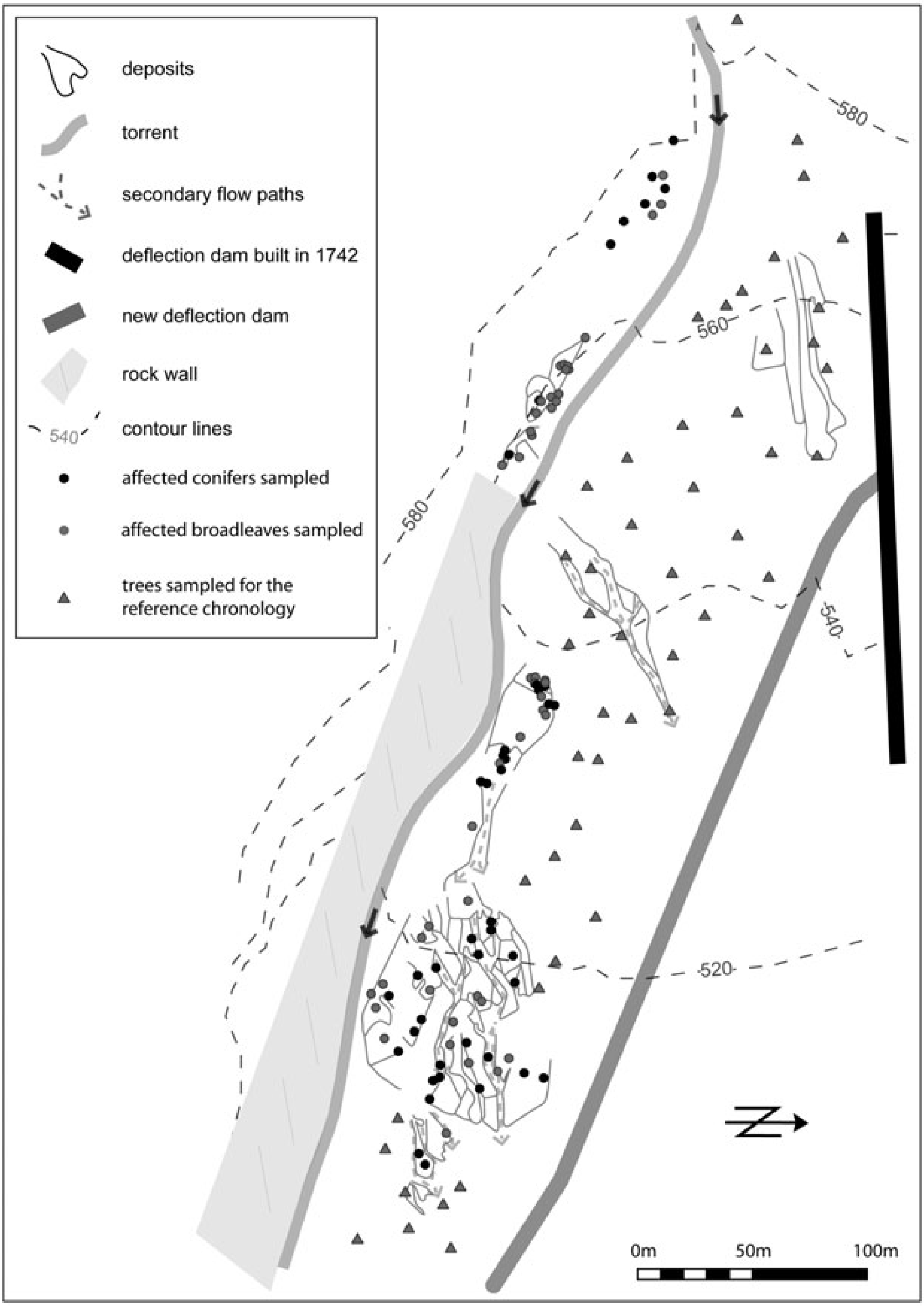


Fig. 4. Geomorphic map of all deposits related to past debris-flood activity and the position of trees sampled.


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Table 3. Growth disturbances identified in the tree-ring series.

| Growth disturbance | Conifers | | Broadleaves | | Total | |
|---|---|---|---|---|---|---|
| | Number | % | Number | % | Number | % |
| TRD* | 386 | 75.39 | 0 | 0.00 | 386 | 62.46 |
| Growth release | 54 | 10.55 | 56 | 52.83 | 110 | 17.80 |
| Growth suppression | 47 | 9.18 | 40 | 37.74 | 87 | 14.08 |
| Compression wood | 14 | 2.73 | 0 | 0.00 | 14 | 2.27 |
| Injury | 11 | 2.15 | 10 | 9.43 | 21 | 3.40 |
| Total | 512 | 100 | 106 | 100 | 618 | 100 |

* = Tangential rows of traumatic resin ducts

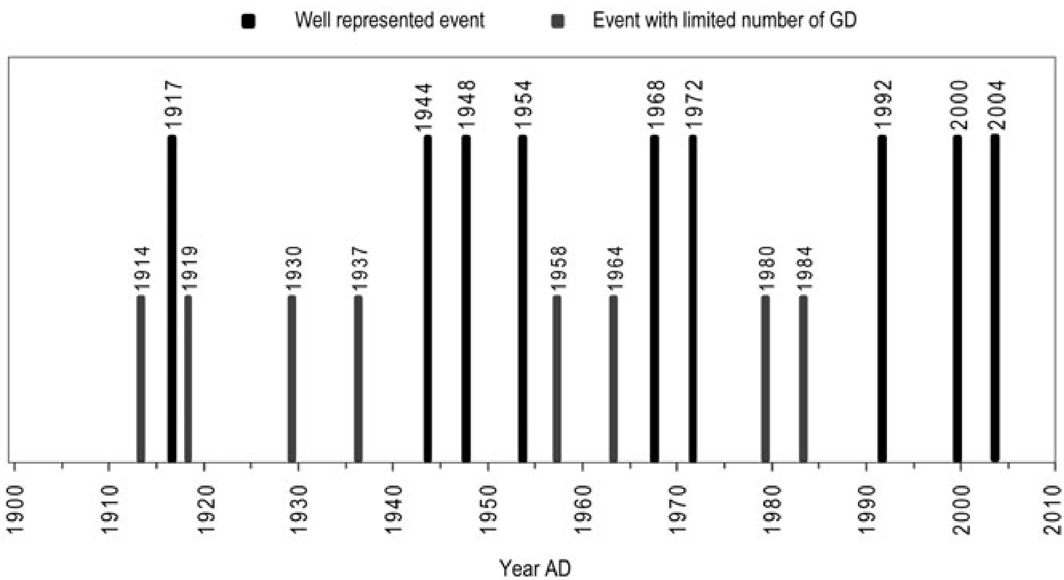


Fig. 5. Tree-ring based reconstruction of debris-flood activity at Torrent de la Greffe between AD 1900 and 2007 containing 17 events: 9 events could be assessed with a large number of growth disturbances (black lines). In contrast, for the 8 events represented with grey lines, there is good evidence for the existence of events in these years as well, but the reduced number of trees did not allow for them being considered events with equal confidence.

predominance of strong reactions (see Table 4 for details). The event of 1944 is less represented with 11 GD, but 7 out of the 11 GD were strong TRD, i.e. a reaction of conifers to strong impact pressures and thus very reliable indicators of past geomorphic activity.

### *4.3 Spatial behaviour and breakout locations of past events*

The position of all trees showing GD in a specific year was then used to assess spatial patterns and breakout locations of past events on the fan. Based on the affected trees, we identified five different sectors and six breakout locations for the reconstructed events as can be seen in Fig. 6. Table 5 summarizes the affected sectors and the corresponding breakout locations for each event. Sector C was most often impacted by debris-flood material leaving the channel (N = 16), in contrast, trees sampled in sector B showed growth disturbances only after 5 events. In general, the northern sectors (C, D, E) were more often affected by events than the southern ones. The same pattern can also be observed in the number of breakouts per location where clearly more events towards the north (i.e. breakout locations 4 and 3) can be identified with 12 to 17 events respectively. In contrast, the

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Table 4. Type, number and intensity of GD for all event years. For the definition of events, the spatial distribution of trees with GD (1 = even and meaningful distribution of GD, 0 = scattered distribution of GD) has been taken into account as well. Based on these criteria, debris floods have then been defined as certain (++) and probable events (+).

| Year | 2004 | 2000 | 1992 | 1984 | 1980 | 1972 | 1968 | 1964 | 1958 | 1954 | 1948 | 1944 | 1937 | 1930 | 1919 | 1917 | 1914 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Injury | 2 | 0 | 12 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| TRD | 19 | 24 | 27 | 8 | 9 | 17 | 6 | 4 | 7 | 5 | 4 | 7 | 5 | 8 | 6 | 4 | 10 |
| Growth release | 6 | 8 | 18 | 4 | 6 | 0 | 6 | 5 | 2 | 0 | 1 | 3 | 1 | 0 | 0 | 0 | 1 |
| Growth suppression | 2 | 10 | 18 | 3 | 6 | 15 | 5 | 2 | 6 | 0 | 1 | 1 | 4 | 2 | 1 | 0 | 1 |
| Compression wood | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 3 | 1 | 2 | 2 | 0 | 0 | 1 | 0 | 0 | 0 |
| TOTAL GD | 29 | 42 | 75 | 17 | 22 | 33 | 17 | 14 | 16 | 8 | 8 | 11 | 10 | 11 | 7 | 5 | 12 |
| No. of intense GD | 23 | 26 | 55 | 11 | 18 | 21 | 13 | 8 | 12 | 7 | 7 | 7 | 5 | 4 | 4 | 4 | 7 |
| No. of weak GD | 6 | 16 | 10 | 6 | 4 | 12 | 4 | 6 | 5 | 1 | 1 | 4 | 5 | 7 | 3 | 1 | 5 |
| Spatial distribution | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| Classification | ++ | ++ | ++ | + | + | ++ | ++ | + | + | ++ | ++ | ++ | + | + | + | ++ | + |

lowermost part of the fan seems to have been less affected with only nine events recorded for breakout location 5. Based on our reconstruction, the debris flood of 2004 left the channel at various locations in the central and lower parts of the fan whereas the event of 1992 avulsed at the fan apex resulting in less tree damage in the lower segments of the fan. These findings are well in concert with the archival record pointing to a large spread of the debris flood and deposition of material in most parts of the entire fan.

## 5. Discussion

In the study we report here, increment cores, cross-sections and wedges extracted from 44 living *P. abies* and from 55 broadleaved trees of various species allowed detection and dating of 618 growth disturbances (GD) attributed to 17 debris-flood events since AD 1900 on the fan of the Torrent de la Greffe. In addition, breakout locations and affected sectors of past events were identified.

The reconstruction of past events was mainly based on tangential rows of traumatic resin ducts (TRD) in conifers and on abrupt growth changes in broadleaved trees. In contrast, injuries represent only 3.5% of all GD identified. Injuries were more often assessed in broadleaves (10%) than in conifers (2.1%) as the thinner and softer bark present in most broadleaved tree species tends to be more easily injured by debris floods than the thicker and more protecting bark of conifers (Stoffel and Perret 2006). Conifers are known to overgrow injuries more quickly and there is a risk that internal (hidden) scars are not selected for sampling. Older and overgrown scars in conifers can, however, be detected rather easily on the increment cores through the presence of TRD formed next to injuries.

On the basis of the GD identified in the tree-ring samples of conifer and broadleaved trees, it was possible to complement the database of known debris floods from three events (1944, 1992 and 2004) to 17 events for the twentieth century. All events recorded in the archives and occurring in the twentieth century were identified in and documented with the tree-ring samples as well. The three older documented events (1792, 1878 and 1891) could not be reconstructed with dendrogeomorphic methods as the number of trees reaching back to the eighteenth and nineteenth centuries was limited. Even though we identified some GD in the tree-ring series of the


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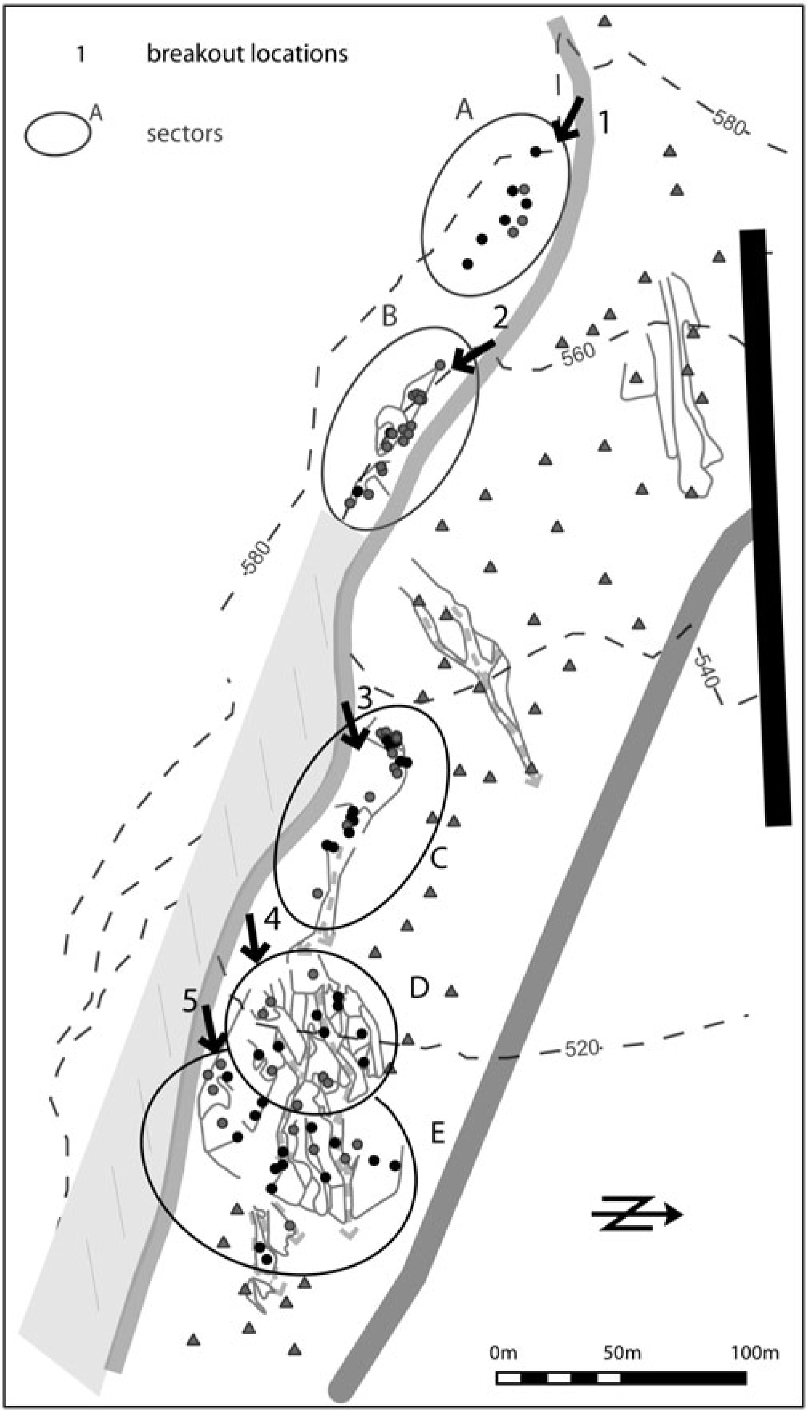


Fig. 6. Sectors identified on the fan and preferential breakout locations on the fan. For the number of events per sector and breakout location see Table 5.

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Table 5. Sectors affected by debris-flood events and related breakout locations.

| | Sector | | | | | Breakout location | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | A | B | C | D | E | 1 | 2 | 3 | 4 | 5 |
| 2004 | | x | x | x | x | | x | x | x | x |
| 2000 | x | x | x | x | x | x | x | x | x | x |
| 1992 | x | x | x | x | x | x | x | x | x | |
| 1984 | x | | x | (x) | x | x | | x | x | |
| 1980 | x | x | x | x | (x) | x | x | x | x | x |
| 1972 | x | x | x | | x | x | x | x | | x |
| 1968 | x | | x | | x | x | | x | x | |
| 1964 | | | x | | x | | | x | | x |
| 1958 | x | | x | (x) | x | x | | x | (x) | x |
| 1954 | | | x | | | | | x | | |
| 1948 | | | x | | | | | x | | |
| 1944 | | | x | (x) | (x) | | | x | x | |
| 1937 | | | | x | x | | | (x) | x | x |
| 1930 | | | (x) | x | x | | | x | x | x |
| 1919 | | | (x) | (x) | (x) | | | x | x | x |
| 1917 | | | x | | | | | x | | |
| 1914 | | | x | x | | | | x | x | |
| Total | 7 | 5 | 16 | 11 | 13 | 7 | 5 | 17 | 12 | 9 |

existing trees, their number was not sufficient to allow definition of events with reasonable confidence. Based on the tree ages and the spatial distribution of trees, we limited our reconstruction to the period 1900 to 2007.

When talking about debris-flood histories, we also need to stress that the tree-ring based reconstructions of past activity remains a minimum frequency and that some events may have been missed as a result of tree selection in the field or through the fact that debris floods did not leave any signs in the trees present on the current-day fan surface. The rather fine-grained material and the high water content of debris floods may produce events leaving the channel and affecting the fan, whereas energies involved are too small to cause growth disturbances discernable in the tree-ring series. In contrast, debris flows possess normally higher energies leaving larger damage in trees and their impact is therefore more easily recognizable in the tree-ring series. Another reason why tree-ring records may only produce a minimum frequency stems from the fact that the approach used in this paper most certainly fails in determining the frequency of smaller flows, as these incidences usually remain confined to the channel without causing recordable damage to trees. This limitation is not, however, significant for hazard and risk studies, as it only truncates the debris-flood frequency for lower magnitude events. Most prudent debris-flow and debris-flood mitigation measures will however focus on high-magnitude events, whose occurrence is scarcer than that of the more frequently occurring smaller events (Wolman and Miller 1960; Jakob *et al*. 2005; Hungr *et al*. 2008).

The reconstructed debris-flood frequency for the Torrent de la Greffe amounts to 0.16 events $yr^{-1}$ for the period 1900 to 2007. This frequency is considerably lower than the frequencies reconstructed in most other catchments in the Swiss Alps. Bollschweiler and Stoffel (2007) report on a mean frequency of 0.25 events $yr^{-1}$ for the same time period in Val Ferret, located at a distance of approximately 40 km. Frequencies are even higher in the Zermatt Valley where frequencies between 0.31 and 0.42 events $yr^{-1}$ were reconstructed with tree rings (Bollschweiler *et al*. 2008a; Stoffel *et al*. 2008; Bollschweiler and Stoffel 2010c). The reason for this lower frequency in the Torrent de la Greffe can be attributed to geomorphic and (probably) climatic factors present at the study site. Sediment availability in Torrent de la Greffe is not as abundant as it is in the high-alpine catchments of the Val Ferret and the Zermatt valley where unlimited sediment supply is guaranteed from the periglacial environments. At Torrent de la Greffe, material available for entrainment is stored on scree slopes covering only 4% of the catchment area. In addition, these scree slopes are mainly formed by repeated rockfall activity from the mountain crests delimiting the catchment area. Therefore, loose material is not always readily available and debris floods cannot be triggered at any moment. In addition, soil properties in the catchment of Torrent de la Greffe are more prone to infiltration of water and therefore favour lagged run-off.

In addition to these geomorphic differences, rainfall regimes responsible for the triggering of events show different properties. Events in the high-Alpine catchments are either triggered by local summer thunderstorms or persistent advective rainfall caused by strong low-pressure systems located in the Mediterranean Sea. In contrast, the Torrent de la Greffe is more vulnerable to low-pressure cells bringing warm-wet air from the Atlantic Ocean toward the Alps. Blocking situations with persistent rainfall are much scarcer with this situation and events at the study site are therefore most probably triggered rather by local summer thunderstorms (Frei *et al*. 1998; Frei and Schär 1998; Gyarmati 2004).


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The analysis of breakout locations and the spatial behaviour of events on the fan evinced a higher activity in the northern part of the fan and especially in its lower sectors. In contrast, activity seems to have been rather limited at the fan apex as hardly any characteristic deposits can be discerned and no trees with obvious signs of past activity were found. This is somewhat surprising as the torrent shows a dogleg at the fan apex and increased outbreak activity form the dogleg onto the fan should be expected. Apparently, the channel is (and has been) incised deep enough to prevent the outbreak of material at this location during events. Nowadays, channel banks have been reinforced so as to hinder future debris floods from causing overbank sedimentation at the cone apex. Sector C and breakout location 3 have been particularly active during past events, this probably stems from the fact that the rock face immediately on the south of the torrent would have repeatedly coerced debris floods to the north. In addition, the resulting bend in the torrent bed may also have induced higher energies, therefore facilitating outbreaks on the fan and favouring incision.

## 6. Conclusion

Dendrogeomorphic analysis of tree samples allowed the reconstruction of 17 debris-flood events between AD 1900 and 2007 at Torrent de la Greffe of which three events (1944, 1992 and 2004) were recorded in local archives. Moreover, analysis of the spatial distribution of disturbed trees contributed to the identification of preferential breakout locations of events. The debris-flood frequency reconstructed in this pre-alpine catchment is considerably lower than tree-ring based debris-flow frequencies obtained for most high-elevation catchments in the Swiss Alps. Debris floods involve generally lower energies than debris flows and may therefore not leave abundant and strong growth disturbances in affected trees. In the torrent investigated, sediment supply for the entrainment of debris floods is limited and can thus be seen as another reason for the comparably low frequency of past event. Broadleaved trees proved to be a valuable source of information on former events and should be more widely used in future tree-ring studies. As the age of broadleaved trees is often limited, tree-ring analysis of geomorphic activity should always be complemented with data from conifers as they normally attain higher tree ages. Therefore, a coupling of broadleaved and conifer trees is promising to provide valuable data on the short and longer term debris-flood activity in mountain channels. Further investigations should aim at providing more details on growth disturbances and wood anatomical changes in broadleaved after the impact by debris-flood events so as to help improve the sampling strategy of broadleaved trees and to avoid destructive sampling.

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