Geomorphology 118 (2010) 199–206

Contents lists available at ScienceDirect

Geomorphology

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

Frequency and spread of debris floods on fans: A dendrogeomorphic case study from a dolomite catchment in the Austrian Alps

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A R T I C L E I N F O

Article history:
Received 26 October 2009
Received in revised form 20 December 2009
Accepted 23 December 2009
Available online 6 January 2010

Keywords:
Dendrogeomorphology
Tree-ring analysis
Debris flood
Hazard assessment
Austrian Alps

A B S T R A C T

Growth disturbances in tree-ring series have been regularly used to date debris-flow events in mountain environments. In contrast, no studies are available to date that have reconstructed debris floods by means of dendrogeomorphology. Therefore, the aim of this study was to determine the event frequency and the spread of debris floods in the Gratzental (Tyrol, Austria). The analysis of growth disturbances in the tree-ring series of 227 *Picea abies* (L.) Karst. and *Larix decidua* Mill. allowed the reconstruction of 37 events for the last 200 years. The lateral spread and preferable avulsion locations of reconstructed debris-flood events were assessed based on the dating of the events and the spatial position of trees affected by an event on the fan. Results show that the Gratzentalbach preferentially avulsed to the east, but affected trees were evenly spread over the fan. Reconstructed data illustrates the high potential of dendrogeomorphology for hazard assessment of debris floods.

1. Introduction

Torrential processes constitute a widespread hazard in Alpine regions where they repeatedly cause severe damage and destruction to settlement areas, transportation corridors, and infrastructure or even lead to loss of life, especially on alluvial fans and debris cones. In order to avoid damage or fatalities, an appropriate hazard assessment is needed, that demands knowledge about event frequency and magnitude (Jakob and Bovis, 1996). At present, no rigorous methods are available that would allow determination of event probability, be it based on physically measured characteristics of a catchment or on statistical approaches (Rickenmann, 1999).

Archival data of past torrential events often lacks spatial and temporal information, satisfying resolution or precision, and is biased toward events that caused damage to structures or loss of life on one hand and is 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. Therefore, archival records should be supplemented with other techniques (Jakob, 2005). An accurate method for the reconstruction of torrential processes on forested cones and fans is dendrogeomorphology, i.e., the analysis of trees that have been affected by past geomorphic activity (Alestalo, 1971; Stoffel and Bollschweiler, 2008).

Growth anomalies in tree rings have been used to gather information on former events and to complete records from written sources (Hupp et al., 1984; Strunk, 1991; Baumann and Kaiser, 1999). So far, studies primarily focused on the reconstruction of frequencies (May and Gresswell, 2004; Bollschweiler and Stoffel, 2007; Stoffel et al., 2008), magnitudes (Strunk, 1997; Stoffel, 2010), or spatial patterns of debris flows (Bollschweiler et al., 2007; Arbellay et al., in press) as well as on the investigation of the spatial and temporal distributions of meteorological conditions triggering events (Stoffel and Beniston, 2006).

Previous dendrogeomorphic research of torrential processes primarily focused on debris flows that usually cause heavy disturbances to trees growing on steep cones. Alluvial fans with low gradients (2–6°; Blair and McPherson, 1994) are dominated by debris floods and mud flows and have, in contrast, not been studied with tree rings to date.

In a similar way, dendrogeomorphic reconstructions of debris-flow activity have abundantly been performed in North America (e.g., Butler, 1979; Cook and Jacoby, 1983; Hupp et al., 1984) and in the western European Alps (e.g., Baumann and Kaiser, 1999; Stoffel et al., 2005; Bollschweiler et al., 2008), but are largely missing for the eastern Alps in general and for the Austrian torrents in particular.

Therefore, the goal of this study was to reconstruct debris floods on a low gradient alluvial fan in the Austrian Limestone Alps. Through the analysis of tree-ring series of 227 conifers, we (i) reconstruct the

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doi:10.1016/j.geomorph.2009.12.019

event frequency, (ii) determine the spatial extent, and (iii) identify preferential avulsion locations of past events in order to improve the database of events for future hazard assessment.

2. Study site

The present study was performed in the Gratzental (47°27′ N., 11°38′ E.), a small glacial valley located NE of Innsbruck, Tyrol, Austria (Fig. 1). Geology of the catchment is dominated by grey or grey-brown dolomite (so called “Hauptdolomit”) of the Late Triassic and local Pleistocene moraines (Geologische Bundesanstalt, 2008). In the course of the Holocene, the ephemeral Gratzentalbach has formed an alluvial fan composed of highly permeable colluvium with mean grain sizes (d_m) of 28.4 mm measured on the channel surface. At the fan apex, the waters of the Gratzentalbach infiltrate in the colluvium, except during intense rainfall events (Fig. 2B).

The catchment (see Fig. 2) has an area of ~2.5 km^2 and extends from 2106 m asl (above sea level) at the Mondscheinspitze to 1166 m asl at the confluence with the Pletzachbach River. Between the fan apex (1240 m asl) and the confluence with the Pletzachbach (1145 m asl), the mean slope angle averages 5°. Dolomitic debris at the study site consists primarily of gravel and sand (maximum grain size: 64–256 mm; Gawlick and Rudolf-Miklau, 2006). Flood processes show fluctuating or pulsatory transport conditions with dune-like bedload waves, forming gravel bars, cross-bedded sheets, and lobes that tend to evenly cover large parts of the fan (Rudolf-Miklau, 2001, 2002). Because of these sedimentary and morphologic properties, the dominating process in the Gratzentalbach can be defined as a debris flood according to the classification by Hungr (2005).

The Gratzental is characterized by a cool-humid climate, with mild winters and cool summers. Annual rainfall varies between 1300 and 2500 mm y^{-1} with a mean of 1526 mm for the period 1895–2008. The most intense rainfall normally occurs in July or August. During thunderstorms, a high amount of precipitation can fall in a short time. The maximum values measured for a 3- to 4-h precipitation event was 74.6 mm on 1 August 1992 (Hübl et al., 2002; Skolaut et al., 2004).

Typical forest stands in this area are of the *Abieti-Fagetum montanum* type growing on humus-rich soils, *Abietetum* or *Piceetum*. The eastern part of the Gratzental is dominated by Norway spruce (*Picea abies* (L.) Karst.), European larch (*Larix decidua* Mill.), and Scots pine (*Pinus sylvestris* L.). Mountain pine shrubberies (*Pinus mugo* T.) can be found in the higher parts of the valley around Pertisau. The western part of the fan is covered with small, broad-leaved trees (e.g., *Salix* ssp.) and Norway spruce, and the forest may be subject to timber harvesting, cattle pasture, and overpopulation of deer.

Archival records on former activity in the Gratzental contain only information on two events, namely in 2007 and 2005. More information is available for the receiving Pletzachbach (see Fig. 1): after strong thunderstorms, the Pletzachbach overspilled the channel banks and flooded the village of Pertisau in 1977, 1992, and 1995.

3. Material and methods

3.1. Sampling strategies

In a first analytical step, the Gratzental was examined to identify sectors exclusively influenced by torrential processes. To avoid misinterpretations, trees growing in sectors influenced by other natural hazards (e.g., rockfall and snow avalanches) or anthropogenic activity were disregarded for analysis.

From the sectors suitable for the reconstruction of past debris-flood events, trees obviously influenced by past activity were sampled. Based on an outer inspection of their stems, *P. abies* or *L. decidua*—that showed scars, exposed root systems, tilted stems, or buried stem base—were sampled.

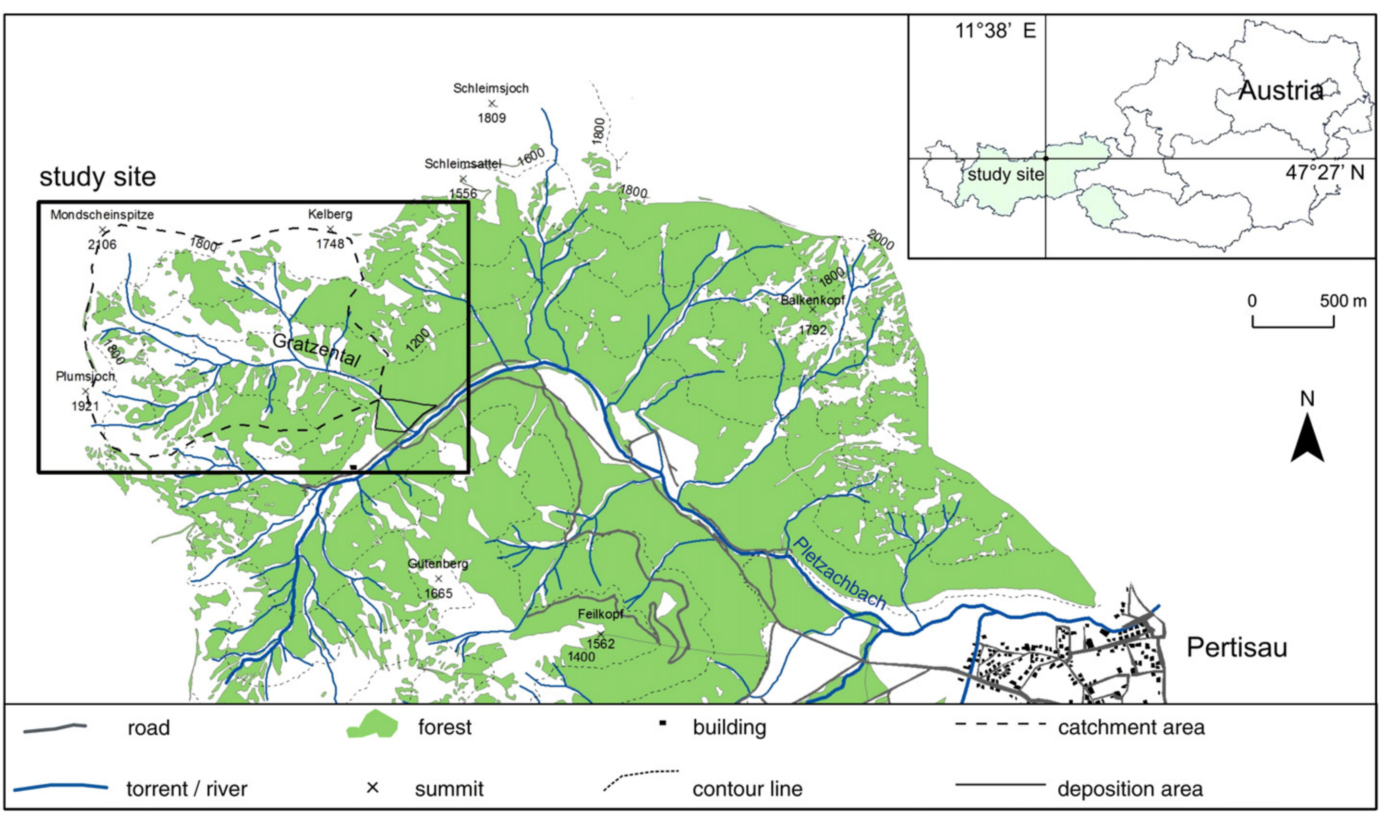

Fig. 1. The study site is located in the Gratzental (=study site) near Pertisau, Tyrol, Austria.

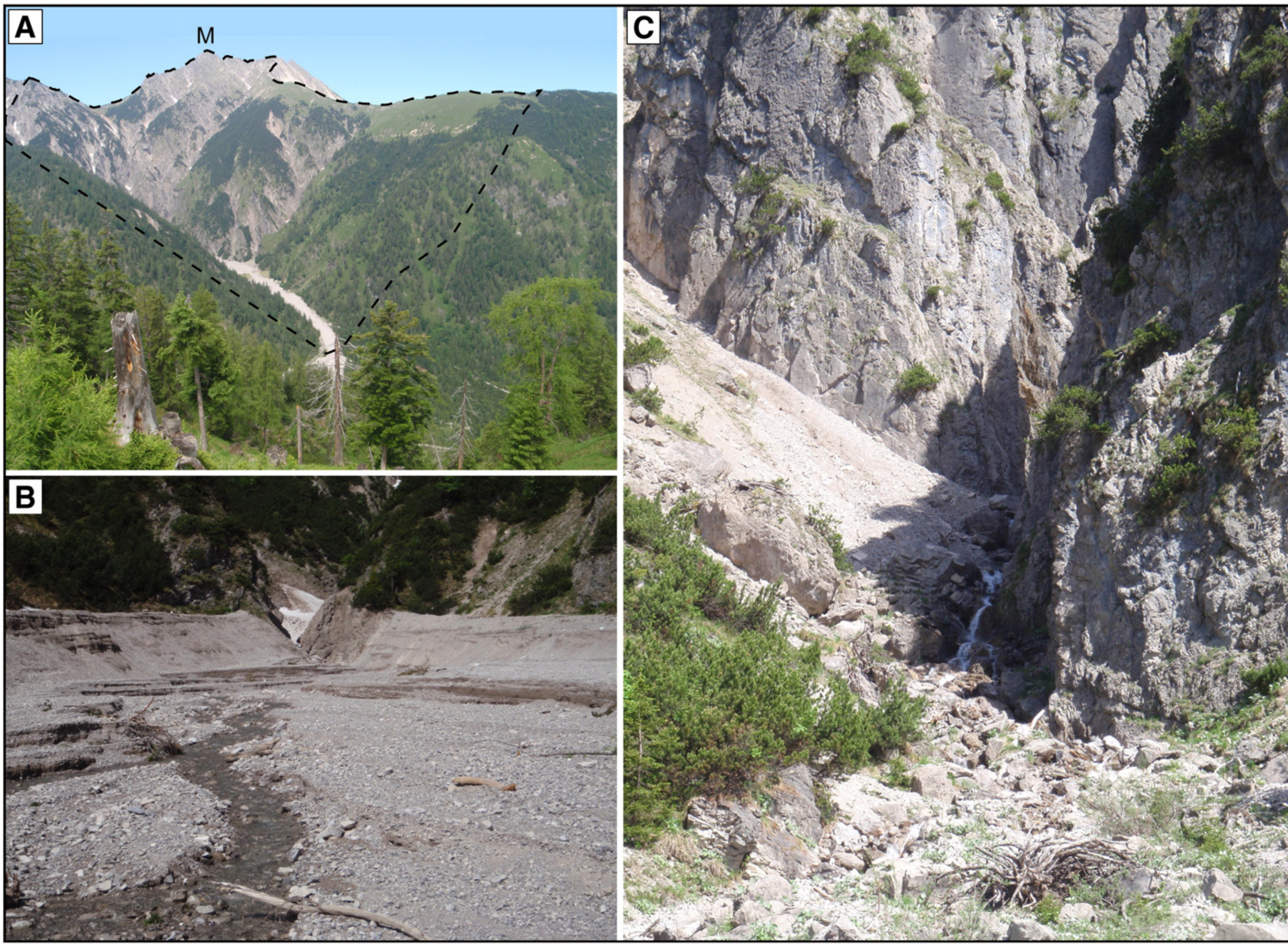

Fig. 2. (A) Overview of the Gratzental with the catchment area beginning at the Mondscheinspitze (M) and the upper part of the debris-flood fan; (B) the cone apex with its typical fine sediments, just before the water infiltrates into the colluvium; (C) slope angles average 5° on the Gratzentalbach fan and attain up to ~35° above the fan apex.

Normally two cores per tree were extracted; one in the supposed flow direction of debris floods and the other on the opposite site of the stem. In order to gather the greatest amount of data on past events, trees were sampled (i) within the tilted segment of the stem or (ii) close to the ground in the case of a buried stem base. Trees with visible injuries were usually small and were therefore cut with a handsaw.

In total, 227 trees were sampled (224 *P. abies* and three *L. decidua*) with 10 cross sections and 490 increment cores. In addition, data on (i) tree species, (ii) tree height, (iii) diameter at breast height (DBH), (iv) visible defects in tree morphology (sketch and photographs), (v) position of the extracted sample on the stem surface, (vi) data on deposits around the tree (measurements, photographs), (vii) photographs of the entire tree, and (viii) data on neighboring trees were recorded. Because of the dense forest and the high summits around the study area, GPS measurements did not provide the desired precision; and the position of each tree sampled was therefore determined using a tape, inclinometer, and compass.

Undisturbed trees located NW of the study site were sampled in order to establish a reference chronology. Again, two cores per tree were extracted, but sampling was performed parallel to the slope direction and systematically at breast height. The reference chronology represents normal growth conditions at the study site, i.e., those influenced by climate or insect outbreaks (Cook and Kairiukstis, 1990; Vaganov et al., 2006).

3.2. Debris-flood frequency and dating of events

Samples were prepared and analyzed and data processed following standard dendrogeomorphic methods described in Stoffel and Bollschweiler (2008, 2009). Single steps of preparation included mounting of the samples on woody support, drying, and sanding. In the laboratory, tree rings were counted and ring widths measured using a digital LINTAB positioning table connected to a Leica stereomicroscope and TSAP-Win Scientific 4.63 software (Rinntech, 2009). To establish the reference chronology, the two measurements of each reference tree were averaged, indexed, and standardized; and the validity of the mean curves was crosschecked using COFECHA (Holmes, 1983). Growth curves of the samples of disturbed trees were then compared with the reference chronology in order to identify missing or false rings (Schweingruber, 1996).

Finally, growth disturbances (GD) such as injuries, callus tissue, tangential rows of traumatic resin ducts (TRD), abrupt growth suppressions or releases, as well as compression wood were identified on the tree-ring series. Determination of growth suppression or release was performed by analyzing the growth curves and by comparing them to the reference chronology. Callus tissue, compression wood, and TRD were identified by visual inspection of the cores (Schweingruber, 2001).

Determination of events was based on the number of samples showing GD in the same year and the spatial distribution of the affected tress on the fan (Bollschweiler et al., 2008). To avoid

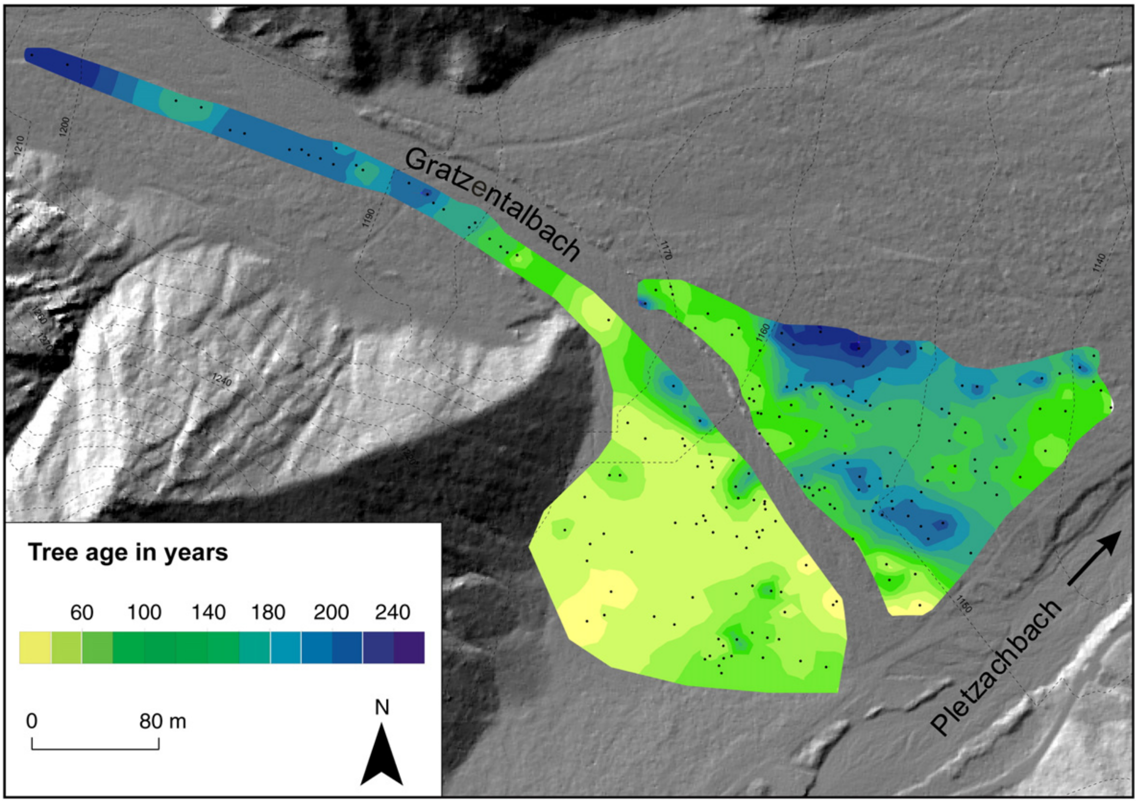

Fig. 3. Age structure of the forest stand on the cone.

overestimation of GD within the tree-ring series in more recent years because of the larger sample of trees available for analysis, we calculated an index value (I_t) following Shroder (1978) or Butler and Malanson (1985):

$$I_t = \left(\sum_{i=1}^{n} R_t \Big/ \sum_{i=1}^{n} A_t\right) \times 100\% \qquad (1)$$

where R is the number of trees showing a GD as a response to a debris flood in year t, and A is the total number of sampled trees alive in year t.

After dating, the GD on the increment cores and cross sections, the lateral spread and preferable avulsion locations of the reconstructed debris-flood events were assessed based on the dating of the events and the spatial position of trees affected by an event on the fan.

4. Results

4.1. Tree age and growth disturbances

The oldest tree cored at Gratzental shows 280 tree rings at sampling height (A.D. 1728), while only 13 growth rings (A.D. 1995) were counted in the youngest tree. As a rule, the youngest trees are located on the western part of the fan (see Fig. 3) where most of them reached sampling height in the 1940s. The oldest trees can, in contrast, be found on the fan apex and in the northeastern part of the fan. The average tree age on the Gratzental fan amounts to 124.2 years (STDEV 70.9 years).

The analysis of the 227 trees sampled on the fan allowed the identification of 1155 GD relating to past debris-flood events (see Table 1). Because of the very small mean grain size of material transported by debris floods at Gratzental, injuries (1%) and callus tissue (6%) were very scarce. Most frequently, signs of past debris floods were preserved in the tree-ring series in the form of TRD (35%) as well as abrupt growth increases (30%) and decreases (28%).

By way of example, Fig. 4 illustrates abrupt growth changes resulting from a debris flood. The tree-ring series presented in Fig. 4A shows an abrupt growth increase as a response to an event in 1973. Fig. 4B, in contrast, demonstrates a sudden growth decrease caused by a debris flood in 1983.

Table 1
Growth disturbances (GD) assessed in the 227 *P. abies* (L.) Karst. and *L. decidua* Mill. trees.

	Amount	%
Tangential rows of traumatic resin ducts	408	35
Growth increase	344	30
Growth decrease	326	28
Compression wood	70	6
Injuries	7	1
Total	1155	100

4.2. Debris-flood frequency and dating of events

The GD identified in the 224 *P. abies* and three *L. decidua* trees allowed the reconstruction of 37 debris-flood events between A.D. 1800 and 2008. Fig. 5 illustrates the reconstructed frequency series, indicating that the dating of 24 events was based on a very large number of GD (represented with bold lines). In contrast, for the 13 events represented with dashed lines, there is good evidence for the existence of events in these years as well, but the reduced number of trees available for analysis, and the nature and quality of the response in the tree-ring series did not allow for them to be considered events with equal confidence. The number of increment cores available for the analysis at any moment in the past is shown by the dot-dashed line indicating sample depth. From the data, apparently event frequency in the nineteenth and the beginning of the twentieth century is significantly lower than for the period 1928–2008.

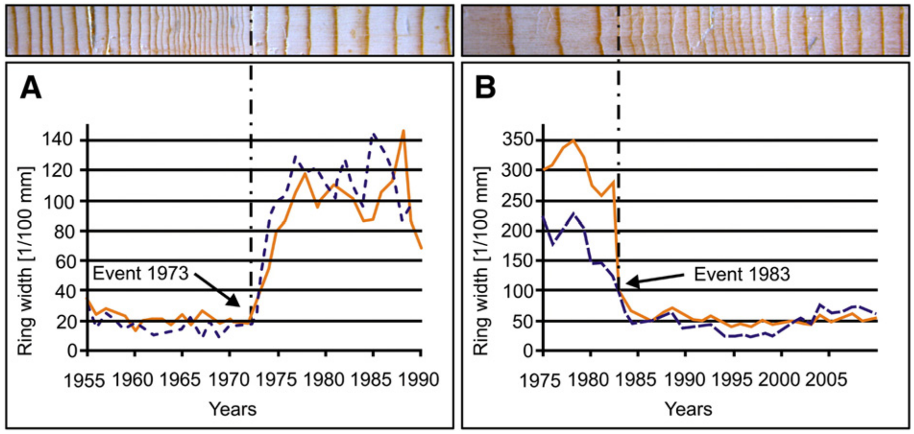

Fig. 4. Tree-ring series illustrating (A) an abrupt growth increase and (B) an abrupt growth decrease with the corresponding increment cores represented above. The dotted line indicates the growth curve of the downslope core and the solid line the upslope core. The event is indicated by the dot-dashed line and links the visible signal of the increment core with the measured signal.

Table 2 provides data on the number of trees showing a response to a debris flood, the number of sampled trees available for analysis, and the I_t. Results illustrate that the I_t remains more or less constant over the entire period covered by the reconstruction. Notably however, for the period 1906–2008, several events (i.e., 1912, 1970, 1979, 1989, and 1995) show I_t above 20%, whereas in none of the events reconstructed before 1900 is the 20% limit being exceeded.

4.3. Spatial extent and avulsion locations of past events

The spatial extent of past events was assessed by investigating the position of all trees showing GD to a particular event. In general, more events could be reconstructed for the eastern part of the fan because of the higher age attained by the trees in this sector. On the western part of the Gratzental fan, in contrast, reconstructions were limited by the less dense and younger forest stand.

Trees showing GD within their tree-ring series following debris floods are, in general, evenly distributed on the fan. Material repeatedly left the channel bed in the uppermost part of the fan (between 1165 and 1160 m asl) and frequently reached the outermost segments of the fan (see Fig. 6A). During avulsion events of this type, debris floods affected trees along the banks of the present-day channel as well as on the western or eastern parts of the fan. Fig. 6B illustrates the spatial behavior of the debris flood in 1970, which was more restricted to the eastern part of the fan. A similar spatial pattern could be identified in 33% of the events, whereas tree-ring evidence was scarce for events with flow patterns concentrated to the western side of the fan (two events; 0.74%). In 83% of the dated events, trees growing near the apex of the fan showed GD within their tree-ring series. Eight of them have an $I_t > 16\%$. Fig. 6C illustrates the spatial pattern of a debris flood in 1912 showing an I_t for the uppermost part of the Gratzental of 52%, and trees were affected on both sides of the fan. In contrast, only trees growing close to the present-day channel were affected by the material of the oldest debris flood on record, dated to 1800 (see Fig. 6D).

Fig. 7 illustrates the preferential avulsion locations of debris floods on the fan of the Gratzentalbach. Avulsion locations were defined through the analysis of the spatial distribution of trees showing GD in a given year. Table 3 provides an overview on the possible avulsion

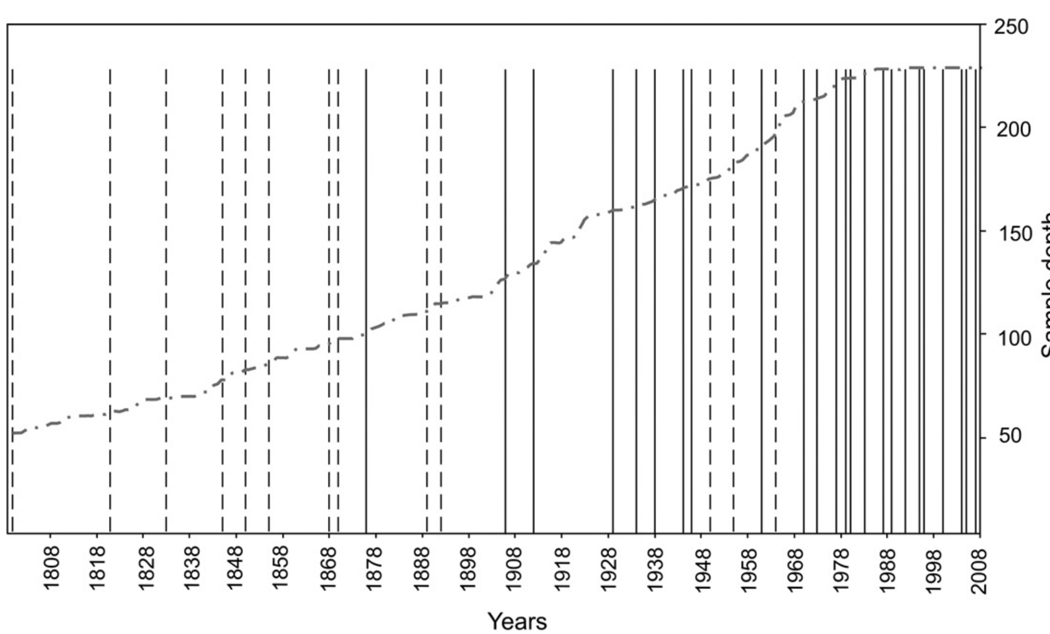

Fig. 5. Minimum frequency of debris-flood events for the Gratzentalbach.

Table 2
Number of responses within the tree ring series (GD), number of sampled trees alive, and index values (I_t) for debris flood events.

Event year	No. response per tree(GD)	No. available trees	Index value [I_t]
2007	11	227	4.8
2005	11	227	4.8
2004	9	227	4.0
2000	32	227	14.1
1996	24	227	10.6
1995	47	227	20.7
1992	8	227	3.5
1989	51	226	22.6
1987	14	226	6.2
1983	26	224	11.6
1980	40	222	18.0
1979	47	222	21.2
1977	29	217	13.4
1973	10	211	4.7
1970	47	210	22.4
1964	13	192	6.8
1961	24	188	12.8
1955	15	178	8.4
1950	14	171	8.2
1946	13	149	8.7
1944	23	166	13.9
1938	28	160	17.5
1934	17	157	10.8
1929	13	155	8.4
1912	36	128	28.1
1906	17	121	14.0
1892	9	108	8.3
1889	12	104	11.5
1876	11	93	11.8
1870	11	91	12.1
1868	7	88	8.0
1855	9	78	11.5
1850	7	71	9.9
1845	12	70	17.1
1833	3	61	4.9
1821	6	54	11.1
1800	4	43	9.3

locations of particular debris-flood events. One out of three debris floods presumably left the channel at location 2, and material either affected trees in the northeastern (10 events; avulsion location 2a) or in the southeastern part of the fan (7 events; avulsion location 2b). Avulsion locations 4–7 were only used by debris floods in the twentieth century. For the events in 1800, 1821, and 1833, sample depth and the number of trees affected was too small for a reconstruction of flow routing.

5. Discussion

Dendrogeomorphological analysis of 490 increment cores and 10 cross sections of 227 *P. abies* and *L. decidua* trees allowed the reconstruction of 37 debris floods between A.D. 1800 and 2008. In addition, we analyzed the position of disturbed trees and therefore identified the spatial extent of events as well as preferential avulsion locations on the fan.

The dendrogeomorphic reconstruction of debris floods in Gratzental was primarily limited by tree age. This is especially true for the forest stand located on the western part of the fan where average tree age only totaled 63 years. As the length of the reconstruction was limited by the number of old trees present on the fan, the reconstructed event frequency represents the minimum number of debris floods that occurred in the Gratzental, but most likely contains a majority of large events for the torrent and for the period A.D. 1800–2008.

Events in the Gratzentalbach are characterized by debris floods transporting bedload ranging from coarse gravel (cobbles) to sand sedimenting on a low gradient fan. As a result, impact energy of debris floods will only rarely be large enough to locally destroy the cambium or to destabilize entire trees. For this reason, injuries, adjacent callus tissues, or compression wood could only be found in a small minority of the trees. On the other hand, the small number of injuries may also stem from the sampling strategy, as we only took cross sections of trees showing visible injuries on their outer surface. As small injuries are easily overgrown and no longer visible after only a few years (Stoffel and Perret, 2006), these trees were not felled but sampled with increment cores. In this case, the presence of cambium damage resulting from debris floods could be identified via the presence of TRD formed next to the injuries.

A majority of past events were, however, dated via the presence of abrupt growth changes resulting from the deposition of sediments around the stem base. Growth suppression after stem burial is caused by reduced water and nutrient supply (LaMarche, 1968; Hupp et al., 1984; Friedman et al., 2005; Stoffel and Bollschweiler, 2008). As a result of its shallow roots, *P. abies* is known to react abruptly even to a slight aggradation of material with an abrupt growth suppression (Strunk, 1997). On the other hand and in regions where nutrient-rich material is deposited around the stem base, trees may also react with a sudden growth release to events, provided that burial depth is not too important (Strunk, 1995). As the material transported by the Gratzentalbach is rich in nutrients, it does not seem surprising that 30% of the trees sampled react with growth releases to stem burial.

The I_t introduced by Shroder (1978) was used in this study to avoid overestimation of recent events. As a result of the larger sample depth, the total number of trees showing GD as a response to a debris flood is significantly larger for the recent past than for events of the nineteenth century. Although a trend is discernible for I_t over the period covered by the reconstruction, the relative number of trees reacting was much higher for particular events in the twentieth century (I_t>20) than for incidences of the nineteenth century. This phenomenon can again be explained by the larger sample depth and the higher probability that a tree was affected by a debris flood in more recent years. We used a minimum $I_t \geq 4\%$ to date a debris flood and are well aware that this is a rather small threshold. We are, nevertheless, convinced that such a low I_t can be used for the dating of debris floods with a high degree of confidence because of the reaction quality and lateral spread of tree rings showing GD. The choice of our threshold is supported by the recent and large events of 2007 and 2005—known from reports of the Avalanche and Torrent Control Tyrol (Forsttechnischer Dienst für Wildbach- und Lawinenverbauung, Gbl. Westl. Unterinntal, 2009)—which did affect large parts of the fan but did not, at the same time, affect more than 4.8% of the trees sampled.

From our data it also appears that event frequency was significantly higher for the period 1928–2008 than during the nineteenth and the early twentieth century. This increase can at least partially be explained by increasing sample depth in the twentieth century. Based on the position of disturbed trees on the fan, apparently the avulsion events at Gratzentalbach were more frequent on the eastern side than on the western side of the fan. However, tree age has to be taken into account; dendrogeomorphic reconstructions allow for a spatial analysis of events on the eastern part of the fan back to A.D. 1800, whereas data on the western part of the fan only becomes available after the 1940s. Nevertheless and when based on the last 70 years, debris-flood activity is obviously more accentuated on the eastern than on the western part of the fan. The preferential avulsion of flows to the east can be explained with channel geometry and channel depth, leading to facilitated overspilling at avulsion locations 1, 2, or 3 (see Fig. 7).

Noteworthy, avulsion locations as well as the extent of debris-flood events ultimately depend on the magnitude of the event, channel incisions, and the height and state of the channel walls. On the other hand, channel erosion on the fan may increase the channel depth and therefore prevent events from avulsing onto the fan.

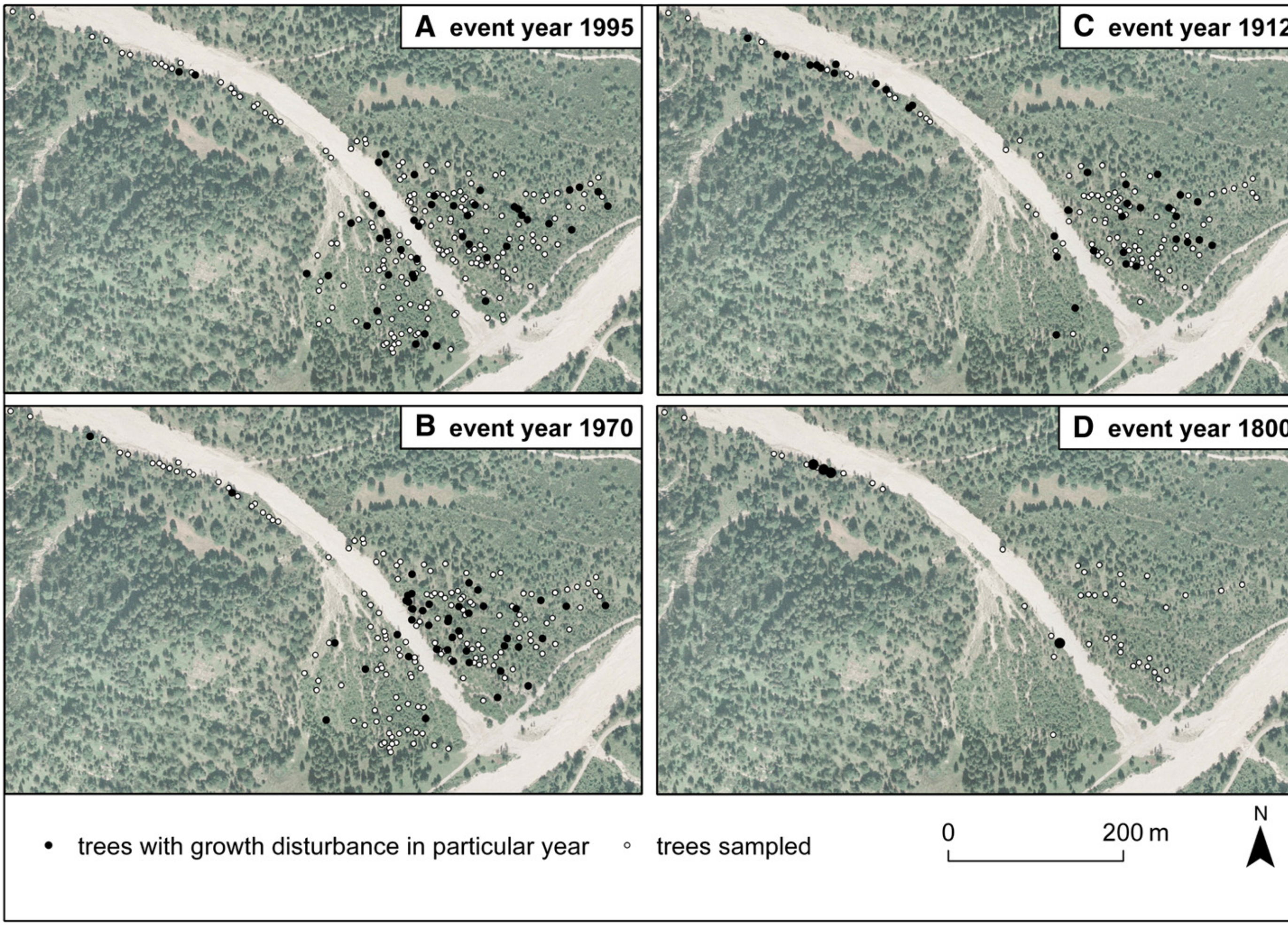

Fig. 6. Spatial extent of debris-flood events in the Gratzental, the position of all trees with GD, as well as all available trees on four events as an example.

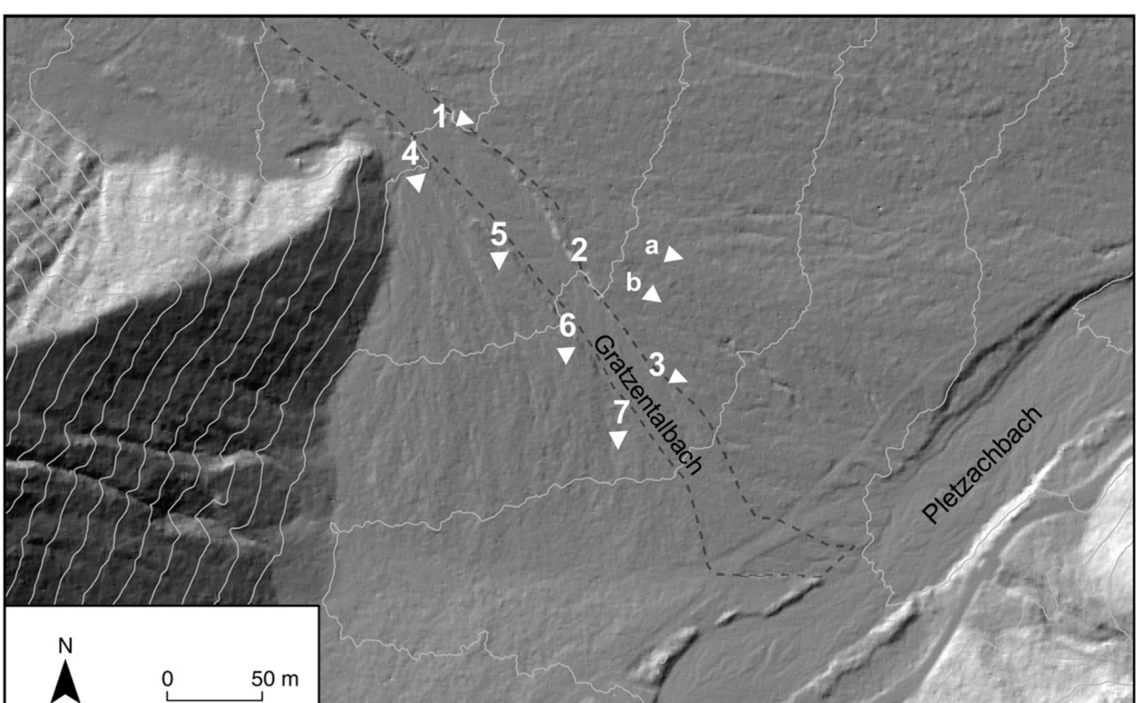

Fig. 7. Localization of possible avulsion locations of debris floods.

Table 3
Preferential avulsion location for particular event year.

Avulsion location	Event	Total	%
1	1876, 1892, 1912, 1934, 1938, 1944, 1970, 1980, 1989, 1995	10	13.5
2	1876, 1889, 1906, 1912, 1929, 1950, 1970, 1995	8	10.8
a	1845, 1850, 1855, 1868, 1870, 1946, 1955, 1961, 1980, 1995	10	13.5
b	1938, 1973, 1977, 1983, 1987, 1989, 2007	7	9.5
3	1850, 1855, 1870, 1889, 1906, 1912, 1944, 1961, 1964, 1970, 1977, 1979, 1980, 1983, 1987, 1989, 1996, 2004, 2007	19	25.7
4	1934, 1995, 1996, 2000	4	5.4
5	1980, 1983, 1996, 2007	4	5.4
6	1912, 1929, 1964, 1970, 1989, 1995, 1996, 2000, 2005	9	12.2
7	1977, 1979, 1995	3	4.1

6. Conclusion

Tree-ring analysis allowed the reconstruction of 37 debris-flood events in the Gratzental for the last 200 years. The analysis of 227 conifers in the Gratzental provides data on the event frequency of debris floods in a typical torrent of the Tyrolese Limestone Alps transporting dolomitic debris, their spatial distribution, their extent, and their preferable avulsion locations. As practically no historic data was available concerning debris floods at Gratzentalbach, the frequency series reconstructed in this study will serve as a very valuable basis for hazard assessment in a tourist-oriented area.

Although the reconstruction of debris-flood events based on growth changes in the tree-ring series of slightly buried trees allowed for an extensive spatiotemporal reconstruction, further studies are needed to refine the methods and to improve the knowledge on tree growth response in these dolomite environments.

Nevertheless, we are convinced that tree-ring data on past debris flood events represent a very valuable tool for the calibration of process-based flow models and that they may therefore help to improve model output.

Acknowledgements

The authors would like to thank the Forest Engineering Service in Torrent and Avalanche Control Westliches Unterinntal for providing access to digital terrain model, orthophoto, and historical data on past events. We also acknowledge the Bundesforst AG for coring permissions in their forest stand and Heinrich Moser, for all the contact data. This paper is a contribution of the EU-Project AdaptAlp and supports the improvement of hazard assessment methods and condensation of historic event data sets.

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