Geomorphology 132 (2011) 41–50

Contents lists available at ScienceDirect

Geomorphology

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

A regional reconstruction of debris-flow activity in the Northern Calcareous Alps, Austria

Emily Procter [a], Michelle Bollschweiler [a,b], Markus Stoffel [a,b,*], Mathias Neumann [a,c]

[a] Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland
[b] Climatic Change and Climate Impacts, Environmental Sciences, University of Geneva, 7 chemin de Drize, CH-1227 Carouge-Geneva, Switzerland
[c] Institute of Mountain Risk Engineering, University of Natural Resources and Applied Life Sciences, Peter Jordanstrasse 82, A-1190 Vienna, Austria

ARTICLE INFO

Article history:
Received 22 January 2011
Received in revised form 29 April 2011
Accepted 30 April 2011
Available online 6 May 2011

Keywords:
Debris flow
Dendrogeomorphology
Tree rings
Dolomite
Austrian Alps
Pinus mugo ssp. *uncinata*

ABSTRACT

Dendrogeomorphic dating of historical debris-flow events is a highly valuable tool for improving historical records in the field of natural hazard management. Previous dendrogeomorphic investigations generally have focused on case studies of single torrents; however, regional investigations may offer a more accurate reconstruction of regional patterns of activity and therefore may have an advantage over individual cases. The aim of the study is to provide a regional reconstruction of debris-flow events for a site in the Northern Calcareous Alps of western Austria (Gamperdonatal, Vorarlberg) and to document spatial and temporal morphological changes in individual and neighboring torrents. Analysis of 442 trees (268 *Pinus mugo* ssp. *uncinata*, 164 *Picea abies*, and 10 *Abies alba*) allowed identification of 579 growth disturbances corresponding to 63 debris-flow events since A.D. 1839. The majority of growth disturbances were in the form of growth suppression or release (76%) owing to the nature of both the deposited material and the process characteristics. Regional patterns of event frequency indicated a paucity of activity in the early to mid-twentieth century and increased activity since A.D. 1948, whereby large events were followed by subsequent years of continued activity of smaller magnitude. Patterns of frequency could be attributed primarily to spatiotemporal changes in channel morphology, but may also be reflective of changes in transport conditions within the valley. This study provides the first regional investigation in the Austrian Alps and contributes to the documentation of tree responses to geomorphic disturbances in calcareous material.

1. Introduction

The application of dendrogeomorphic techniques for the dating of past geomorphic processes originates in the work of Alestalo (1971). This technique has been widely applied for both a basic understanding of responses in trees in the face of geomorphic disturbance (Shroder, 1980; Stoffel et al., 2010), as well as for the reconstruction of frequency and magnitude (Hupp et al., 1984; Strunk, 1997; Bollschweiler and Stoffel, 2010b; Stoffel, 2010), spatial distribution and extent (Bollschweiler et al., 2007, 2008; Stoffel et al. 2008b; Ballesteros et al., 2011), and triggers (Stoffel et al., 2005, 2011) of hydrogeomorphic processes, including debris flows, debris floods, and flash floods with bedload. Dendrogeomorphic techniques, both as a stand-alone technique and as a complement to other traditional analysis methods (e.g., aerial photograph interpretation), have proved to be a valid method to support natural hazard management and planning efforts by improving limited archival records and allowing for a more realistic estimation of flow parameters. This knowledge is of vested interest for both the local population and the authorities responsible for natural hazard management, as hydrogeomorphic processes present the most damaging mass movements in mountain areas (Jakob, 2005).

Most tree-ring analyses of natural hazards have focused primarily on isolated case studies, e.g., debris flows at specific sites. Although single-site studies are important, regional studies may (in some cases) be more valuable to understand regional patterns of hydrogeomorphic processes with different histories and patterns of flow activity. In addition, in cases with repeated hazard in a specific site, the process under study may have damaged or removed those trees containing evidence of past activities, thus reducing available sampling populations and eliminating potential historical records. In such cases, dendrogeomorphic techniques are limited and the risk exists that observed frequencies may be biased (Stoffel et al., 2010). Dendrogeomorphic investigations on a regional scale may therefore be of more value than investigations of individual systems as the range of activity will be better preserved at the level of a site network. Wilkerson and Schmid (2003) reported on a 7-year monitoring project of 41 debris-flow channels in Glacier National Park, Montana, in which the risk imposed by debris flows on park infrastructure and

* Corresponding author at: Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland. Tel.: +41 316318773; fax: +41 316314843.
E-mail address: markus.stoffel@dendrolab.ch (M. Stoffel).

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doi:10.1016/j.geomorph.2011.04.035

recreation was evaluated. May and Gresswell (2004) made a dendrogeomorphic investigation of 125 drainage basins in the Oregon Coast Range with the aim to define the recurrence intervals of debris flows and factors affecting the likelihood of occurrence in different channels. In the Swiss Alps, Bollschweiler and Stoffel (2010a) created a regional debris-flow chronology for eight torrents (steep stream channels) in the Zermatt valley using dendrogeomorphic data from 2467 *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees and reported on changes and trends in event frequency since A.D. 1850. In northern Italy, Pelfini and Santilli (2008) reconstructed debris-flow frequency for 14 torrents in the upper Valle del Gallo using dendrogeomorphic data from 757 *Pinus montana* Mill. trees. Dendrogeomorphic studies in the Austrian Alps, in contrast, remain few; existing work focused exclusively on debris flows or debris floods in single catchments using *L. decidua* and *P. abies* trees (Mayer et al., 2010; Kogelnig-Mayer et al., in press). Therefore, the aim of this study is to (i) reconstruct debris-flow frequency in eight neighboring torrents in a dolomite- and limestone-containing valley in western Austria using dendrogeomorphic techniques; (ii) document spatial and temporal dynamics of flow processes on the cones of individual and neighboring torrents; and (iii) compare the reconstructed time series with archival records and local precipitation data.

Table 1
Characteristics of the eight investigated torrents; *catchment* refers to only the upper source area, and *cone* to the area between initial and end deposition points.

Code	Area (km^2)	Channel length (m)	Inclination (°)		Elevation max/min (m asl)	
1	0.23	1475	*Catchment*	55	*Catchment*	2140/1500
			Cone	30	*Cone*	1500/1180
2	0.29	1610	*Catchment*	53	*Catchment*	2200/1440
			Cone	23	*Cone*	1440/1180
3	0.04	775	*Catchment*	60	*Catchment*	1860/1540
			Cone	26	*Cone*	1300/1260
4	0.60	1990	*Catchment*	58	*Catchment*	2380/1350
			Cone	17	*Cone*	1350/1190
5	0.23	1226	*Catchment*	59	*Catchment*	2240/1340
			Cone	18	*Cone*	1300/1200
6	0.03	715	*Catchment*	57	*Catchment*	1820/1350
			Cone	23	*Cone*	1300/1240
7	0.18	1381	*Catchment*	53	*Catchment*	2120/1380
			Cone	25	*Cone*	1380/1210
8	0.85	1890	*Catchment*	19	*Catchment*	1900/1680
			Cone	14	*Cone*	1320/1280

2. Study area

The Gamperdonatal is an alpine valley situated in the westernmost reaches of the Northern Calcareous Alps (province of Vorarlberg, Austria; 47°5′ N., 9°38′ E.; Fig. 1). It has a north–south orientation and is bordered at the southernmost extent by the Rätikon mountain range, which forms the political border with Switzerland (Canton Graubünden) to the south and with the Principality of Liechtenstein to the southwest. The Meng River (‘Mengbach’) drains the 65-km^2 catchment and flows from its highest reach at 2859 m asl (Panüeler Kopf) over a 16-km course to its confluence with the Ill River at 500 m asl. The catchment is characterized by innumerable tributary torrents, especially in its upper reaches.

This study investigated eight of these tributary torrents located between km 10 and 13 of the Mengbach (Fig. 1). All selected channels have a western aspect. Torrents 1–7 are situated in close proximity and have a maximal extension from the Fundel Kopf at 2401 m asl to the confluence of the Mengbach at ca. 1200 m asl (Table 1). These torrents are characterized by incised channels in the upper rock face, forming steep upper sections with inclinations ≥53° in all cases. In the lower sections, slopes range between 17 and 30° with either (i) long, semiformed primary channels (torrents 1 and 2); (ii) cone-shaped deposits with an absence of well-defined primary channels (torrents 4, 5, and 7); or (iii) small, singular lobate deposits in the upper forested areas (torrents 3 and 6). Torrent 8 extends between 1900 and 1280 m asl and has a lower grade with a defined, narrow channel over the entire flow course. Further torrent characteristics are given in Table 1. In torrents 1–7, debris flows can be described as having a granular flow type with low water content and grain size of ca. 5–20 cm with isolated larger blocks. Debris flows in torrent 8 also have a granular flow type; but water content is significantly higher, and grain size is ca. 20–60 cm with instances of larger material.

The Gamperdonatal is located within the Bajuvarian unit of the Northern Calcareous Alps. The dominant geological material is limestone and dolomite (Permian to Lower Cretaceous), with some intrusions of carbonatic melange material such as gypsum, carbonatic slate, and sandstone in the upper reaches of the Mengbach catchment (Geologische Bundesanstalt, 2000). The area is characterized by weathered rock surfaces and scree slopes in the higher elevation

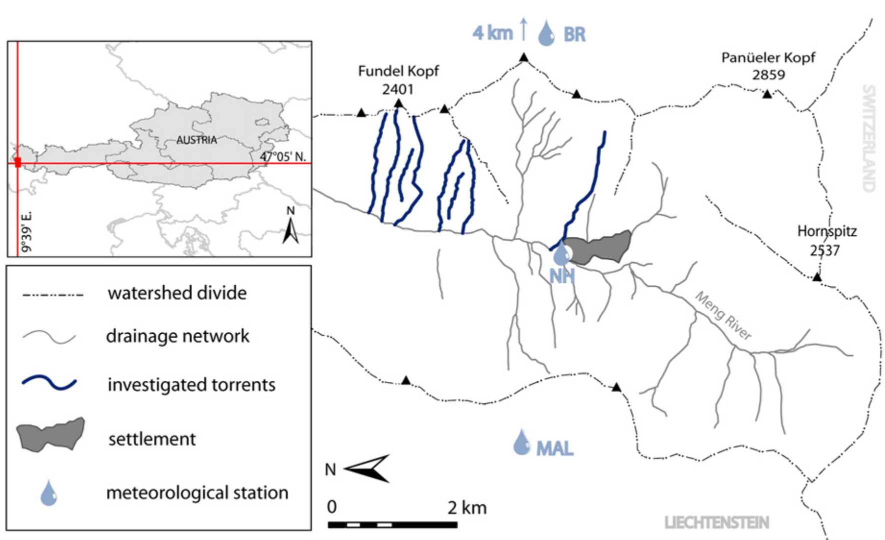

Fig. 1. Location of the study site in the western province of Austria (inset) and overview of the uppermost section of the Meng River catchment.

zones and by fluvial erosion and alluvial processes in the lower zones of the study area, where depositional material is alluvial in origin or has been formed by subglacial till (Seijmonsbergen, 1992). The typical forest structure for this montane elevation zone is a mixed stand of *P. abies* and *Abies alba* Mill. In addition, *P. mugo* ssp. *uncinata* comprise almost pure stands on many of the debris flow cones in this valley (including torrents 4 and 5), as this species has a competitive advantage on very dry, matrix-poor, debris-flow deposits (Mayer, 1974).

The climate in the Gamperdonatal is typically cool and humid with an average annual precipitation of 1720 ± 235 mm (s.d.) for the period 2000–2009 with the majority of precipitation recorded in summer (June to August: 649 ± 83 mm or 38%), followed by spring (March to May: 384 ± 63 mm or 22%) and winter (December to February: 280 ± 42 mm or 16%) (Hydrographischer Dienst Vorarlberg, 2010). Extreme precipitation sums are recorded typically during thunderstorms in summer. The average seasonal temperatures are 12 °C in summer and 3 °C in winter (mean for the period 2000–2009).

The only settlement within this valley is the seasonally occupied village of Nenzinger Himmel (47°05′ N., 9°39′ E.; elevation 1370 m asl). Land ownership is restricted to citizens of the local municipality of Nenzing, who accordingly hold exclusive road access permits. Tourism is restricted to summer, day usage, and public transport into the valley. Anthropogenic influences, including forest management activities, are therefore minimal, with the most notable issues limited to some hunting and wintertime game feeding.

Archival records of past events within the Gamperdonatal include (i) debris-flow events in unspecified tributary channels in 1956 and 1968, and debris-flow events of greater magnitude in torrent 4 in 1948, 1979, 1991, and 1999; (ii) flooding of the Mengbach in 1762, 1910, 1970, 1976, 1999, 2000, 2002, and 2005; and (iii) snow avalanches in the village of Nenzinger Himmel in 1926, 1945/1946, and 1999.

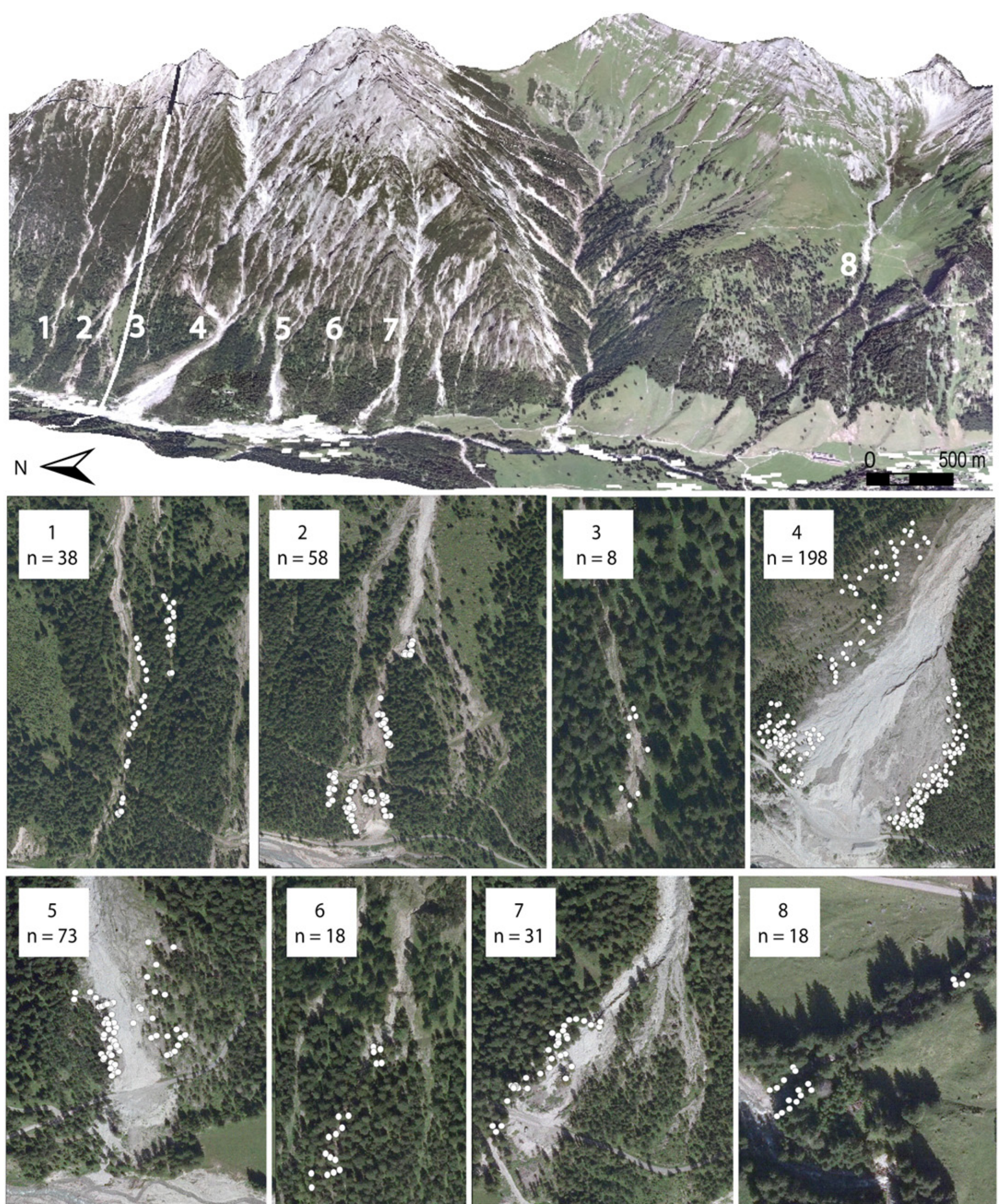

Fig. 2. Overview of the eight investigated catchments. Spatial distribution of sampled trees and sample size are shown for individual torrents.

3. Materials and methods

3.1. Sampling method

A thorough field investigation was performed in order to identify geomorphic processes present and to select torrents appropriate for sampling. Areas affected by geomorphic processes other than debris flows were discarded in order to avoid spurious identification of event types. In total, eight torrents were chosen for investigation (Fig. 2), and nine others were discarded because of the predominance of avalanche activity or low availability of trees.

Trees were selected based on visible exposure to past debris-flow activity with buried stem base, tilted growth, scarring, and/or exposed root systems as indicators (see Stoffel and Bollschweiler, 2008, 2009). In order to avoid oversampling of visible and/or recent events, the spatial distribution of sampled trees covered the entire depositional area of interest. A minimum of two increment cores was extracted per tree, with one in the assumed direction of past flow events and one in the opposite direction. Cores were taken as low as possible for buried stems or in the area of tilting for tilted stems. For trees with visible scars, either additional cores or wedges were taken laterally to the over-walling callus tissue. Stem cross sections were cut from dead trees in torrents 4 and 5 in areas of deep burial. In total, 442 trees were sampled (268 *P. mugo* ssp. *uncinata*, 164 *P. abies*, 10 *A. alba*), amounting to 779 increment cores, 69 cross sections, 2 wedges, and 4 root samples.

Additional reference parameters were collected in the field (e.g., tree height, remarkable growth characteristics, diameter at breast height (DBH), and photographs); and tree locations were defined by manual positioning techniques (compass and measurement tape), as measurements by global positioning systems (GPS) are not accurate in such steep and forested terrain.

3.2. Laboratory analysis

The preparation and analysis of samples followed standardized dendrogeomorphic procedures as described in Stoffel and Bollschweiler (2008, 2009). Ring-width measurements were made with a digital LINTAB positioning table with an adjoining Leica stereomicroscope and the time-series analysis software TSAP 6.43 (Time Series Analysis and Presentation; Rinntech, 2011). Resulting measurements were graphically and statistically compared with a species-specific reference chronology, and missing or false rings were corrected where necessary. Reference curves were created from a selection of sampled trees (*P. mugo* ssp. *uncinata* $n = 30$; *P. abies* $n = 15$) by producing a mean curve for each individual tree, standardization, indexation, and merging (Stokes and Smiley, 1968; Vaganov et al., 2006).

All samples were visually inspected under a stereomicroscope to identify relevant growth disturbances (GD)—abrupt growth suppression or release, tangential rows of traumatic resin ducts (TRD), compression wood, injuries, and adjacent callus tissue (for details see Stoffel and Bollschweiler, 2008, 2009). Growth curves and reference chronologies were used to verify and date visual observations in the case of growth suppression or release. The GD occurring in the first two decades of juvenile growth were not regarded as reliable indications of past events, as juvenile trees are more susceptible to all mechanical influences. All GD were assigned to an intensity class following the recommendations of Schneuwly et al. (2009) and Ruiz-Villanueva et al. (2010).

3.3. Dating of events

The definition of debris-flow events was based on a semiquantitative approach (Bollschweiler and Stoffel, 2010a) in which the spatial distribution of trees containing GD in concurrent years is crucial and no minimum threshold is defined for absolute number of affected trees required to define an event. The premise is that years showing a limited number of affected trees and weak intensity GD cannot be confidently identified as events and that the spatial distribution of the trees (and type of GD) must be plausible. Events were reconstructed for individual torrents first, and a qualitative intertorrent comparison was made secondarily.

The analysis of debris-flow events was supplemented in two additional ways. In order to facilitate an understanding of geomorphic changes occurring in the channels over time, two sets of archival orthophotos were retrieved (photo acquisition date: 30 August 1951, 15 August 1973; Land Vorarlberg, 2010) and compared to the most recent orthophoto (26 July 2009). Changes in active channel location and extent of forested area were used to verify plausibility of dated events. Secondly, precipitation data from three local meteorological stations (Fig. 1) provided information for dating heavy rainfall events. Precipitation data were not intended for statistical correlation with debris-flow events, but simply as supplementary information for an understanding of possible triggering conditions in this area. The site-specific station in Nenzinger Himmel (NH, 47°06′ N., 9°39′ E.; elevation 1305 m asl) provided total daily precipitation, total daily new snow depth, and average daily temperature for the time period 2000–2010. Longer time series for daily precipitation were retrieved from two immediate neighboring valleys: (i) 3 km westward in Malbun, Liechtenstein (MAL, 47°06′ N., 9°37′ E.; elevation 1610 m asl; 1974–2010) and (ii) 4 km eastward in Brand, Austria (BR, 47°06′ N., 9°45′ E.; elevation 1005 m asl; 1920–1923 and 1961–2009).

4. Results

4.1. Sample age and growth disturbances

The results of laboratory dating of samples are shown in Table 2. The years reported here refer to the 'sampled age', that is, the number

Table 2
Tree characteristics based on laboratory analysis[a].

Tree characteristics						
Code	Sampled trees			Sampled age		
	Species	Count	Total	Range	Mean	Stdev
1	PCAB	33	38	1849–1971	126	22
	ABAL	5				
	PIUN	0				
2	PCAB	47	58	1694–1963	126	58
	ABAL	1				
	PIUN	10				
3	PCAB	8	8	1695–1954	116	93
	ABAL	0				
	PIUN	0				
4	PCAB	5	198	1560–1967	145	75
	ABAL	0				
	PIUN	193				
5	PCAB	8	73	1722–1986	141	50
	ABAL	0				
	PIUN	65				
6	PCAB	16	18	1573–1964	205	123
	ABAL	2				
	PIUN	0				
7	PCAB	29	31	1626–1972	177	105
	ABAL	2				
	PIUN	0				
8	PCAB	18	18	1904–1979	69	22
	ABAL	0				
	PIUN	0				
Sum	PCAB	164	442	1560–1979	142	74
	ABAL	10				
	PIUN	268				

[a] Tree species include *Picea abies* (L.) Karst. (PCAB), *Abies alba* Mill. (ABAL), and *Pinus mugo* ssp. *uncinata* (PIUN). Sampled age may not represent the true age of the tree, and age range provides the range of the earliest dated growth rings.

of growth rings visible on each sample. For cross sections, reported years are the true tree age at the sampled height. The overall mean sampled age was 142 ± 74 years, corresponding to an overall range of earliest dated growth rings between A.D. 1573 and 1957. The oldest samples were found in torrent 6 (mean sampled age 205 ± 123 years) and the youngest samples in torrent 8 (mean sampled age 69 ± 22 years). The additional cross sections taken from dead or dying trees were successfully dated using statistical cross dating with reference curves. The mean age of this subsample was 169 ± 68 years (age range A.D. 1638–1928). In torrent 5, the outermost ring of dead trees ranged between 1985 and 2007, with 12 of the 15 samples showing an outer ring at or after 2001. Although mean sampled ages were similar between species (*P. abies*: 142 ± 74 years; *A. alba*: 155 ± 79 years; *P. mugo* ssp. *uncinata*: 142 ± 73 years), there were markedly more *P. mugo* ssp. *uncinata* with a sampled aged >200 years (258 trees, 96%) compared to the other species (88 trees, 52%).

Analysis of the 442 trees resulted in 579 GD related to past debris-flow activity (Table 3). All types of GD were found in *P. abies* and *A. alba* trees, whereas *P. mugo* ssp. *uncinata* trees – owing to a different genetic makeup – do not contain TRD. As a result, abrupt growth suppression or release were by far the most frequently identified GD (76%), followed by TRD (19%), injuries (5%) and compression wood (<1%). Given the high percentage of *P. mugo* ssp. *uncinata* samples in torrents 4 and 5, GD in these torrents were most frequently seen as abrupt growth suppression or release (93% and 91%, respectively).

4.2. Dating of events

The 579 GD allowed identification of 63 different debris-flow events in 31 different years ranging from A.D. 1839 to 2010 (Table 3; Fig. 3). Identification of GD from the seventeenth to the early nineteenth century was possible; however, a limited sample depth during this period inhibited a reliable determination of events, and these years are not reported. Considering a time period of 150 years (since A.D. 1860), the overall return period (i.e., the average number of years between events) for the valley is 2.5 years and for individual torrents is shortest for torrent 4 (9.4 years) and longest for torrents 1, 3, and 6 (30 years; Table 4). Periods of higher and lower event frequencies are evident throughout this time period (Fig. 3). For

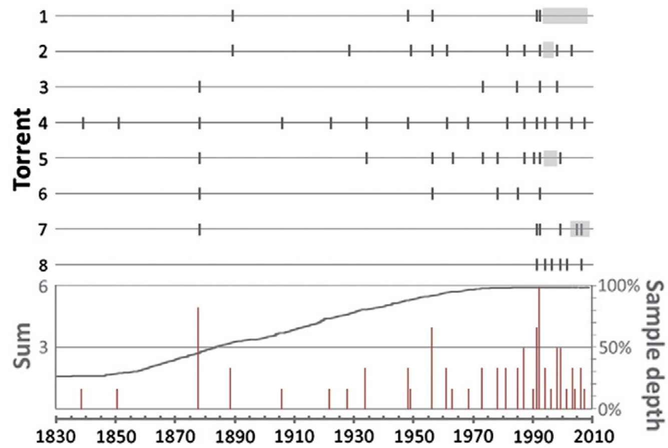

Fig. 3. Reconstructed debris-flow frequency containing 63 events between A.D. 1839 and 2010. There is evidence for additional events in intervals following larger events (gray boxes), but the definition of all event years was not possible.

Table 3
Growth disturbances (GD) corresponding to past debris-flow events listed by year and GD type[a].

Event year	1			2			3			4			5			6			7			8			Σ/year
	TRD	GC	i	TRD	GC	i	TRD	GC	i	TRD	GC	i	TRD	GC	i	TRD	GC	i	TRD	GC	i	TRD	GC	i	
1839										0	10	0													10
1851										0	6	0													6
1878							0	2	0	0	4	0	0	4	1	0	5	0	0	11	0				27
1889/90	1	7	0	1	6	0																			15
1906										0	3	0													3
1922										0	20	0													20
1928				2	13	0																			15
1934										0	5	0	0	7	0										12
1948*	8	5	0							0	13	0													26
1949				4	10	0																			14
1956*	0	15	0	1	8	0							0	5	2	1	3	0							35
1961				3	7	0				0	10	0													20
1963/64													2	5	0										7
1968*										0	6	0													6
1973							0	4	0				0	6	0										10
1978													1	6	0	1	6	0							14
1981				1	9	0				0	21	1													32
1985							0	3	0							1	6	0							10
1987				1	7	0				0	21	1	0	14	0										44
1990													0	10	0										10
1991*	10	6	0							1	11	6							3	4	0	2	2	0	45
1992	8	11	0	23	11	4	2	0	0				0	3	1	4	5	0	1	4	0				77
1994										1	7	0										1	1	1	11
1996																									3
1998				3	10	0	2	3	0	0	11	0													29
1999*													0	13	0				2	5	0	2	0	1	23
2001																						2	6	2	10
2003				6	4	0				0	9	0													19
2004																			5	2	0				7
2006																			3	6	4	0	1	1	15
2007										0	2	2													4
Σ by type	27	44	0	45	85	4	4	12	0	2	159	10	3	73	4	7	25	0	14	32	4	7	12	6	–
Σ by torrent	71			134			16			171			80			32			50			25			579

[a] TRD = tangential rows of traumatic resin ducts; GC = growth changes in the form of growth release or suppression; i = injuries. Previously documented event years are indicated with an asterisk.

Table 4
Return period in years for individual torrents and on a regional scale considering a period of 150 and 62 years (represents the period of increased activity since A.D. 1948); given the young sample age, the 150-year period is not relevant for torrent 8.

Code	Return period	
	150-year	62-year
1	30.0	15.5
2	15.0	7.8
3	30.0	15.5
4	9.4	6.2
5	15.0	7.8
6	30.0	15.5
7	25.0	12.4
8	–	10.3
All	2.5	1.3

example, only four events could be identified in the entire sample between the early and mid twentieth century (1906, 1922, 1928, and 1934); whereas the period from 1948 to 2007 showed a much higher overall event frequency with a total of 49 events. Considering only the time period since this increase in activity (i.e., 1948–2010), the shortest return period was again seen in torrent 4 (6.2 years) and the longest in torrents 1, 3, and 6 (15.5 years). Frequency was variable within these past six decades as well, whereby, for example, larger events seemed to be followed by periods of continued activity (of presumably smaller debris flows). This was the case for events in 1991 and 1992, as well as 1998 and 1999, where the presence of several consecutive years with GD of varying intensity suggested recurrent events in the time periods 1993–1997 and 2000–2006, respectively. In such intervals, dating of all events was not possible with any degree of confidence, and for this reason events were only reported when supported by injuries or well-defined TRD responses. The results presented here are therefore a minimal dating frequency and do not assume to provide an exhaustive record of all past debris-flow events.

An intertorrent comparison revealed that the majority of dated event years (61.3%) contained events in more than one torrent. There were no years containing events in all torrents; however, 12.9% of event years contained events in more than 4 torrents (maximum of 6 torrents) including 1878, 1956, 1991, and 1992. There were, however, no distinct patterns of simultaneous event occurrence in any pairs or sets of torrents, nor was there an obvious relationship between event frequency and simultaneous event occurrence.

The dendrogeomorphic analysis identified five of the six debris-flow events contained within the archival records (1948, 1956, 1968, 1991, and 1999); the archival event of 1979 was not identifiable in the sample, suggesting that this event was not large enough to have affected the sampled trees. Years of flooding in the Mengbach were not always correlated to the identified debris-flow events in these tributary torrents.

4.3. Spatiotemporal shifts in debris-flow activity on the cone

Archival orthophotos provided important visual information for understanding spatial and temporal dynamics of events on the debris-flow cones. Significant changes in channel morphology have occurred in torrents 2, 6, and 7 since the first (30 August 1951) or second (15 August 1973) orthophoto acquisition. In torrent 2, for example, clearly all three comprising channels (north, south, and central) have been active at different times (Fig. 4). Dated events suggest that the central channel was previously active but was heavily forested and inactive in the mid–late twentieth century, during which time the northern and southern areas were active (Fig. 4A,B). The massive deforestation and reactivation of this central section occurred after a large event in 1992 and now serves as the primary channel (Fig. 4C).

In torrent 6, depositions in the sampled area are first visible in the most recent orthophoto (26 July 2009) and are not present in the two previous orthophotos. We can infer that this area became active at some point after 15 August 1973 (orthophoto acquisition date). The reconstructed events would suggest that the first recordable deposition occurred in 1978, with following events in 1985 and 1992. In torrent 7, changes in channel morphology were similar to those in torrent 2 (Fig. 5). Archival photos revealed that only the southern sections were active during the mid–late twentieth century, explaining the lack of reconstructed events during this period (Fig. 5A). An event in the late nineteenth century suggests that the sampled northern section had been previously active. A large event in 1991 caused an avulsion out of the primary channel and a major deforestation and reactivation of this northern section (Fig. 5B). A series of subsequent events followed, including incision of a new channel and root washout in a lower section

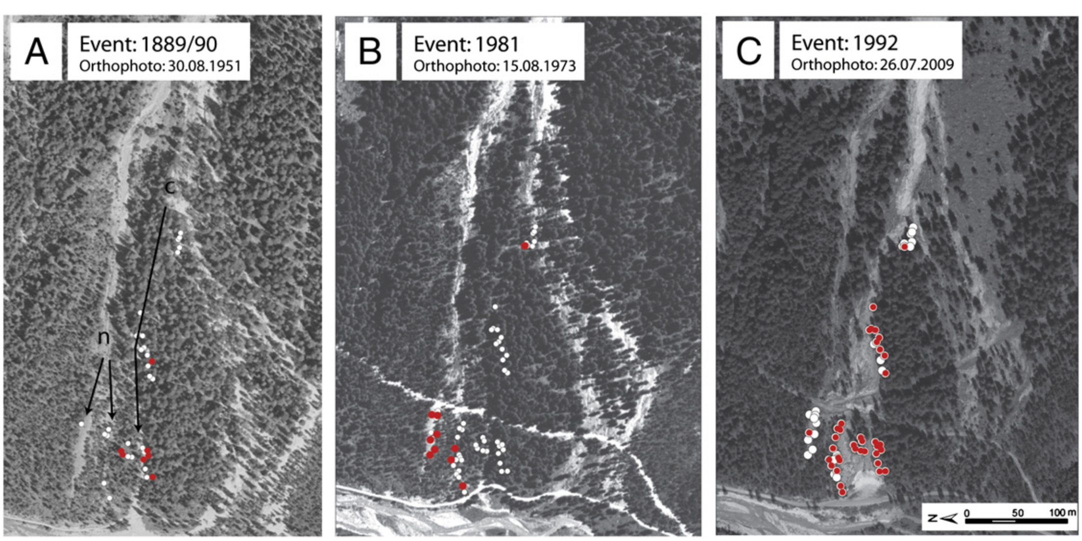

Fig. 4. Spatial distribution of trees affected by past debris-flow events (red) are supported by visual evidence of changing channel morphology in archival orthophotos for torrent 2. An event from the late nineteenth century suggests that the central channel was previously active (A), but was less active than the northern channels in the mid–late twentieth century, as exemplified by the event of 1981 (B). A larger event in 1992 caused significant reduction in forest coverage in the central channel (C), thereby reactivating it in the following years. All sampled trees alive in the given event year are shown in white. Channels are indicated as north (n) and central (c).

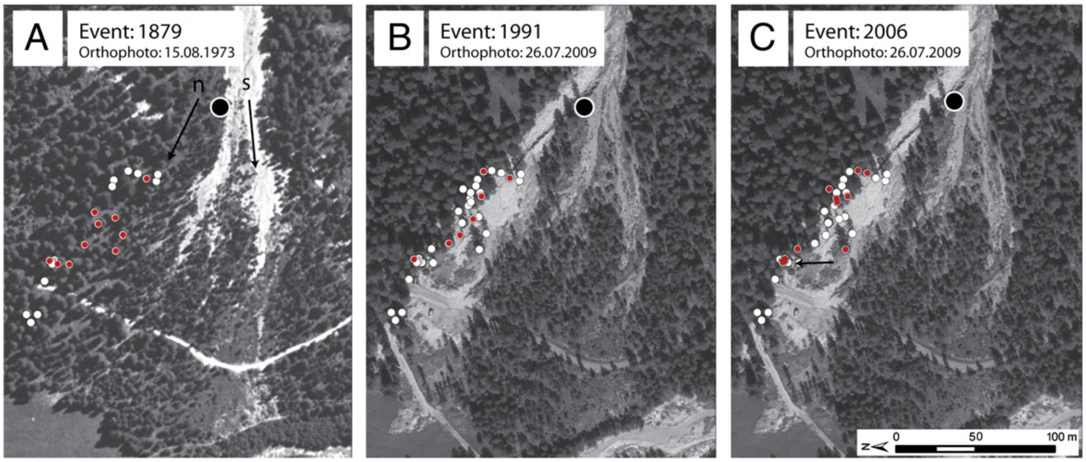

Fig. 5. Spatial distribution of trees affected by past debris-flow events (red) are supported by visual evidence of changing channel morphology in archival orthophotos for torrent 7. An event in the late nineteenth century (A) shows that the northern sector of the cone was previously active, but was densely forested up until the late twentieth century (A). This sector became reactivated after a large event in 1991 (B) and continues to be the primary channel. An event in 2006 caused root washout and further incision of the channel (C, arrow). All sampled trees alive in the given event year are shown in white, and identical positions within the photos are marked with a black circle. Sectors are indicated as north (n) and south (s).

of the cone in 2006 (Fig. 5C). This remains the primary channel and southern areas are now largely inactive.

Orthophoto comparison for torrents 1 and 3 revealed decreases in forest coverage but no significant morphologic changes. Large decreases in forest coverage were visible on the cones of torrents 4 and 5 from significant increases in extent (and presumably magnitude) of depositions. Finally, significant regeneration of trees along the channel course and at the channel mouth was visible in torrent 8.

4.4. Meteorological conditions associated with debris-flow activity

Maximum 1-day precipitation values for the months of June to September of all available years ranged between 10 and 120 mm (mean 39 ± 18 mm; 1961–2009). Maximum 1-day precipitation values for only those years with dated debris-flow events did not differ greatly (range 10–80 mm, mean 39 ± 15 mm). Dated event years did not necessarily correspond to those years containing the highest maximum precipitation values. Years containing debris-flow events in multiple torrents also did not correspond to years containing higher maximum values—maximum 1-day precipitation of up to 70 mm were recorded in years with single events (range 31–70 mm), and values as low as 39 mm were recorded in years with multiple events (range 39–80 mm).

Therefore, considering all possible single or consecutive heavy precipitation days occurring in dated or previously known event years (Table 5) was necessary, and no minimum precipitation threshold was defined. Precipitation data for all dated event years suggest that daily maximum precipitation sums > 40 mm (1-day) or 60 mm (2-day) are not infrequent in this region. Maximum 1-day precipitation values occurred most frequently in July and August (65%) and extreme values (defined here as over 60 mm) occurred primarily in August and September (60%). Years of previously documented extreme flooding events (e.g., 1999, 2000, 2002, and 2005) contained maximum 1-day precipitation sums of over 100 mm or 2-day sums of up to 207 mm. Similarly high precipitation was recorded in four reconstructed event years (18–20 July 1981, 24–26 August 1985, 17–18 July 1987, and 16–17 June 1991).

5. Discussion and conclusion

This study presented a dendrogeomorphic reconstruction of regional debris-flow events for a valley in the western Austrian Alps. The 442 sampled trees (268 *P. mugo* ssp. *uncinata*, 164 *P. abies*, 10 *A. alba*) enabled the identification of 63 debris-flow events between A.D. 1839 and 2010. Spatiotemporal changes in channel morphology were inferred from visual evidence in archival orthophotos and supported the understanding of event frequency in individual torrents. Precipitation data from one local and two regional meteorological stations were collected and assessed for patterns in precipitation events.

The type of material present and the process of deposition on the debris-flow cones had an effect on the kind of growth disturbances seen in the analysis. In torrents with clearly formed depositional cones (torrents 4, 5, and 7), the deposited material is medium sized, dry, and highly unstable with minimal water holding capacity (Fig. 6A, C). Although remobilization on the cone is frequent, trees are primarily influenced by low impact movements and only secondarily by high impact flows during larger events. The consequence for a dendrogeomorphic analysis is that injuries are rare and growth disturbances are found primarily in the form of abrupt changes in tree growth. In contrast, in torrents with more clearly defined channels (torrents 1, 2, and 7), trees were influenced by high impact processes and less frequently by sedimentation (superficial injuries on tree stems were frequent; Fig. 6B). For these torrents, identification of events was largely supported by TRD reactions.

Abrupt growth suppressions were by far the most common growth reaction seen in the total sample. Although tree burial generally results in abrupt growth suppression (Stoffel and Wilford, in press), it has been reported that growth release may follow deposition of calcareous material because of the nutrient content of such substrates (Stoffel et al., 2008a; Stoffel and Wilford, in press). This was observed for several events in both torrents 4 and 5, in which continued growth increase for a span of at least 3 years following the event was seen. Torrent 6, in comparison, showed relatively few instances of growth release following an event, despite showing the most pronounced tree burial of any torrent (Fig. 6C). It is plausible that burial depth here exceeded some threshold value beyond which the negative effects of burial outweighed the fertilizing effect of deposited material. Furthermore, the sensitivity to sedimentation is likely dependent on tree species—samples were limited primarily to *P. mugo* ssp. *uncinata* in torrents 4 and 5 and *P. abies* and *A. alba* in torrent 6. Stoffel et al. (2008a) reported a high frequency of growth release in *Pinus sylvestris* trees following sedimentation in calcareous material. Growth suppression was only present in cases of deep burial, decapitation, or root

Table 5
Heavy spring or summer precipitation events corresponding to dated and/or previously documented (*) event years; precipitation values were taken from the first listed meteorological station; other stations reporting similar values are noted additionally.

Year	Date		Precipitation (mm)		Station
	Day	Month	1-day sum	2-day sum	
1961	14–15	May	45	71	BR
	11–12	Aug	39	74	BR
	17	Aug	71	-	BR
1963	6–7	Oct	71	101	BR
1964	28–29	June	31	61	BR
1968*	16–20	July*	36	62	BR
	8–9	Aug*	66	121	BR
1970*	20	Aug*	60	-	BR
1973	17	July	46	-	BR
	4	July	44	-	MAL
1978	7	Aug	82	-	MAL/BR
	18–20	July	82	155	MAL/BR
1981	22	Sept	53	-	MAL
	28	Sept	64	-	MAL
	5–6	Aug	50	100	MAL/BR
1985	24–26	Aug	80	114	MAL/BR
1987	17–18	July	64	122	MAL/BR
1990	22–23	Aug	33	52	MAL
	16–17	June	85	143	MAL/BR
1991	26	Sept	83	-	MAL/BR
	9–10	July	38	61	BR
	31	Aug	50	-	BR
	5–6	July	61	80	MAL/BR
1994	8	Sept	49	-	MAL/BR
	14	Sept	42	-	MAL/BR
	21–22	June	39	75	MAL/BR
1996	7–8	July	41	74	MAL/BR
	10–11	June	51	83	MAL/BR
1998	11	Sept	61	-	MAL/BR
	20–21	May	174	200	BR/MAL
1999*	9–10	Aug	37	67	BR
	25–26	Sept	55	99	BR/MAL
	5–6	Aug	102	143	MAL/BR
2000*	20–21	Sept	78	104	NH
	9–10	June	50	85	NH/MAL/BR
2001	3–4	Aug	55	80	NH/MAL/BR
2002*	10–11	Aug	99	131	NH/MAL
	28–29	May	43	69	MAL
2003	3–4	Oct	36	68	NH
	2–3	June	37	53	NH/MAL
2004	27	June	61	-	NH/BR
	8	July	65	-	NH/BR
2005*	21–23	Aug*	168	207	NH/MAL/BR
	28–29	May	38	67	NH
2006	27–28	Aug	35	62	NH
	16	Sept	83	-	NH/MAL
	7–8	Aug	29	51	NH/MAL/BR
	3–6	Sept	35	64	NH/MAL/BR
Mean			54	95	
Max			82	207	

exposure. It has been reported that *P. abies* also respond to sedimentation with growth release (Strunk, 1991; Mayer et al., 2010) but are particularly sensitive to deep burial (Strunk, 1995; Stoffel and Wilford, in press).

The regional debris-flow frequency reported here (mean recurrence interval: 2.5 years; mean decadal frequency: 3.2 events) is lower than in other comparable European sites. For example, Bollschweiler and Stoffel (2010a) reported an average regional decadal frequency of 18.5 events for eight debris-flow systems with high elevation, permafrost-dominated catchments. This can be partially attributed to differences in the nature of the catchments. Whereas other studies have investigated transport-limited catchments, the torrents investigated in this study can be characterized as supply-limited, meaning that potential transportable material must accumulate between events (i.e., channel recharge time; Bovis and Jakob, 1999). In supply-limited catchments, triggering circumstances (e.g., heavy precipitation event) may not initiate debris-flow events if material availability is insufficient. The higher event frequency found in torrent 4 is an exception in the Gamperdonatal and is reflective of a greater overall availability and transport of material—the catchment has a higher concentration of runoff because of a large upper catchment area, a comparatively small transport area at the cone apex, and readily eroding main transport channels.

On the other hand, event frequency in individual torrents is influenced by tree availability and age structure of the stands, which is largely a product of the history of destructive events on the cone. It is therefore crucial that the course of spatiotemporal changes in channel morphology and forest structure is assessed. For this reason, the archival orthophotos were of utmost importance in this study, as they provided visual information regarding the history of sampled areas. In torrent 8, for example, significant forest regeneration has occurred between 1973 and 2009, which explains the young sample age and short span of reconstructed events. In other torrents (2, 6, and 7), it was apparent from the orthophotos that some sectors have only recently become active or reactivated, and in some cases drastic changes in areas of primary activity have occurred (Figs. 4 and 5). Trees in these sectors, having been newly exposed after periods of low to no activity, became subject to subsequent clustered periods of sedimentation. In such cases, trees responded to both initial and consecutive events, resulting in a disproportionate number of responses in the past two decades compared to previous periods. Orthophotos also highlighted the degree of tree loss in heavily aggraded, central sectors of some cones (e.g., torrent 5; Fig. 7). These records, therefore, do not contain information from trees in areas of highest activity and sampling was limited in some sectors to less active peripheral areas (e.g., torrents 4, 5, and 7). The result was the reconstruction of earlier activity in the nineteenth century (an exhaustive record was limited by sample depth) and only minimal activity in the early twentieth century (sampling was limited by tree availability).

On a regional scale, however, it is unclear whether the temporal increase in event frequency since the mid-twentieth century can be attributed entirely to changes in channel routing and tree availability or if it is at least partially a result of changes in other parameters, e.g., freeze-thaw cycles and transport conditions. Large events equivalent to those in 1991, 1992, or 1999 were not visible in the tree-ring records for the first half of the twentieth century. The possibility that transport conditions have changed by way of greater maximal precipitation is not, however, indicated in the precipitation data—apart from a cluster of extreme maximal 1-day values between 1999 and 2005, no distinctive trends are apparent. As these data cover a comparatively short time period, a verification of long-term trends was made with data from the closest station at a similar elevation (Davos, 9°51′ N., 46°49′ E., 1594 m asl; 1867–2010). No trends can be reported based on either of these data sets at the given resolution. Therefore, the reason for the occurrence of multiple events in the 1990s is unclear, but is not considered an indication of a general increase in event frequency (decadal event frequency shows no overall trend).

Finally, the absence of a clear relationship between seasonality or magnitude of precipitation and regional debris-flow events underlies the fact that these catchments are supply-limited systems. Daily precipitation sums in this region (mean 39 ± 18 mm, range 10–120 mm) are equivalent to or in excess of those reported in other similar investigations—Pelfini and Santilli (2008) reported a mean of 37.8 mm for a site in northern Italy, and Stoffel et al. (2011) reported a triggering of events with 24-h sums of <20 mm in the Zermatt valley. The close proximity of the torrents excludes the possibility that weather systems act differentially on each catchment. Extreme precipitation days generally occurred within one- to three-week periods of low to moderate precipitation (defined roughly as 10–30 mm) with total sums of 200–400 mm. It is plausible that debris flows were triggered at different times throughout these extended periods of precipitation, as

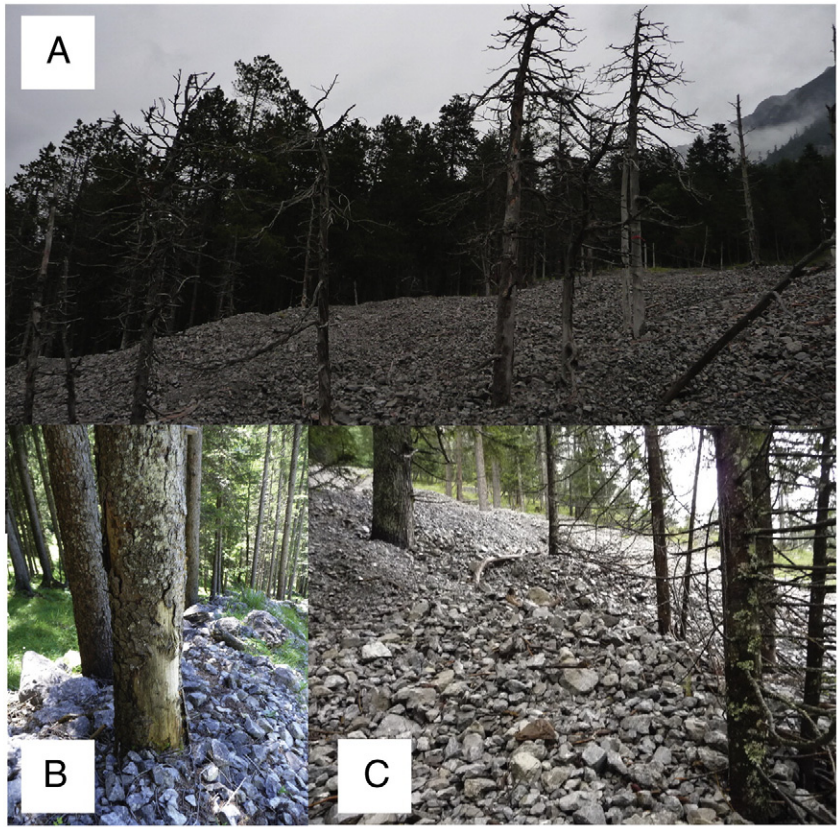

Fig. 6. Depositional characteristics of different torrents including the deep and highly unstable depositional cone of torrent 5 (A), the typical impact and partial sedimentation of a stem on a side levee in torrent 1 (B), and the deep burial of *P. abies* trees on the cone in torrent 7 (C).

torrential activity is this region is presumably not solely dependent on maximal precipitation events, but rather on multiple triggering factors. This would explain why reconstructed events were not always coincident with maximal precipitation days nor with events in neighboring torrents.

In conclusion, the debris-flow events reconstructed in this investigation greatly improved the existing historical records for the Gamperdonatal. An exhaustive reconstruction of all previous activity is not possible and was hindered in this study primarily because of significant tree loss by sedimentation and traumatic injury in areas of highest activity on the cones. Such shortcomings in sampling populations in individual torrents can be accounted for by comparisons on a regional scale. A more accurate estimation of overall frequency was enabled in this case by a multitorrent reconstruction. Finally, meteorological data for the region showed that this valley receives abundant precipitation in the months of June to September, and that debris-flow activity is presumably not directly dependent on seasonality or magnitude of precipitation.

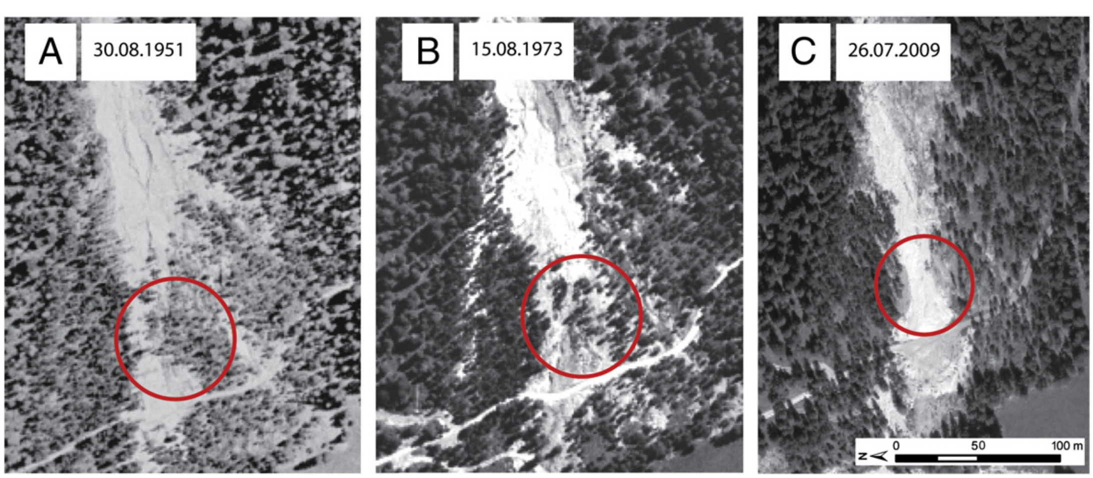

Fig. 7. Comparison of tree density in torrent 5 in the active, central depositional area (circle) since 1951. An estimated 150 trees have died because of depositional processes between 1951 (A) and 2009 (C).

Acknowledgments

This study was funded in part by the EU project AdaptAlp. The authors extend thanks to the Forest Engineering Service of the Torrent and Avalanche Control Bregenz for providing access to historical data, digital terrain models, and orthophotos and to Harry Seijmonsbergen for the use of geomorphic data and maps. We also acknowledge Florian Rudolf-Miklau and the Agrargemeinschaft Nenzing for logistic support and site access. The constructive input of two anonymous reviewers helped improve the quality of this paper.

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