EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **35**, 399–406 (2010)

Published online 19 January 2010 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/esp.1934

Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees

Estelle Arbellay,[1,2]* Markus Stoffel[1,2] and Michelle Bollschweiler[1,2]
[1] Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1-3, CH-3012 Berne, Switzerland
[2] Department for Environmental Sciences, University of Geneva, Chemin de Drize 7, CH-1227 Carouge-Geneva, Switzerland

Received 9 July 2009; Revised 31 August 2009; Accepted 14 September 2009

*Correspondence to: E. Arbellay, Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1-3, CH-3012 Berne, Switzerland. Email: estelle.arbellay@dendrolab.ch

ESPL
Earth Surface Processes and Landforms

ABSTRACT: Tree-ring records from conifers have been regularly used over the last few decades to date debris-flow events. The reconstruction of past debris-flow activity was, in contrast, only very rarely based on growth anomalies in broad-leaved trees. Consequently, this study aimed at dating the occurrence of former debris flows from growth series of broad-leaved trees and at determining their suitability for dendrogeomorphic research. Results were obtained from gray alder (*Alnus incana* (L.) Moench), silver birch and pubescent birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.), aspen (*Populus tremula* L.), white poplar, black poplar and gray poplar (*Populus alba* L., *Populus nigra* L. and *Populus x canescens* (Ait.) Sm.), goat willow (*Salix caprea* L.) and black elder (*Sambucus nigra* L.) injured by debris-flow activity at Illgraben (Valais, Swiss Alps). Tree-ring analysis of 104 increment cores, 118 wedges and 93 cross-sections from 154 injured broad-leaved trees allowed the reconstruction of 14 debris-flow events between AD 1965 and 2007. These events were compared with archival records on debris-flow activity at Illgraben. It appears that debris flows are very common at Illgraben, but only very rarely left the channel over the period AD 1965–2007. Furthermore, analysis of the spatial distribution of disturbed trees contributed to the identification of six patterns of debris-flow routing and led to the determination of preferential breakout locations of events. The results of this study demonstrate the high potential of broad-leaved trees for dendrogeomorphic research and for the assessment of the travel distance and lateral spread of debris-flow surges. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: dendrogeomorphology; debris flow; broad-leaved tree; Swiss Alps

Introduction

Debris flows are a major natural hazard in most mountain regions of the world. They endanger the security of humans and damage their assets. The high flow velocity and poor temporal predictability of debris flows cause them to be one of the most dangerous landslide types (Jakob and Hungr, 2005). They occur in many parts of the Alps, which has increased the need for mitigation measures. For example, Swiss Federal regulations require cantonal authorities to compile hazard maps, which are used in land-use planning and in the design of protection measures (Raetzo *et al.*, 2002). From this perspective, a spatio-temporal reconstruction of past debris-flow activity is essential to appraise this phenomenon. It is apparent, however, that there is a considerable lack of data, as archival records of past debris-flow events are infrequent and information on previous incidences largely missing.

Dendrogeomorphology allows a reconstruction of past geomorphic activity to be inferred from information preserved in tree rings (Alestalo, 1971; Stoffel and Bollschweiler, 2008), hence the possibility of complementing archival records. In the Swiss Alps, several forested debris-flow fans have been analyzed with this method (Baumann and Kaiser, 1999; Bollschweiler and Stoffel, 2007). Dendrogeomorphic research on debris flows has dated events and determined their frequency and the spatial spread of surges (Bollschweiler *et al.*, 2007). In addition, tree-ring investigations have compared reconstructed debris-flow events with archival records of flooding in neighboring rivers (Stoffel *et al.*, 2005b) or have evaluated possible impacts of global warming on event frequency or magnitude (Stoffel *et al.*, 2008b). Previous tree-ring reconstructions of past debris-flow activity have almost exclusively been conducted with conifers. Broad-leaved trees have been used occasionally to complement data obtained with conifers (Kaczka and Morin, 2006; Szymczak *et al.*, in press), but have never been the sole tree species examined. This can be partly explained by the fact that conifers are the dominant tree species in mountain regions, in which debris-flow hazards normally occur. Moreover, conifers generally attain a greater age and exhibit a simpler wood structure, thus facilitating tree-ring analysis.

In contrast to debris flows, broad-leaved trees have been used in several dendrogeomorphic studies aiming at dating floods (Yanosky, 1983; Astrade and Bégin, 1997; St. George and Nielsen, 2003), landslides (Fantucci and McCord, 1995; Fantucci and Sorriso-Valvo, 1999; Stefanini, 2004) and snow avalanches (Bryant *et al.*, 1989; Mundo *et al.*, 2007; Decaulne and Sæmundsson, 2008).

The primary objective of this study was to date the occurrence of former debris flows through the analysis of injured broad-leaved trees. Hupp *et al.* (1987) and Strunk (1991) first demonstrated the value of studying injuries for the reconstruction of debris-flow events. This study was also designed to determine the suitability of broad-leaved trees for dendrogeomorphic research. Results were obtained from 315 samples from nine broad-leaved tree species. Stoffel *et al.* (2008a) have investigated conifers (*Pinus sylvestris* L.) and overbank sedimentation events affecting the Illgraben fan, whereas we examined broad-leaved trees from the lower terraces that border the presently active channel.

Study Area

The Illgraben (Valais, Swiss Alps, 46° 18′N/7° 38′E) is considered one of the most active debris-flow torrents of the Alps, with several events per year (Rickenmann *et al.*, 2001). It is located on the southern slopes of the upper Rhone river valley (Figure 1) opposite the town of Leuk. The catchment area has a size of 10·5 km^2 and extends from the Illhorn at 2717 m a.s.l. to the apex of the Illgraben fan at 860 m a.s.l. (Geo7, 2000). The impressive cirque between the Gorwetschgrat, Illhorn and Meretschihorn is developed in limestones, dolomites and quartzites of Permian and Triassic age (Escher, 1988). The rockwalls of the catchment area are almost devoid of vegetation and have mean slope angles varying between 40 and 50° (Geo7, 2000). The catchment slopes provide storage of material that is remobilized by debris flows. Mean annual precipitation ranges from 700 mm in the lower part of the catchment area to 1700 mm at its summits (FOWG, 1999).

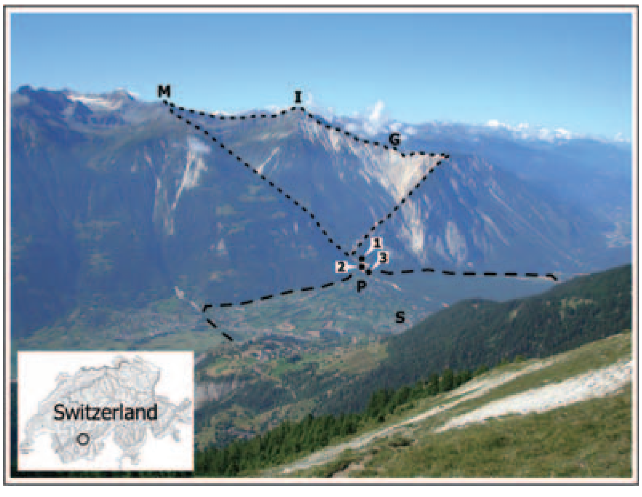

Figure 1. The Illgraben catchment lies between the Gorwetschgrat (G), Illhorn (I) and Meretschihorn (M). The village of Susten (S) and the hamlet of Pletschen (P) are also shown. The dotted line and the dashed line, respectively enclose the catchment area and the debris-flow fan. The three sectors investigated located at the fan apex are indicated as well. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Intense rainstorms occur mainly in summer. The northern part of the catchment area shows no signs of debris-flow activity, in contrast to the southern part where erosion of the catchment slopes provides ample material for debris-flow initiation (Hürlimann *et al.*, 2003).

The Illgraben fan has a size of 6·6 km^2, a mean slope angle of 10·2° and extends from the fan apex at 860 m a.s.l. to the confluence of the Illgraben with the Rhone river at 610 m a.s.l. (Geo7, 2000). The imposing fan has a radius of 2 km, displacing the Rhone river to the northern slopes of the valley. The eastern part of the Illgraben fan includes hedged farmland, the village of Susten and the hamlet of Pletschen. The western part is covered by the large Scots pine (*Pinus sylvestris* L.) forest of Finges. Broad-leaved trees are found mainly on the lower terraces that border the presently active channel and form narrow and discontinuous strips of riparian vegetation predominantly composed of gray alder (*Alnus incana* (L.) Moench). Silver birch and pubescent birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.), aspen (*Populus tremula* L.), white poplar, black poplar and gray poplar (*Populus alba* L., *Populus nigra* L. and *Populus x canescens* (Ait.) Sm.), goat willow (*Salix caprea* L.) and black elder (*Sambucus nigra* L.) are present as well.

Archival data on debris-flow events at Illgraben are available from different sources (Geo7, 2000; T&C and WSL, 2005; Stoffel *et al.*, 2008a). They cover more than 200 years and indicate the presence of 15 overbank sedimentation events that affected significant parts of the Illgraben fan between AD 1793 and 2005 (Stoffel *et al.*, 2008a). On 26 March 1961, a rockslide mobilized considerable amounts of material (~5 × 10^6 m^3) in the northern part of the catchment area and significantly increased debris-flow frequency in the following years (Geo7, 2000). As a consequence, a large retention dam was built in the initiation zone and a series of smaller check dams was constructed inside the channel (Hürlimann *et al.*, 2003). These countermeasures contributed to a reduction of debris-flow activity in the 1970s. By the early 1980s, however, the retention dam was completely filled and debris flows have increased in frequency during the last 20 years (Hürlimann *et al.*, 2003). Archival records on debris-flow activity at Illgraben were rather irregular and incidental before a debris-flow observation station was installed in 2000 in the lower reaches of the channel (Rickenmann *et al.*, 2001), allowing a detailed documentation and analysis of about 40 debris-flow events between AD 2000 and 2008 (C. Graf, pers. commun., 2008). In addition, several projects have been initiated to study erosion processes in the source area of debris flows as well as in the channel (McArdell *et al.*, 2007; Badoux *et al.*, 2009; Schlunegger *et al.*, 2009).

The Illgraben has formed a 100 m wide incised valley cut below the main fan surface. The presently active channel is inset in this wider valley up to 20 m below the main fan surface. The present study concentrated on three sectors located at the fan apex (Figure 1) on the lower terraces that border the presently active channel (Figure 2). Sector 1 is a 350 m long north-west terrace extending from a dogleg of the channel at 890 m a.s.l. to the Bhutanese bridge (840 m a.s.l.). Sector 2 extends from the Bhutanese bridge to a check dam located at 820 m a.s.l. and includes three degradation terraces built by the present and past activity of the Illgraben. Erosion resulted in a vegetated island (175 × 50 m) enclosed by the current channel to the north and by an abandoned channel to the south. Sector 3 is a 125 m long western terrace located at about 780 m a.s.l. in the proximity of the hamlet of Pletschen. The depth of the current channel at the three investigated sectors is 2 to 4 m, whereas its width is 10 to 20 m (Figure 2).

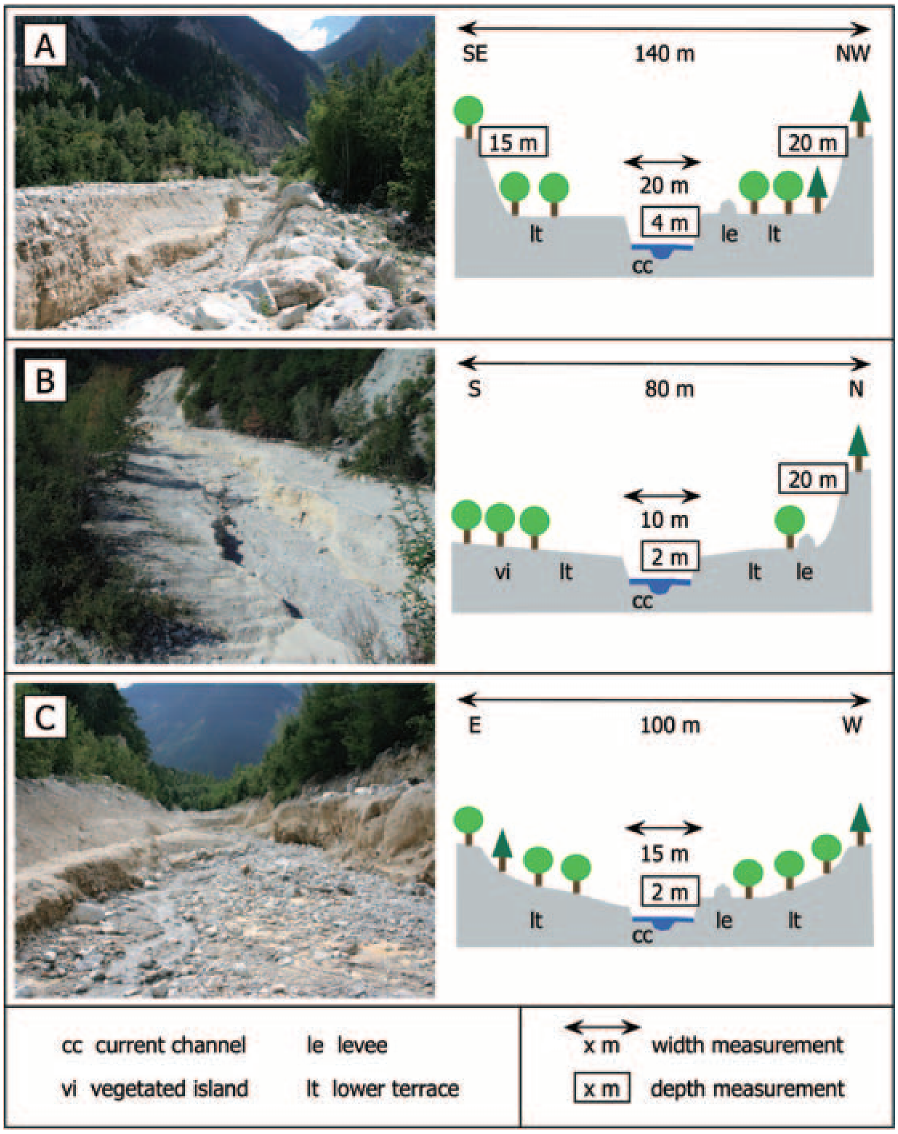

Figure 2. Views and cross-sections of the current channel and lower terraces at the three investigated sectors. In sector 1 (A), the channel is deeply incised. By contrast, the Illgraben has formed a much less incised channel in sector 2 (B) and in sector 3 (C). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Material and Methods

Geomorphic mapping

Fieldwork started with the mapping (scale 1 : 1000) of features associated with past debris-flow activity such as levees, lobes as well as abandoned flow paths and channels. Due to the relatively dense riparian vegetation along the channel, GPS devices could not be used and therefore geomorphic mapping utilized a tape, inclinometer and compass.

Sampling strategy

Based on the geomorphic maps and on an outer inspection of the stem surface, 154 injured broad-leaved trees were selected. Only trees with injuries exposed to the assumed flow direction of former debris flows were sampled. Trees that became dry or completely rotten after injury were neglected. Table 1 provides the number and percentage of the different broad-leaved tree species sampled, which reflects the species distribution in the riparian vegetation belt formed along the channel. One wedge per injury was extracted with a handsaw or a chain saw according to the dimension of the overgrowing callus. The upper side of the wedge, used for tree-ring analysis, was cut horizontally through the callus tissue, whereas the lower side was cut obliquely (Figure 3A). In addition, one core per tree was obtained by using an increment borer at the base of the uninjured side of the stem. Cross-sections were preferred to wedges and cores whenever tree diameter permitted the simple use of the handsaw. In total, 104 increment cores, 118 wedges and 93 cross-sections were sampled and data recorded for each tree included (i) tree species; (ii) tree position within or on debris-flow deposits; (iii) tree height and base circumference; (iv) position and dimensions of the injuries; and (v) position of the extracted samples on the stem surface.

Dating of past debris-flow events

In the laboratory, samples were analyzed and data processed following the standard procedures described in Stoffel and Bollschweiler (2008). Single working steps involved surface preparation, counting of tree rings as well as ring-width measurements using a digital LINTAB positioning table connected to a Leica stereomicroscope and TSAP-Win Scientific 4·63 software (Rinntech, 2009). Tree-ring widths were measured on the side of the sample opposite to the injury. The dating of past debris-flow events was based on a dendrogeomorphic analysis of injuries and abrupt growth changes (i.e. abrupt decrease and increase in ring-width) in samples. Tension wood was purposely disregarded because trees tend to grow towards the light in riparian vegetation belts. Therefore, the resulting tilting of trees would primarily be ecologically driven.

The wedges and cross-sections were used to date injuries (i) to the year by counting the number of annual growth rings formed after the event and (ii) to the season by observing the radial position of the injury within the increment ring (Alestalo, 1971; Schweingruber, 2001). As illustrated in Figure 3B, tree rings were subdivided into early (EE) and late (LE) earlywood, followed by a very limited latewood (L). While EE starts in late spring, LE ceases in late summer and L forms in early autumn. Injuries caused by debris-flow events occurring outside or within the first days of the growing season were attributed to dormancy (D) (Stoffel *et al.*, 2005a). Scars dated to the same year and to the same season within a tree were counted as one single injury.

Tree rings were measured from the cores and cross-sections to produce growth curves, which were visually analyzed to determine the initiation of abrupt growth decrease or increase (Schweingruber, 2001). Abrupt growth changes were taken into consideration only if they were maintained for over 2 years at least. They were then classified into three categories according to the abruptness and persistence of suppression or release. A strong reaction was defined when tree-ring width was at least 66·6% smaller or 300% larger than that of the preceding ring. A weak reaction was defined when tree-ring width was less than 50% smaller or 200% larger. An intermediate response fell between these two categories.

Table I. Overview of the different broad-leaved tree species sampled

Tree species	Absolute number	%
Alnus incana (L.) Moench	80	52
Betula pendula Roth, *Betula pubescens* Ehrh.	28	18
Populus alba L., *Populus tremula* L., *Populus nigra* L., *Populus x canescens* (Ait.) Sm.	29	19
Salix caprea L.	15	10
Sambucus nigra L.	2	1
Total	154	100

Identification of patterns of debris-flow routing

Preferential breakout locations as well as the travel distance and lateral spread of the reconstructed debris-flow events were assessed in sectors 1 and 2 by the analysis of the spatial distribution of disturbed trees in a specific event year. The number of sampled trees in sector 3 was too small for this kind of interpretation.

Results

Tree characteristics and growth disturbances

The average age of the 154 selected trees was 27·1 years (σ = 13·2 years) at sampling height. Counted tree rings ranged from 7 (AD 2001) to 91 (AD 1917). Tree height ranged from 2·5 m to 23 m and base circumference from 18 cm to 150 cm. There is a concentration of older trees 50 m away from the channel at about 850 m a.s.l. in the northern part of sector 1. Their average age is 41·96 years (σ = 5·21 years) at sampling height and counted tree rings range from 29 (AD 1979) to 50 (AD 1958). Tree-ring analysis of the 104 increment cores, 118 wedges and 93 cross-sections permitted the detection of 444 growth disturbances. Signatures of past debris-flow events were identified in the trees via injuries (41%), growth suppression (40%) and release (19%).

Past debris-flow events and frequency

Tree-ring analysis of the growth disturbances allowed the reconstruction of 14 debris-flow events between AD 1965 and

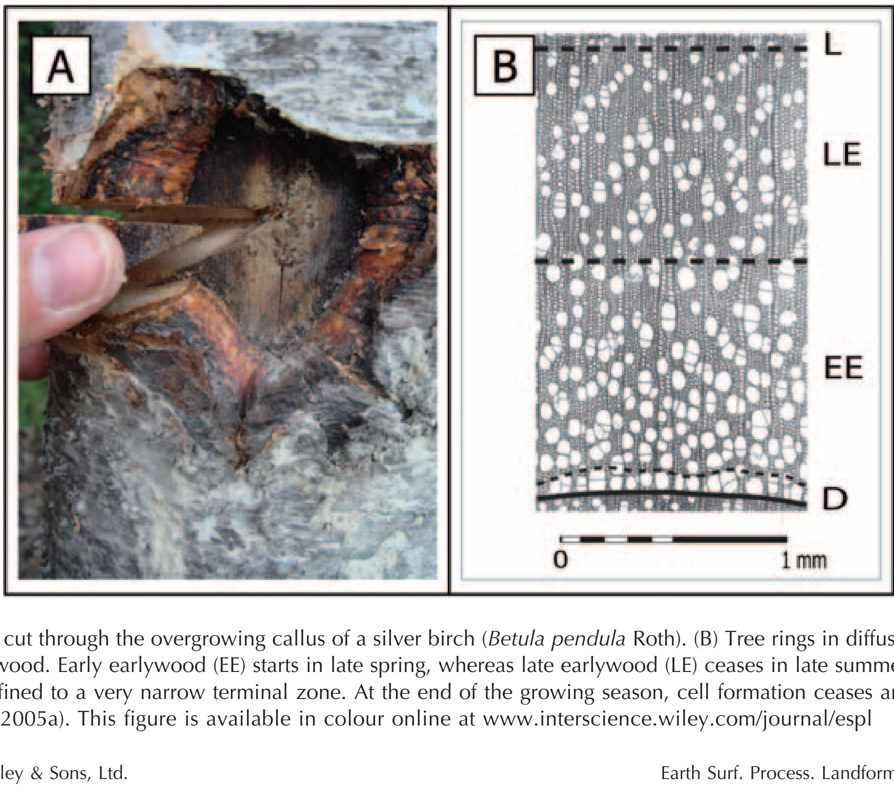

Figure 3. (A) A wedge cut through the overgrowing callus of a silver birch (*Betula pendula* Roth). (B) Tree rings in diffuse-porous species consist almost entirely of earlywood. Early earlywood (EE) starts in late spring, whereas late earlywood (LE) ceases in late summer. Latewood (L), formed in early autumn, is confined to a very narrow terminal zone. At the end of the growing season, cell formation ceases and dormancy (D) occurs (based on Stoffel *et al.*, 2005a). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table II. Overview of the number of injuries and abrupt growth changes attributed to the 14 reconstructed debris-flow events. The events in bold relate to the three event years (1995, 2002, 2005) identified in the three investigated sectors and during which debris flows affected more than 30% of trees alive and larger than sampling height at the time of the event

Event	Injuries				Abrupt growth changes		
	D	EE	LE	L	AGS	AGR	Total
1965					5		5
1969					6		6
1973					5		5
1981					6		6
1982					4	1	5
1988					10		10
1991					11	2	13
1995a		**17**					**17**
1995b			**36**		**5**	**2**	**43**
1997			6		11	1	18
1998				4			4
1999					21	2	23
2002					**47**		**47**
2005		**98**			**9**	**43**	**150**
Total		115	42	4	140	51	352
Total	161				191		352

D, dormancy; EE, early earlywood; LE, late earlywood; L, latewood; AGS, abrupt growth suppression; and AGR, abrupt growth release.

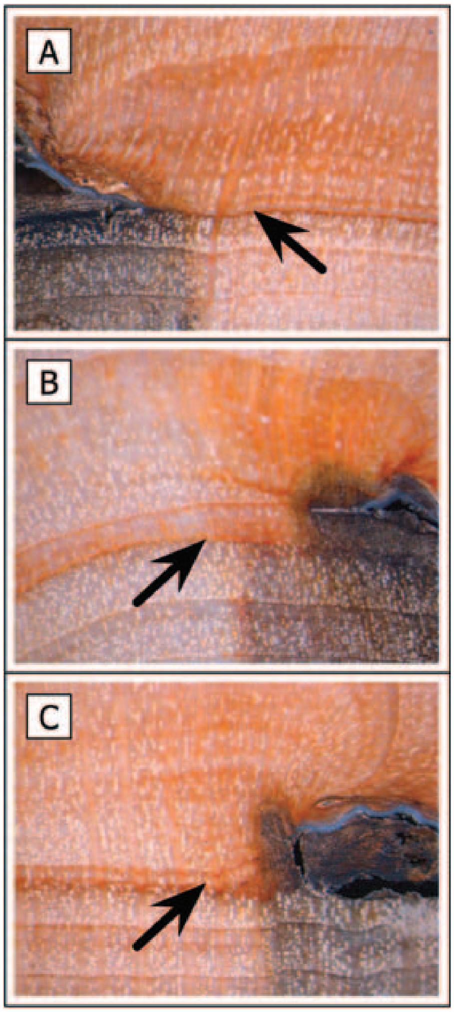

Figure 4. Examples of debris-flow injuries located at different radial positions within the tree rings of gray alder (*Alnus incana* (L.) Moench). The arrows indicate the radial position of the injury within the increment ring. The injury was dated to (A) early earlywood (EE); (B) late earlywood (LE); and (C) latewood (L). This figure is available in colour online at www.interscience.wiley.com/journal/espl

2007. Three event years (1995, 2002, 2005), identified in the three investigated sectors, had debris flows affecting more than 30% of trees alive and larger than sampling height at the time of the event. The other event years (1965, 1969, 1973, 1981, 1982, 1988, 1991, 1997, 1998, 1999) were derived from a smaller amount of information, but did include strong growth disturbances. It is therefore conceivable that debris flows would have left the Illgraben channel during these years as well. Table 2 reports on 352 growth disturbances and details the number of injuries and abrupt growth changes for the 14 reconstructed debris-flow events. It can be seen that two events occurred in the same year but in different seasons since an early earlywood (EE) event was followed by a late earlywood (LE) event in 1995. Table 2 also shows that some events were recorded entirely by abrupt growth suppression and others mainly by injuries. Moreover, it is interesting to note the relative rarity of injuries compared with abrupt growth changes. Most injuries were the result of only two events (1995b and 2005) and were attributed to EE (71%). The other injuries were related to LE (26%) and latewood (L) (3%). Figure 4 provides examples of injuries dated to different periods of the growing season. As for abrupt growth changes, suppression (73%) occurred much more often than release (27%). Nevertheless, abrupt growth increase was detected on numerous samples in 2005.

Debris-flow routing on the lower terraces

Analysis of the spatial distribution of disturbed trees resulted in the identification of six patterns of debris-flow routing, namely three in sector 1 and three in sector 2.

Flow patterns of debris flows in sector 1

Flow pattern A, illustrated with a debris-flow event dated to the EE of 1995, bursts out of the Illgraben channel at the dogleg formed at 890 m a.s.l. (Figure 5A). The event had an initial lateral spread of 20 m, which decreased with distance from the breakout location, and a total travel distance of 200 m. Flow pattern B, represented with a debris flow of 2002, shows two breakout locations (Figure 5B). The event apparently left the channel at the dogleg and flowed through the entire length of the terrace (350 m), but affected the northern part of the sector as well by overtopping the channel banks at about 870 m a.s.l. Flow pattern C, displayed in Figure 5C with a debris flow of 2005, is somewhat similar to flow pattern B. The difference is that the event ceased its course halfway through the terrace as in flow pattern A.

Flow patterns of debris flows in sector 2

Flow pattern D corresponds to a debris flow of 1997, which flowed through the current channel and affected the northern terraces of the sector (Figure 5D). Flow pattern E is illustrated with the debris flow of 2002 (Figure 5B), which either left the channel at about 860 m a.s.l. or took the direction of the abandoned channel and affected the southern terraces (Figure 5E). Flow pattern F, depicted in Figure 5F with the debris flow of 2005 (Figure 5C), can be described as a combination of the two preceding flow patterns. The event massively disturbed trees on both terraces over a distance of 200 m and 130 m respectively.

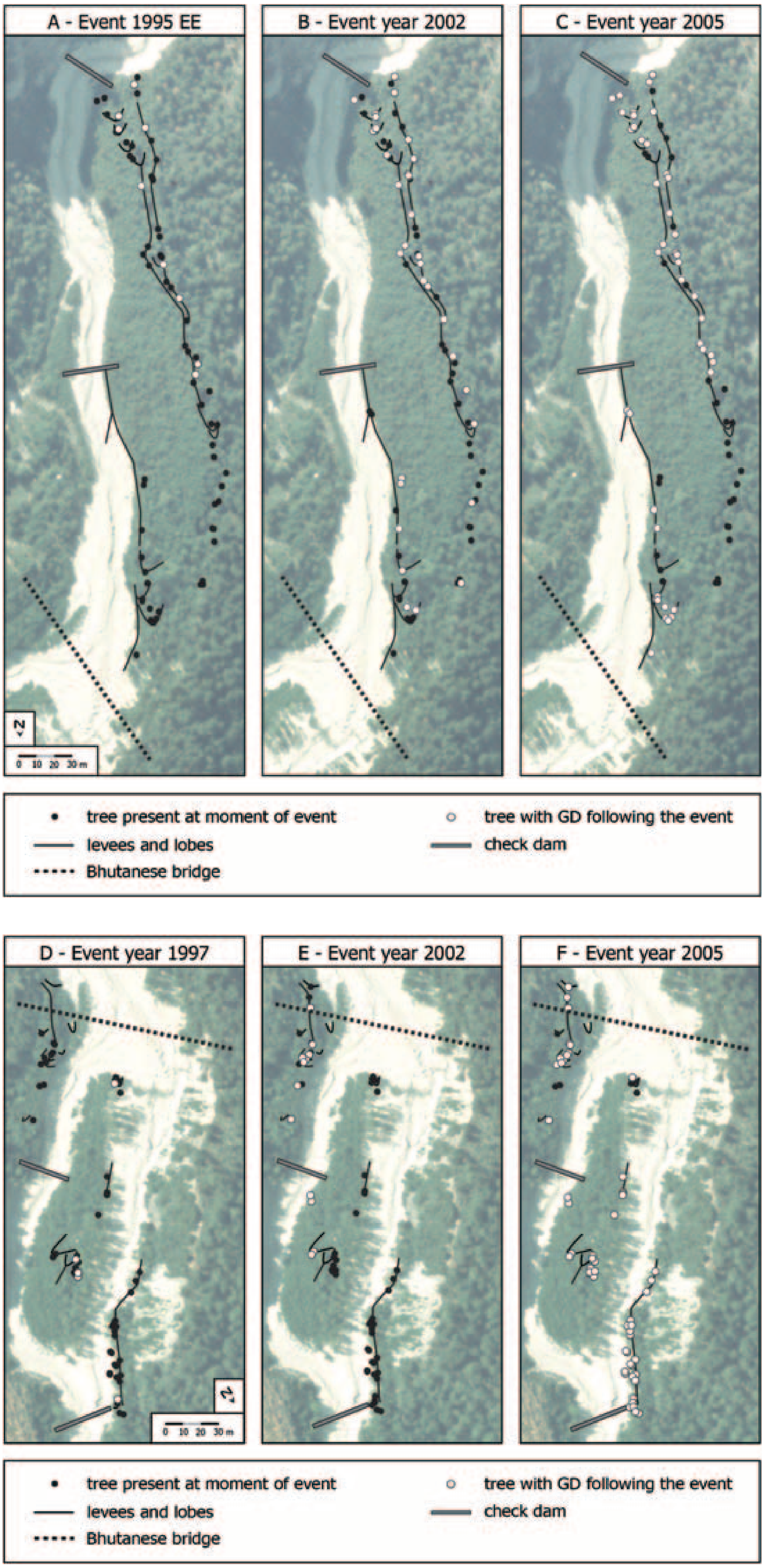

Figure 5. Location of trees showing growth disturbances (GD) in sector 1 during selected debris-flow events. The figure illustrates (A) flow pattern A; (B) flow pattern B; and (C) flow pattern C. For more explanations see text. Abbreviation: EE, early earlywood. (Aerial photograph: © 2009 swisstopo – BA091308.)
Location of trees showing growth disturbances (GD) in sector 2 during selected debris-flow events. The figure illustrates (D) flow pattern D; (E) flow pattern E; and (F) flow pattern F. For more explanations see text. (Aerial photograph: © 2009 swisstopo – BA091308.) This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table III. Debris-flow events for which dendrogeomorphic reconstruction and archival records coincide. The events of 1991, 1999 and 2002 could not be dated to the season since they were exclusively inferred from abrupt growth changes. Maximum, minimum and mean volumes are based on 24 debris-flow events recorded over the period AD 2000–2005

Event	Volume (m^3)	Event seasonality (Tree-ring data)	Source
12.07.1991	75,000–250,000	unknown	Geo7, 2000
21.08.1997	25,000–75,000	late summer (LE)	Geo7, 2000
16.08.1999	75,000–250,000	unknown	Geo7, 2000
10.08.2002	71,000	unknown	T&C and WSL, 2005
28.05.2005	140,000	late spring (EE)	C. Graf, pers. comm., 2008
Max. AD 2000–2005	140,000		
Min. AD 2000–2005	3,000		
Mean AD 2000–2005	32,667		

Discussion

The present study reports on 14 debris-flow events between AD 1965 and 2007. This is a minimum estimate as it only considers debris flows that actually left the channel. It is indeed frequent that intermediate debris flows, such as those registered in late June 2000 and mid-May 2003 (Geo7, 2000), are contained within the channel. It is also known that debris flows may have partly or entirely eliminated former forest stands. In addition, trees may have contained internally hidden scars that have not been identified in the field and that are consequently missing in the tree-ring reconstruction. However, despite possible limitations, we are confident that the reconstructed frequency includes a majority of debris-flow events that disturbed trees on the lower terraces over the period AD 1965–2007 because more than 90% of scars indeed remained visible on the stem surface. Furthermore, trees with thin and smooth bark such as gray alder (*Alnus incana* (L.) Moench) experience a slower wound healing than trees with thicker and rougher bark (Stoffel and Perret, 2006).

The 14 reconstructed debris-flow events were compared with archival records on debris-flow activity at Illgraben (Geo7, 2000; T&C and WSL, 2005). Table 3 displays the five events (1991, 1997, 1999, 2002, 2005) that show a match between tree-ring data and archival records. The other events (1965, 1969, 1973, 1981, 1982, 1988, 1995a, 1995b, 1998) dated from growth series of broad-leaved trees therefore complement archival records on debris-flow activity. Based on a dendrogeomorphic analysis of injuries, we know that the debris flow registered in the archival records in early October 1995 (Geo7, 2000) was preceded by two other events that occurred at different times during summer. Debris-flow events occur at Illgraben from early May to late October (Geo7, 2000; T&C and WSL, 2005), which encompasses the growing season of trees. Surges can thus be dated if they overtop the channel banks and disturb trees. Most events were identified in the trees via abrupt growth changes because of the fine-grained calcareous and dolomitic material that is generally transported by debris flows at Illgraben. The infliction of injuries is normally limited to surges transporting larger boulders.

The outbreak and extent of debris flows on the lower terraces partially depends on the channel capacity at the time of the events. The material deposited by former debris flows or landslides may have increased the elevation of the channel bed or blocked the channel at critical locations. This may explain how the events of 1997 and 2002, with relatively small volumes (≤75,000 m^3; Table 3), were able to leave the channel. We also infer that debris-flow velocity may influence debris-flow routing on the lower terraces. For instance, the event of 2005 burst out of the channel at the dogleg of sector 1 despite the relatively high elevation of the terrace at this location (Figure 2A). Moreover, the exceptionally large debris flow (~500,000 m^3) registered in early June 1961 (Hürlimann *et al.*, 2003) certainly left the channel at this location. This event could not be reconstructed from growth series of broad-leaved trees because the surge partly eliminated the former forest stand. The site was later recolonized by vegetation and currently corresponds to the concentration of older trees in the northern part of sector 1. Finally, we also think that certain check dams act as ramps that launch the rapidly flowing material to higher elevations. Debris-flow deposits were found on the lower terraces downstream of check dams in sectors 1 and 3.

Archival records on debris-flow activity show that debris flows are very common at Illgraben (Geo7, 2000; T&C and WSL, 2005), but only very rarely left the channel over the period AD 1965–2007 or during the last 200 years (Stoffel *et al.*, 2008a). Based on the observations of this study and on the mean volume of recorded events (Table 3), we estimate 50,000 m^3 to be the lower volume limit for debris flows to affect the lower terraces. The threshold for debris flows to reach the main fan surface is 250,000 m^3 (Graf *et al.*, 2007) and is in agreement with the findings of this study. However, factors other than volume may influence overbank flow on the lower terraces. This phenomenon appears to be more channel-dependent than volume-dependent since even small debris flows left the channel in 1997 and 2002. Besides channel capacity, we also find that debris-flow velocity may have helped surges overtop elevated channel banks.

Conclusion

Dendrogeomorphic analysis of tree samples allowed the reconstruction of 14 debris-flow events between AD 1965 and 2007. Moreover, analysis of the spatial distribution of disturbed trees contributed to the identification of six patterns of debris-flow routing. Preferential breakout locations of events could be determined and the travel distance and lateral spread of debris-flow surges could be assessed. Broad-leaved trees proved to be a valuable source of information on former events at Illgraben and should be more widely used in future tree-ring studies especially because they colonize riparian zones from which conifers are generally absent. Even though the young age of sampled trees limited the reconstruction, broad-leaved trees provided very detailed insights into recent debris-flow activity, channel evolution and debris-flow routing on the lower terraces. The results also suggest that dendrogeomorphic reconstruction of past debris-flow activity is more accurate if (i) analyses are performed on conifers as well as on broad-leaved trees and (ii) investigations are conducted on the main fan surface as well as on the lower terraces adjacent to the channel. The methods developed in this study can be readily transferred to other forested debris-flow fans colonized by broad-leaved trees.

Acknowledgments—The authors are grateful to the referees and editors for their insightful comments on the manuscript. They would like to thank Dr Oliver Hitz for his assistance in the field and in the laboratory. They acknowledge Christoph Graf from the Swiss Federal Research Institute WSL for valuable data on debris flows at Illgraben. They are also indebted to Service des Forêts et du Paysage (SFP) and the Service des Routes et des Cours d'Eau (SRCE), Canton of Valais, for financial support of this study as part of the RUFINE project.

References

Alestalo J. 1971. Dendrochronological interpretation of geomorphic processes. *Fennia* **105**: 1–139.

Astrade L, Bégin Y. 1997. Tree-ring response of *Populus tremula* L. and *Quercus robur* L. to recent spring floods of the Saône river, France. *Ecoscience* **4**: 232–239.

Badoux A, Graf C, Rhyner J, Kuntner R, McArdell BW. 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. *Natural Hazards* **49**: 517–539.

Baumann F, Kaiser KF. 1999. The Multetta debris fan, eastern Swiss Alps: a 500-year debris flow chronology. *Arctic, Antarctic, and Alpine Research* **31**: 128–134.

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

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

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

Decaulne A, Sæmundsson Þ. 2008. Dendrogeomorphology as a tool to unravel snow-avalanche activity: preliminary results from the Fnjóskadalur test site, Northern Iceland. *Norsk Geografisk Tidsskrift–Norwegian Journal of Geography* **62**: 55–65.

Escher A. 1988. Structure de la nappe du Grand Saint-Bernard entre le Val de Bagnes et les Mischabel. Service hydrologique et géologique national, Bern. Rapport géologique 7.

Fantucci R, McCord A. 1995. Reconstruction of landslide dynamic with dendrochronological methods. *Dendrochronologia* **13**: 43–58.

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

FOWG (Federal Office for Water and Geology). 1999. *Hydrological Atlas of Switzerland*. Federal Office for Water and Geology: Biel.

Geo7. 2000. Geomorphologische Analyse des Illgrabens. Unpublished technical report, Geo7: Bern.

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

Hupp CR, Osterkamp WR, Thornton JL. 1987. Dendrogeomorphic evidence and dating of recent debris flows on Mount Shasta, northern California. *US Geological Survey Professional Paper* **1396B**: 1–39.

Hürlimann M, Rickenmann D, Graf C. 2003. Field and monitoring data of debris-flow events in the Swiss Alps. *Canadian Geotechnical Journal* **40**: 161–175.

Jakob M, Hungr O. 2005. *Debris-flow Hazards and Related Phenomena*. Praxis, Springer: Berlin, Heidelberg, New York.

Kaczka RJ, Morin H. 2006. The dendrochronological records of debris flow activity in SE Quebec. *Proceedings TRACE 2006*, Tervuren, Belgium; **5**: 233–239.

McArdell BW, Bartelt P, Kowalski J. 2007. Field observations of basal forces and fluid pore pressure in a debris flow. *Geophysical Research Letters* **34**: L07406, doi:10.1029/2006GL029183.

Mundo IA, Barrera MD, Roig FA. 2007. Testing the utility of *Nothofagus pumilio* for dating a snow avalanche in Tierra del Fuego, Argentina. *Dendrochronologia* **25**: 19–28.

Raetzo H, Lateltin O, Bollinger D, Tripet JP. 2002. Hazard assessment in Switzerland – codes of practice for mass movements. *Bulletin of Engineering Geology and the Environment* **61**: 263–268.

Rickenmann D, Hürlimann M, Graf C, Näf D, Weber D. 2001. Murgang-Beobachtungsstationen in der Schweiz. *Wasser Energie Luft* **93**(1/2): 1–8.

Rinntech. 2009. http://www.rinntech.com/content/blogcategory/2/28/lang,english/ (site accessed 1 July 2009).

Schlunegger F, Badoux A, McArdell BW, Gwerder C, Schnydrig D, Rieke-Zapp D, Molnar P. 2009. Limits of sediment transfer in an alpine debris-flow catchment, Illgraben, Switzerland. *Quaternary Science Reviews* **28**: 1097–1105, doi:10.1016/j.quascirev.2008.10.025.

Schweingruber FH. 2001. *Dendroökologische Holzanatomie. Anatomische Grundlagen der Dendrochronologie*. Haupt: Bern, Stuttgart, Wien.

Stefanini MC. 2004. Spatio-temporal analysis of a complex landslide in the Northern Apennines (Italy) by means of dendrochronology. *Geomorphology* **63**: 191–202.

St. George S, Nielsen E. 2003. Paleoflood records for the Red River, Manitoba, Canada, derived from anatomical tree-ring signatures. *Holocene* **13**: 547–555.

Stoffel M, Perret S. 2006. Reconstructing past rockfall activity with tree rings: some methodological considerations. *Dendrochronologia* **24**(1): 1–15.

Stoffel M, Bollschweiler M. 2008. Tree-ring analysis in natural hazards research – an overview. *Natural Hazards and Earth System Sciences* **8**: 187–202.

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

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

Stoffel M, Bollschweiler M, Leutwiler A, Aeby P. 2008a. Tree-ring reconstruction of debris-flow events leading to overbank sedimentation on the Illgraben cone (Valais Alps, Switzerland). The Open Geology Journal **2**: 36–47.

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

Strunk H. 1991. Frequency distribution of debris flows in the Alps since the Little Ice Age. *Zeitschrift für Geomorphologie* **83**: 71–81.

Szymczak S, Bollschweiler M, Stoffel M, Dikau R. in press. Debris-flow activity and snow avalanches in a steep catchment of the Valais Alps (Switzerland): dendrogeomorphic reconstruction and identification of triggering rainfall events. *Geomorphology*. doi: 10.1016/j.geomorph.2009.10.012.

T&C, WSL (Swiss Federal Institute for Forest, Snow and Landscape Research). 2005. *Technischer Bericht Notfallkonzept Illgraben. PROGE Notfallkonzept Illgraben*. T&C and WSL: Visp, Birmensdorf.

Yanosky TM. 1983. Evidence of floods on the Potomac River from anatomical abnormalities in the wood of flood-plain trees. *US Geological Survey Professional Paper* **1296**: 1–42.

