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Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating

Markus Stoffel [a,b,*], David R. Butler [c], Christophe Corona [a,d]

[a] University of Berne, Institute of Geological Sciences, Laboratory of Dendrogeomorphology, Baltzerstrasse 1 + 3, CH-3012 Berne, Switzerland
[b] University of Geneva, Institute for Environmental Sciences, Climatic Change and Climate Impacts, 7 chemin de Drize, CH-1227 Carouge, Switzerland
[c] Texas State University — San Marcos, Department of Geography, 601 University Drive, San Marcos ,TX 78666, USA
[d] Centre National de Recherche Scientifique (CNRS) UMR6042 Geolab, 4 rue Ledru, F-63057 Clermont-Ferrand Cedex, France

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ABSTRACT

Trees affected by mass movements record the evidence of geomorphic disturbance in the growth-ring series, and thereby provide a precise geochronological tool for the reconstruction of past activity of mass movement. The identification of past activity of processes was typically based on the presence of growth anomalies in affected trees and focused on the presence of scars, tilted or buried trunks, as well as on apex decapitation. For the analyses and interpretation of disturbances in tree-ring records, in contrast, clear guidelines have not been established, with largely differing or no thresholds used to distinguish signal from noise. At the same time, processes with a large spatial footprint (e.g., snow avalanches, landslides, or floods) will likely leave growth anomalies in a large number of trees, whereas a falling rock would only cause scars in one or a few trees along its trajectory.

Based on the above considerations, we examine issues relating to the interpretation and dendrogeomorphic dating of mass movements. Particular attention is drawn to sampling in terms of sample distribution across a study site, the actual selection of trees as well as to sample size (i.e., number of trees sampled). Based on case studies from snow avalanche, debris flow, and landslide sites, we demonstrate that thresholds can indeed improve dating quality and, at the same time, minimize noise in time series. We also conclude that different thresholds need to be used for different processes and different periods of the reconstruction, especially for the early stages of the reconstruction when the number of potentially responding trees will be much smaller. This paper seeks to set standards for dendrogeomorphic fieldwork, analysis, and interpretation for different processes of mass movements.

1. Introduction

Trees affected by mass movements record the evidence of geomorphic disturbance in the growth-ring series (Alestalo, 1971; Stoffel et al., 2010a). As a result, they potentially provide a precise geochronological tool for the reconstruction of the activity of past mass movements and, thus, have been used widely to reconstruct time series of various types of geomorphic (e.g., McAuliffe et al., 2006; Stoffel et al., 2008a,b, 2012; Bollschweiler et al., 2009; Lopez Saez et al., 2012a; Osterkamp et al., 2012), hydrological (St. George and Nielsen, 2002; Ballesteros et al., 2011a,b; Stoffel and Wilford, 2012), and geological (Jacoby et al., 1988; Stoffel et al., 2005a; Salzer and Hughes, 2007; Baillie, 2008; Bekker, 2010; Corona et al., in press—a) processes. The identification of past processes typically was based on the presence of growth anomalies in affected trees and, thereby, focused on the presence of scars, tilted or buried trunks, as well as on apex decapitation.

Trees record mechanical disturbance (i.e., impact, loading, burial or erosion; see Stoffel and Bollschweiler (2008) and references therein for details) to the year and even to the season under ideal circumstances (Bollschweiler et al., 2008a; Schneuwly and Stoffel, 2008a,b; Stoffel et al., 2008a; Schneuwly et al., 2009a,b), but typically fail to provide information on the nature of the process that caused the disturbance. Exceptionally, the nature of the mass movement can be reconstructed from the growth-ring record of affected trees based on the timing of the reaction. This is the case for snow avalanches occurring before the tree starts to form a new increment ring (with a reaction at the boundary of two rings) and high elevation debris flows in summer (i.e., somewhere between the earlywood and the latewood of the growth ring; Stoffel et al., 2006a). In addition, a distinction of processes can also be based on a wood-anatomical analysis of reactions induced by processes occurring at the same time of the year (e.g., rockfall and snow avalanches; Stoffel and Hitz, 2008). In any case, however, trees should only be sampled after careful evaluation of the study site

* Corresponding author at: University of Berne, Institute of Geological Sciences, Laboratory of Dendrogeomorphology, Baltzerstrasse 1 + 3, CH-3012 Berne, Switzerland. Tel.: +41 31 631 87 73; fax: +41 31 631 43 41.
E-mail address: markus.stoffel@dendrolab.ch (M. Stoffel).

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and a detailed comprehension of processes occurring at the site under investigation.

Another critical issue in dendrogeomorphic investigations has been the interpretation of signals in the tree-ring record, for which clear guidance and guidelines have yet to be established. As a result, largely differing thresholds have been used in the past to distinguish signal from noise. Some studies have dated mass movement based on a single growth disturbance (GD) in just one tree, whereas other authors only added events to their reconstructed time series as soon as 40% of all trees sampled showed reactions in a specific year (Butler et al., 1987; Butler and Sawyer, 2008). As a consequence, these differences in thresholds have given rise to repeated and contentious discussions on the value, accuracy and completeness of dendrogeomorphic dating and, therefore, call for the definition of more objective standards and guidelines.

At the same time, evidence left in trunks, as well as the nature and extent of damage in trees, will ultimately be dictated by the nature of the mass movement itself (Stoffel and Perret, 2006; Stoffel et al., 2010a), implying that different thresholds should be defined for different types of mass movements. For processes with a large spatial footprint (such as landslides, floods, or snow avalanches), GD will likely be visible in a large number of trees; whereas an individual rockfall would only leave scars in one or a few trees along the fall line of the rock (Stoffel and Perret, 2006).

Based on the above considerations, this paper aims at (i) providing guidelines for the selection and dendrogeomorphic sampling of trees in the field and at (ii) examining issues relating to the interpretation and dating of mass movements based on information contained in growth-ring records. Particular attention is drawn to sampling in terms of the distribution of sampled trees across the study site, the actual selection of trees in the field as well as to sample size (i.e., number of trees sampled). Based on selected examples from snow avalanche, debris flow, and landslide sites in the European Alps, we demonstrate that the definition of thresholds is indeed needed to improve the quality of dating and to reduce faulty dating (noise) of events. In addition, we illustrate that different thresholds have to be defined for different types of mass movements and for different periods covered by the reconstruction, especially for the early (i.e., the oldest) stages of the time series for which the number of potentially responding trees will be much smaller than for the recent past. This paper, thus, seeks to establish a coherent set of standards for dendrogeomorphic fieldwork, analysis, and interpretation for different types of mass movement processes.

2. How and where to sample trees in the field

A careful dendrogeomorphic study typically starts with a detailed assessment and delineation of mass movement processes and anthropogenic activities in the field. This work should also involve analysis of diachronic time series of aerial photographs or satellite imagery. The initial assessment should then be complemented with a detailed geomorphic reconnaissance in the field and the mapping of geomorphic features and deposits at a scale appropriate for the purpose of the study. In the case of landslides, debris flows, lahars, and other torrential processes, mapping should be done at the finest scale possible (e.g., 1:1000), whereas a coarser scale and the identification of deposition or flooding areas might be sufficient for the analysis of snow avalanches, rockfall activity, or floods.

Best results are usually obtained when complex sectors of the study site, with geomorphic forms shaped by different mass movement processes, are excluded from analysis, as the nature of the damage normally will not allow identification of the causative process (Stoffel et al., 2006a; Stoffel and Hitz, 2008). The same holds true for doubtful damage (e.g., trees located close to roads or walking paths, possible influence of felling activity, scars induced by ungulate browsing) that should be excluded from analysis, as they tend to add noise to the reconstruction.

For those areas of the study site for which anomalies in tree morphology can be unambiguously attributed to the mass movement process under investigation, we would like to address some possible limitations and drawbacks of trees as recorders of past process activity to develop a series of criteria and guidelines for the best possible sampling in the field.

Trees with visible growth defects, be it in the morphology or in the form of visible scars, will tend to provide data on the more recent past, but not necessarily inform the researcher about the activity of mass movement in former times and, thereby, lead to an overestimation of the more recent activity. This is especially true for scars in conifers with ample and peeling bark, such as is the case of *Larix*, *Picea*, or *Pinus*, where damage has been demonstrated to be blurred fully after just a few decades (Stoffel and Perret, 2006).

Older trees, on the other hand, will produce decreasing ring widths with increasing tree age (as they have to allocate their resources to a steadily growing stem and branch surface) and thereby become less suitable and less sensitive recorders of mass movements, especially of events that occurred in the recent past. These trees will likely underestimate recent activity but will still represent excellent candidates for the reconstructions of events farther back in time (Stoffel and Beniston, 2006; Corona et al., in press—b).

Broadleaved trees do not normally live as long as conifers and, therefore, tend to be of limited help in the reconstruction of long time series. At the same time, however, they will be excellent recorders of recent activity (Arbellay et al., 2010b, 2012a,b; Moya et al., 2010; Ballesteros et al., 2011a,b), as many broadleaved species are characterized by relatively thin and smooth bark structures that will tend to record impacts of larger and smaller (or less energetic) events (Trappmann and Stoffel, 2013).

Based on the above considerations, we call for a balanced sampling of older and younger trees as well as for a mixture of conifer and broadleaved species. Trees selected for analysis should be distributed evenly across the study site and sampled in a systematic way. No preference should be given to trees with visible growth defects, but rather samples should be obtained (i) along vertical and/or horizontal transects on snow avalanche, landslide or rockfall sites or (ii) within a distance from the channel (defined by process at the site); and (iii) at specific radial distances from fan and cone apices (Schneuwly-Bollschweiler et al., in review) in the case of torrential and fluvial processes (e.g., floods, debris floods, debris flows, or lahars). The distance between each sampled tree, along the transect or between transects, will again be dictated by the nature of the process; detailed examples are provided in Section 4.

3. Features typically used to date past mass movements

Dendrogeomorphic investigations of mass movement processes typically focus on the occurrence of a limited number of specific GD in tree-ring records to date the occurrence of past events (see Stoffel and Corona (in review) for a detailed overview on tree reactions).

Among the GD used for the reconstruction of mass movement processes, scars (injuries; see Fig. 1A) are certainly one of the most frequently used indicators to infer mass movement. In addition to being the clearest evidence of past impacts, scars have also been demonstrated to allow annual dating and up to monthly resolution (e.g., Stoffel et al., 2005b, 2008a,b, 2011; Arbellay et al., 2010a; Schneuwly-Bollschweiler and Stoffel, 2012).

Certain conifer species — among others, the genus fir *(Abies)*, larch *(Larix)*, spruce *(Picea)*, and Douglas-fir (*Pseudotsuga*; Bannan, 1936; Stoffel, 2008), but not pine (*Pinus*; Ballesteros et al., 2010a) — will produce resin and associated tangential rows of traumatic resin ducts (TRD; Fig. 1B) around scars (Stoffel, 2008; Schneuwly et al., 2009a, b) so as to protect the unaffected wood from attacks by wood-decaying pathogens. The presence of TRD has, thus, been considered a valuable indicator for the dating of mechanical damage — even in the absence of visible wounds.

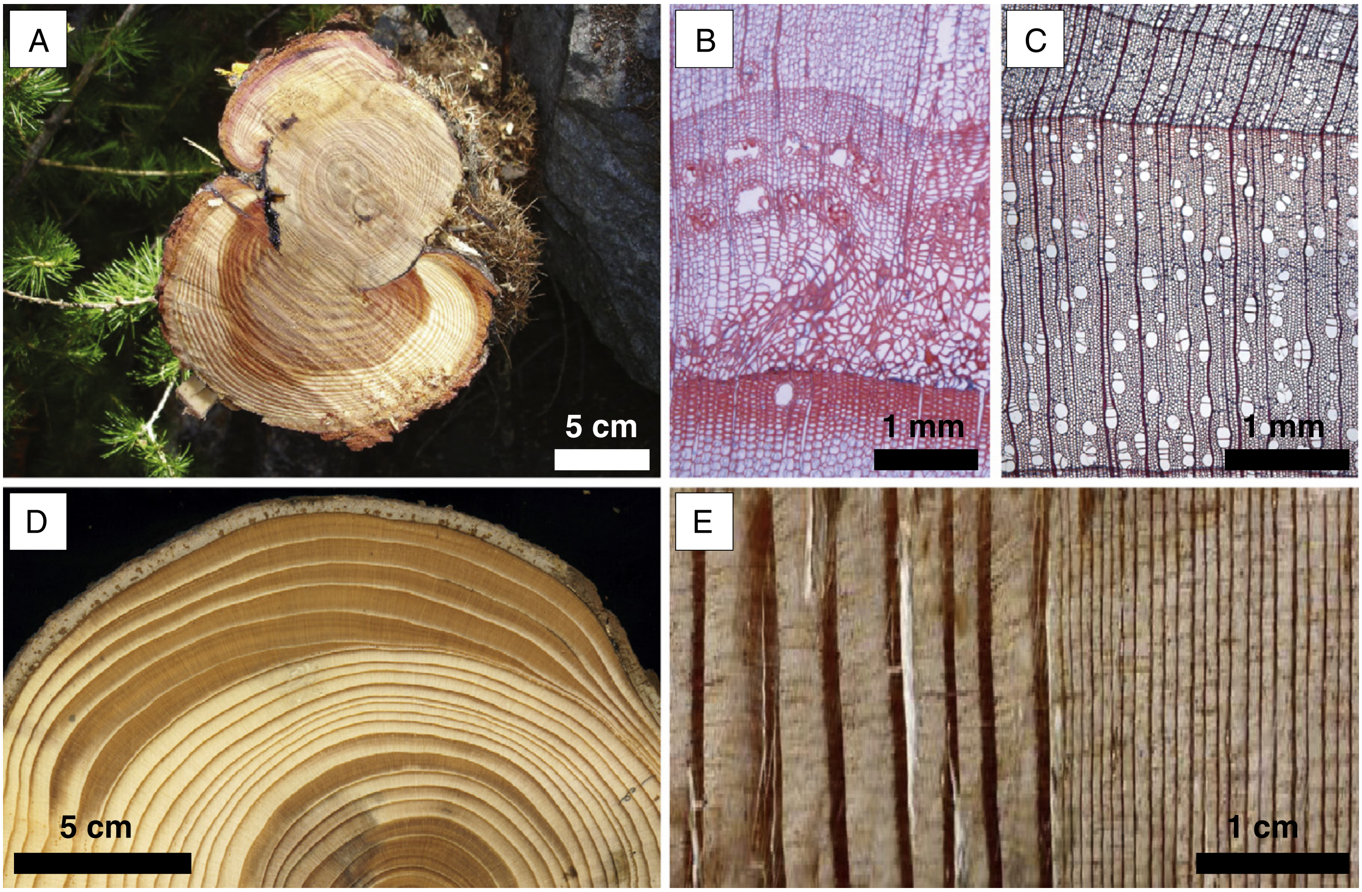

Fig. 1. Characteristic growth reactions in trees after mass movement disturbance: (A) callus pad overgrowing injuries in larch (*Larix decidua*); (B) callus tissue and tangential rows of traumatic resin ducts (TRD) around damage in *L. decidua*; (C) sudden decrease in vessel lumina in birch (*Betula pendula*) after scar infliction; (D) reaction wood formed from tree tilting in spruce (*Picea abies*); and (E) immediate and intense decrease in increment of *L. decidua* after apex decapitation, important loss of branch mass, burial, or root exposure.

In broadleaved trees, scars have typically been dated on cross-sections or wedges, but much less frequently on increment cores extracted at the contact of the callus pad with the intact wood. The sampling of partial or complete cross-sections is destructive and, thus, not necessarily justified. Identification of anatomical evidence (i.e., sharply decreased vessel lumina; Fig. 1C) has considerable potential and might be preferable in many cases (Arbellay et al., 2010a, 2012a,b, in press; Ballesteros et al., 2010b), but also rather time consuming.

The presence of reaction wood (Fig. 1D) is another valuable indicator of past mass movement and is related to the ability of a tree to regain a vertical position after tilting (Timell, 1986; Mattheck, 1993). The presence of reaction wood (i.e., compression wood, in the case of conifers, and tension wood, in the case of broadleaved trees) has been used repeatedly in the past to date past landslides (Braam et al., 1987; Fantucci and Sorriso-Valvo, 1999; Lopez Saez et al., 2012a; Savi et al., in press), but was also used in dating snow avalanches (Butler, 1979a, b; Butler and Malanson, 1985; Butler and Sawyer, 2008; Butler et al., 2010, and references therein; Corona et al., 2010, 2012). Special attention needs to be paid to the influence of snow pressure on steep slopes, which can mimic strong disturbance events and cause the same reactions in trees as would landslides, snow avalanches, or debris flows.

Abrupt reductions in yearly increment are characteristic for trees that have suffered from apex decapitation, branch removal, and/or root erosion of trunk burial as a result of the location of mass movement activity (Fig. 1E; Stoffel and Bollschweiler, 2008). Growth releases, in contrast, can sometimes be found in survivor trees that benefit from the elimination of neighbors during rare avalanches or unusual rockfalls (Stoffel et al., 2005a). The formation of a series of larger increment rings will, however, typically occur with some delay and only as soon as surviving vegetation can take full benefit of the excess availability of water, nutrients, and light (Stoffel and Bollschweiler, 2008). Growth increases have also been reported to occur on sites where deposited material consists of nutrient-rich dolomitic and/or calcareous material (Mayer et al., 2010; Procter et al., 2012), thereby possibly blurring the negative effect of the impacts of mass movement. An inclusion of growth releases is critical in managed stands where forestry actions (such as clearcuts) will leave similar reactions and, therefore, lead to misleading results.

4. Sampling and dating mass movement activity: sample size and dating criteria

In the following, the influence of field sampling (in terms of sample size and reactions) on event reconstruction is presented with three cases illustrating three of the more (if not most) common mass movements in mountainous environments. The example on snow avalanches is from an unusually well-documented path where archival records can be used to check accuracy and completeness of dendrogeomorphic approaches. At the debris flow site, archival records are fragmentary; but ample event data exists for neighboring catchments so that results obtained with an expert's approach can be validated with existing time series as well. In the case of the landslide study, in contrast, analyses had to be based on extensive field investigations and a large number of tree samples as data on past landslides did not exist at all. The overall goal of the study, however, remains the same for all cases: namely the definition of optimal field approaches in terms of sample size as well as specifying minimum quantitative thresholds in terms of reactions (or growth disturbances, GD) and relative amount of responding trees (index value *It*; i.e., the ratio between responding and sampled trees).

Table 1
Overview of past dendrogeomorphic studies of snow avalanche processes and approaches (thresholds) used.

Author and year	Country	Localization	Number of paths	Species	Sample size	Period	Nb of growth disturbances	Minimal Index value	Number of avalanche events
Potter (1969)	USA	Wyoming	5	*Abies lasiocarpa, Pinus albicaulis*	50	1963	50	Not computed	1
Schaerer (1972)	Canada	British Columbia	Not provided	Not provided	Not provided	Not provided	Not provided	Not computed	Unknown
Smith (1973)	USA	Washington	13	Not provided	Not provided	Not provided	Not provided	Not computed	Unknown
Ives et al. (1976)	USA	Colorado	Not provided	*Populus tremuloides, Picea engelmannii*	Not provided	1860–1974	56	Not computed	6
Carrara (1979)	USA	Colorado	1	*Populus tremuloides, Picea engelmannii, Abies lasiocarpa*	50	1880–1976	Not provided	Not computed	4
Butler (1979a)	USA	Montana	Not provided	Not provided	Not provided	Not provided	Not provided	Not provided	Not provided
Butler and Malanson (1985)	USA	Montana	2	*Picea engelmannii, Abies lasiocarpa, Pseudotsuga menziesii, Larix occidentalis, Pinus contorta*	30 + 48	1924–1979 1934–1981	Not provided	40%	10 + 15
Bryant et al. (1989)	USA	Colorado	3	*Populus tremuloides, Picea engelmannii*	60 + 60 + 60	Not provided	Not provided	Not provided	Unknown
Rayback (1998)	USA	Colorado	2	*Abies lasiocarpa, Picea engelmannii*	63	1838–1996	Not provided	Not computed	30
Larocque et al. (2001)	Canada	Québec	1	*Picea glauca, Picea mariana, Abies balsamea, Larix laricina*	111	1885–2000	Not provided	10%	3
Hebertson and Jenkins (2003)	USA	Utah	16	*Picea engelmannii, Abies lasiocarpa*	297 (8–26)	1928–1996	Not provided	Not provided	14
Boucher et al. (2003)	Canada	Québec	1	*Abies balsamea, Picea mariana*	62	1895–1996	Not provided	10%	35
Jenkins and Hebertson (2004)	USA	Utah	1	*Picea engelmannii, Abies concolor, Populus tremuloides*	78	1891–1995	Not provided	Not provided	13
Dubé et al. (2004)	Canada	Québec	3	*Thuya occidentalis, Abies balsamea, Betula papyrifera.*	62 + 20 + 28	1871–1996	Not provided	10%	7
Muntán et al. (2004)	Spain	Pyrenees	1	*Pinus uncinata*	230	1750–2000	Not provided	Not provided	3
Kajimoto et al. (2004)	Japan		1	*Abies mariesii*	34	Not provided	Not provided	Not computed	Not computed
Germain et al. (2005)	Canada	Québec	2	Not provided	78 + 52	1941–2004	420	Not provided	11
Pederson et al. (2006)	USA	Montana	1	*Pseudotsuga menziesii*	109	1910–2003	Not provided	10%	27
Stoffel et al. (2006a)	Switzerland	Alps	1	*Larix decidua*	251	1750–2002	561	Not computed	9
Casteller et al. (2007)	Switzerland	Alps	2	*Larix decidua, Picea abies*	66 + 79	Not provided	Not provided	Not computed	Not computed
Mundo et al. (2007)	Argentina	Andes	1	*Nothofagus pumilio*	20	Not provided	Not provided	Not computed	Not computed
Butler and Sawyer (2008)	USA	Colorado	2	*Abies lasiocarpa, Pseudotsuga menziesii, Pinus contorta*	10 + 12	1945–2008 1963–2008	Not provided	20%, 40%	15 + 9
Reardon et al. (2008)	USA	Montana	1	*Pseudotsuga menziesii*	109	1910–2003	Not provided	10%	27
Germain et al. (2009)	Canada	Québec	12	Not provided	10–243	1895–1999	51–799	10%	19
Laxton and Smith (2008)	India	Himalaya	1	*Cedrus deodara*	36	1972–2006	Not provided	Not computed	4
Casteller et al. (2008)	Argentina	Andes	1	*Nothofagus pumilio*	50	Not provided	Not provided	Not computed	6
Muntán et al. (2009)	Spain	Pyrenees	6	*Pinus uncinata*	26–131	1870–2000	Not provided	16–40%	3
Corona et al. (2010)	France	Alps	1	*Larix decidua*	232	1919–1994	901	10	20
Köse et al. (2010)	Turkey	Kayaarka	2	*Abies bornmuelleriana*	61	Not provided	Not provided	Not computed	Not computed
Casteller et al. (2011)	Argentina	Andes	9	*Nothofagus pumilio*	6–15	1820–2005	Not provided	Not computed	6
Corona et al. (2012)	France	Alps	1	*Larix decidua, Picea abies*	209	1771–2010	645	Variable	34
Corona et al. (in press—b)	France	Alps	1	*Larix decidua*	163	1338–2010	514	5%	38

4.1. Reconstruction of snow avalanches

4.1.1. Introductory remarks

Pioneering dendrogeomorphic work on snow avalanches dates back to the late 1960s when Potter (1969) and Schaerer (1972) developed the first reconstructed time series of snow avalanches for sites in North America (see Table 1, and Butler and Sawyer (2008) for a recent review). Tree-ring based analyses of snow avalanches were unusual in Europe before the early 2000s but have become fairly popular ever since in the Alps (Stoffel et al., 2006a; Casteller et al., 2007; Corona et al., 2010, 2012, in press—b) and the Pyrenees (Muntán et al., 2009).

The pioneering studies of snow avalanches, however, suffered from lack of agreement concerning (i) minimum sample size (i.e., sample size), as well as (ii) intensity and (iii) minimum number of GD needed for a past avalanche event to be dated as such (e.g., Butler et al., 1987; Butler and Sawyer, 2008; Germain et al., 2009). In previous work, sample size varied from 10 (Butler and Sawyer, 2008) to several hundreds of trees (Stoffel et al., 2006a,b; Corona et al., 2010). In addition, different empirical rating systems have been proposed and improved over the past decade (Dubé et al., 2004; Reardon et al., 2008; Corona et al., 2010), but the question on how to accurately and unambiguously define an event from tree rings remained under debate. Several authors have used quantitative approaches based on the proportion of disturbed vs. existing trees (index number) to date events to a given year (Butler and Sawyer, 2008), with thresholds used ranging from 10% (e.g., Dubé et al., 2004) to 40% (e.g., Butler and Malanson, 1985). Similar approaches were used by Germain et al. (2005), Pederson et al. (2006), or Reardon et al. (2008), which in addition added a minimal number of trees showing GD in a specific year (generally 10) to render dating more accurate. Corona et al. (2012) stressed the importance of such thresholds but also added that GD would typically vary in their expression (i.e., in terms of duration, radial encompassment, and degree of development), and, thus, suggested the use of graduated classes of reactions to facilitate discrimination of features clearly associated with snow avalanches against disturbances induced by other factors such as snow pressure or wind. Conversely, Stoffel et al. (2006a) used a qualitative approach where the nature and spatial distribution of trees with GD was analyzed visually to determine past snow avalanche events.

4.1.2. Case study site

The avalanche site selected for analysis is the N-facing slope of the Arve valley (French Alps; Haute-Savoie, 45°54′ N., 6°51′ E., Fig. 2), where the Pèlerins path extends from 1100 to 3650 m asl. The avalanche path dominates the hamlet of Les Pèlerins, located 2 km SW of downtown Chamonix. Snow avalanches tend to be triggered naturally from a starting zone (50 ha) located between 2750 and 3650 m asl (mean slope angle: 36°). The runout zone (15 ha) is found at 1350 m asl. A characteristic transverse vegetation pattern (Butler and Malanson, 1984) can be observed across the track: the inner zone is colonized by dense shrubs and shade-intolerant pioneer tree species with flexible stems, such as green alder (*Alnus viridis* (Chaix) DC), European rowan (*Sorbus aucuparia* L.), and silver birch (*Betula pendula* Roth.). In the outer zone, European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.) are dominant. A vast majority of trees around the track and within the runout zone exhibit clear signs of disturbance from multiple avalanches. The Pèlerins avalanche path threatens the hamlet of Les Pèlerins and the first section of the Aiguille du Midi cable car (Les Pèlerins-La Para) which was constructed for the first Winter Olympics in 1924. In addition, the access road to the Mont Blanc Tunnel crosses the runout zone several times below 1275 m asl. This tunnel is a major north–south connection for Europe, and two million vehicles have been counted on this road per year, of which 33% are trucks (Deline, 2009). As a result of the intense and multipurpose use of the area, abundant and continuous historical records are available for the Pèlerins avalanche path.

Several documentary sources were used in this study to compile a precise and as complete as possible historical chronology of avalanches in the Pèlerins path. Most of the recent data were extracted from the "*Enquête Permanente des Avalanches*" (EPA), a chronicle describing the history of avalanches for ~5000 recognized paths in the French Alps and the Pyrenees (Eckert et al., 2009). These EPA records are usually complemented with a map localizing release zones, lateral extent, runout elevations, and type of snow avalanches (Jamard et al., 2002). As a result of the potential threat to infrastructure, the Pèlerins path has received considerable attention in the past; and activity has been documented continuously and with unusual accuracy since the beginning of the twentieth century. In addition, technical reports (Lagotala, 1927; ETNA, 2000; Leone, 2006), aerial photographs, and terrestrial photographs were used to assess the extent of high magnitude events. Data on pre-twentieth century events were derived from diaries, paintings and municipal archives (Lambert, 2009). Particularly, events of the period 1779–1802, 1830–1850, and 1860–1881 were derived from diaries (Cachat, 2000; Chaubet, 2011). The historical archives used in this approach yield data on 48 events since A.D. 1776, with a large majority

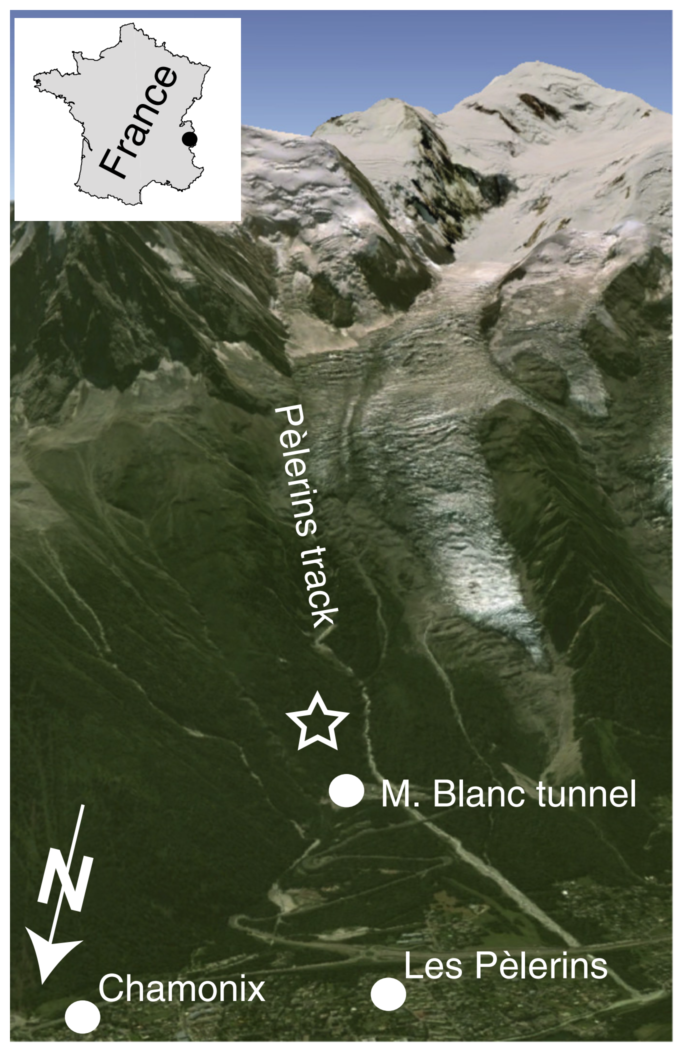

Fig. 2. The Pèlerins avalanche of the Arve valley (French Alps; Haute-Savoie, 45°54′ N., 6°51′ E.) extends from 1100 to 3650 m asl. The path (indicated with a star) dominates the hamlet of Les Pèlerins and crosses the access road to the Mont Blanc tunnel several times below 1275 m asl. Snow avalanches are triggered naturally from a starting zone (50 ha) located between 2750 and 3650 m asl (mean slope angle: 36°). (Image:Google Earth)

of events (37) recorded during the twentieth century (Corona et al., 2012).

4.1.3. Recommended sample size and dating criteria

Based on the analysis of 452 increment cores, a total of 645 GD relating to past snow avalanches could be identified in the 209 *P. abies* trees selected for analysis. The oldest GD in the tree-ring series was dated to 1745, but reactions become clearly more frequent after 1770, and GD occur in most years ever since.

Computation of tree-ring-based avalanche chronologies was performed for subsets of the tree sample using sample sizes varying from 10 to 200 trees and GD (*It*) thresholds ranging from 2 (1%) to 10 (50%). The matrix, presented in Fig. 3, shows the resulting mean percentage of known events (i.e., archival records) identified in the records of 100 trees. It also illustrates the average number of events reconstructed from the tree-ring series but absent in the historical record. Each figure presented is based on 1000 sampling iterations. By way of example, the median percentage of events reconstructed in the tree-ring record is 41% for the Pèlerins site, and the cutoffs for the minimum number of responding trees are GD≥7 and It≥7% to avoid noise in the reconstruction. If analysis is based on 200 trees (data not shown here), the percentage of reconstructed events does not improve (41%), not even with an optimal number of GD≥9 and *It*≥4.5%.

Data from the Pèlerins site, thus, demonstrate quite clearly that the reconstruction of known events (i.e., avalanches noted in the EPA) can be improved when sample is increased to up to 100 trees, but that the relative amount of events reconstructed from tree-ring records would remain fairly stable above this threshold. We, therefore, agree with Butler et al. (1987) that discrete processes such as snow avalanches are more accurately reconstructed with larger sample sizes, and that a plateau apparently exists above ~100 trees. The probable existence of such an upper limit may be helpful for the design of sampling campaigns at new sites and can assist in a more accurate planning of fieldwork, in terms of time and budget. Furthermore, and based on findings from Corona et al. (2012), we strongly recommend the use of the variable *It* and GD thresholds, which would need to be adjusted to changes in sample size so as to capture a maximum of past snow avalanches without introducing noise.

4.2. Reconstruction of debris flows

4.2.1. Introductory remarks

The earliest works using tree rings to reconstruct debris flows were conducted on Mount Shasta (California, USA; Hupp, 1984; Hupp et al., 1987) and in the Italian Alps (Strunk, 1991, 1997). A large number of studies have since been performed, primarily in the European Alps and Carpathians (see Table 2 for an overview of debris flow studies). Because debris flows generally affect more limited areas than snow avalanches, landslides, or floods, they cannot, therefore, be reconstructed with the same thresholds and sample sizes. As debris flows also tend to leave channels in only one or a few sectors of the depositional area, they will not necessarily leave a large spatial footprint in the tree-ring record (Lugon and Stoffel, 2010; Stoffel, 2010). As a consequence, past reconstructions of debris flows were, therefore, repeatedly based on comparably large numbers of samples, i.e., several hundred to several thousand increment cores per fan or cone (Table 2). Quantitative thresholds have not been applied systematically, nor have spatial patterns of affected trees been used as a criterion for the definition and reconstruction of past debris flows. To date, only two published studies (Bollschweiler and Stoffel, 2010a; Mayer et al., 2010) have been based on quantitative thresholds (using *It* values of 2.3 and 4.8%,

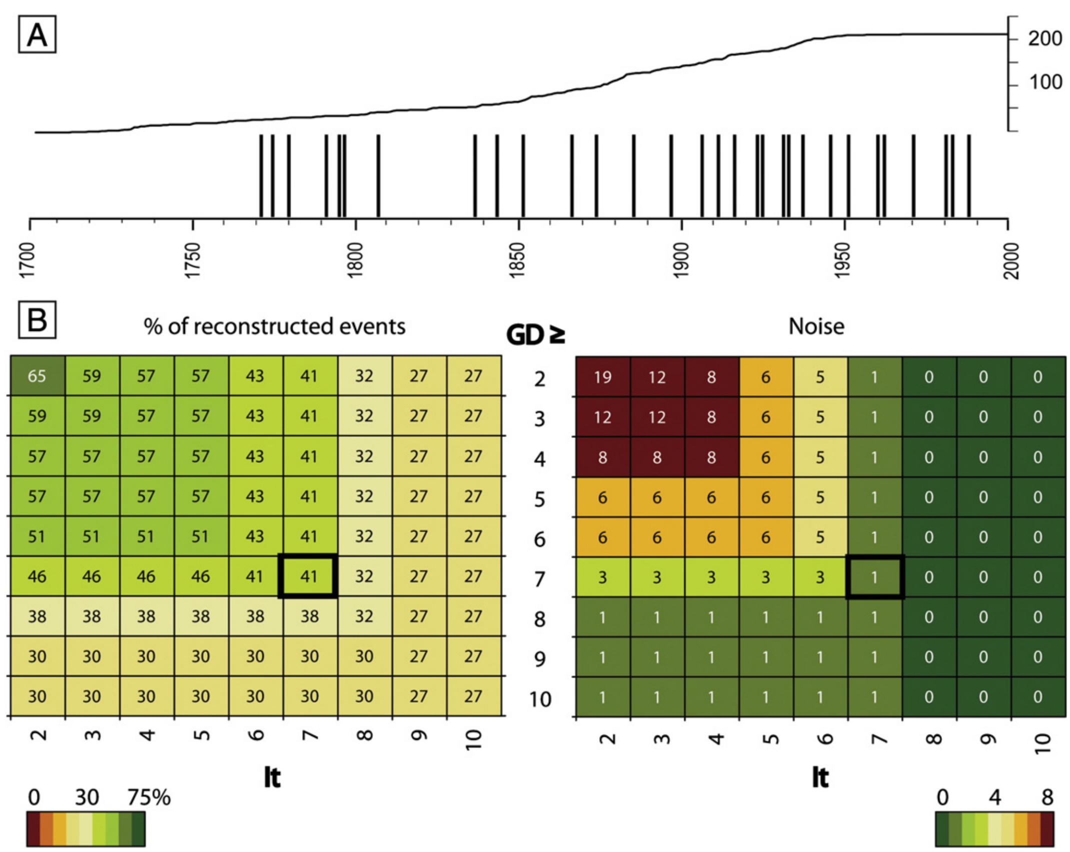

Fig. 3. (A) Avalanche chronology based on an unusually dense archival coverage and 452 growth-ring records from 209 *P. abies* trees, containing 48 events since A.D. 1776. (B) Bootstrap random extraction of subsets of the tree-ring samples (1000 iterations each) and mean percentage of known (archival) avalanches correctly identified in the tree-ring record of 100 trees (left). The second matrix (right) gives the number of events observed in the tree-ring records but absent in the archives. By way of example, the median percentage of events reconstructed in the tree-ring record is 41% for the Pèlerins site if cutoffs for the minimum number of responding trees are GD≥7 and *It*≥7% (left) and noise (right).

Table 2
Overview of past dendrogeomorphic studies of debris-flow processes and approaches (thresholds) used.

Author and year	Localization	Country	Number of torrents	Species	Sample size	Period	Nb of growth disturbances	Minimal Index value	Number of events
Beardsley and Cannon (1930)	California	USA	1	Not precised	Unknown	1500–1924	Not provided	Not computed	3
Dickson and Crocker (1953)	California	USA	1	Not precised	Unknown	1388–1924	Not provided	Not computed	4
Hupp (1984)	Colorado	USA	5	Various species	Unknown	1670–1984	Not provided	Not computed	24
Hupp et al. (1987)	California	USA	9	Various species	1100	1580–1985	Not provided	Not computed	52
Strunk (1991)	Alps	France	1	*Picea abies*	460	1830–1991	Not provided	Not computed	12
Strunk (1997)	Alps	France	5	*Picea abies*	400	Not precised	Not provided	Not computed	Not precised
Yoshida et al. (1997)	Hokkaido	Japan	1	*Abies sachalinensis*	34	1871–1991	Not provided	Not computed	4
Baumann and Kaiser (1999)	Grisons	Switzerland	1	*Pinus mugo*	Unknown	1573–1989	Not provided	Not computed	8
Santilli and Pelfini (2002)	Lombardia	Italy	1	*Pinus montana*	53	1888–1992	Not provided	Not computed	9
Stefanini and Ribolini (2003)	Alps	Italy	5	*Larix decidua*	500	1800–2000	Not provided	Not computed	Unknown
Wilkerson and Schmid (2003)	Montana	USA	12	*Conifers*	53	1857–1979	Not provided	Not computed	7
May and Gresswell (2004)	Oregon	USA	125	*Pseudotsuga menziesii*, *Tsuga heterophylla*	Unknown	Not precised	Not provided	Not computed	Not precised
Stoffel et al. (2005c)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Pinus cembra*	1102	1605–1994	Not provided	Not computed	53
Stoffel et al. (2006a)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*	251	1750–2002	561	Not computed	30
Stoffel and Beniston (2006)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Pinus cembra*	1102	1565–2005	2263	Not computed	123
Bollschweiler et al. (2007)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*	960	1867–2005	940	Not computed	40
Bollschweiler and Stoffel (2007)	Valais	Switzerland	2	*Larix decidua*, *Picea abies*, *Pinus sylvestris*	278	1743–2005	333	Not computed	69
Bollschweiler et al. (2008b)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*	71	1782–2005	242	Not computed	49
Malik and Owczarek (2009)	Sudetes	Poland	1	*Piceas abies*, *Fagus sylvatica*	19	1968–1997	Not provided	Not computed	5
Stoffel et al. (2008a)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Pinus cembra*	1102	1565–2005	2263	Not computed	123
Stoffel et al. (2008b)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Pinus sylvestris*	451	1793–2007	2363	Not computed	30
Stoffel and Bollschweiler (2009)	Valais	Switzerland	1	*Larix decidua*	35	1862–2004	97	Not computed	22
Arbellay et al. (2010a)	Valais	Switzerland	1	*Alnus incana*, *Betula pendula*	315	1965–2007	352	Not computed	14
Bollschweiler and Stoffel (2010a)	Valais	Switzerland	8	*Larix decidua*, *Picea abies*, *Pinus cembra*	2467	1600–2009	Not provided	Not computed	417
Bollschweiler and Stoffel (2010c)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*	210	1752–2006	346	2.3	50
Mayer et al. (2010)	Tyrol	Austria	1	*Larix decidua*, *Picea abies*	227	1800–2008	1155	4.8	37
Owczarek (2010)	Spitzbergen	Norway	Not precised	*Salix reticulata*, *Salix polaris*	Not provided	Not provided	Not provided	Not computed	
Szymczak et al. (2010)	Valais	Switzerland	1	*Various species*	148	1930–2008	340	Not computed	20
Stoffel et al. (2010b)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Betula pendula*	252	1736–2010	1344	Not computed	53
Sorg et al. (2010)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*	28	1913–200§	200	Not computed	13
Bollschweiler et al. (2011)	Valais	Switzerland	1	Various species	99	1900–2007	618	Not computed	17
Kogelnig-Mayer et al. (2011)	Tyrol	Austria	1	*Picea abies*	372	1830–2009	735	Weighted index	20
Lopez Saez et al. (2011)	Alps	France	1	*Pinus sylvestris*	156	1931–2008	375	Not computed	13
Procter et al. (2011)	Vorarlberg	Austria	8	*Pinus mugo*, *Abies alba*, *Picea abies*	442	1839–2010	579	Not computed	63
Stoffel et al. (2011)	Valais	Switzerland	1	*Larix decidua*, *Picea abies*, *Pinus cembra*	1204	1864–2008	Not provided	Not computed	61
Procter et al. (2012)	Vorarlberg	Austria	1	*Pinus mugo*	193	1839–2011	161	Not computed	16
Schneuwly-Bollschweiler and Stoffel (2012)	Valais	Switzerland	8	*Larix decidua*, *Picea abies*, *Pinus cembra*	2467	1864–2010	Not provided	Not computed	257
Šilhán et al. (2012)	Caucasus	Ukraine	1	*Pinus nigra*	54	1741–2009	176	Not computed	47

respectively). More recently, Kogelnig-Mayer et al. (2011) combined the number and intensity of GD in a weighted *It* (W_{it}) to reconstruct past events.

4.2.2. Case study site

The Wildibach torrent (46°07′ N./7°47′ E.; Fig. 4) is located in the Zermatt valley (Valais, Swiss Alps), an inneralpine north–south oriented valley, ca. 8 km north of Zermatt. The catchment extends from 4545 m asl (Dom peak) to the confluence of the Wildibach torrent with the Vispa River at 1420 m asl. About 30% of the catchment is glaciated, and periglacial processes and features (i.e., moraines, rock glaciers) dominate much of the remaining catchment area. Geology is composed of Permian gneisses (Pfiffner, 2009). Mean annual air temperature in Zermatt (1638 m asl) is 3.9 °C, and mean annual

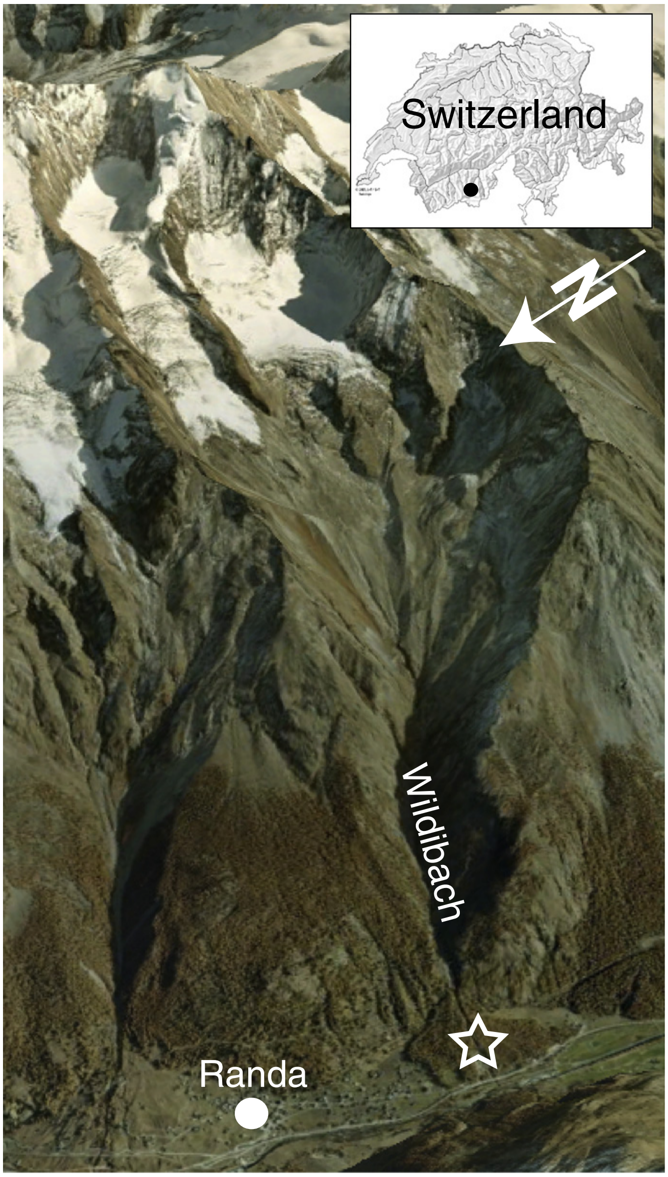

Fig. 4. The Wildibach debris-flow system (46°07′ N., 7°47′ E.) is located ca. 8 km north of Zermatt (Valais, Swiss Alps) and extends from 4545 to 1420 m asl. A large (31 ha), but relatively flat (mean slope angle: 13°) cone (indicated with a star) has formed at the outlet of the steep main channel (mean: 23°); it is covered with a forest composed of *L. decidua* and some *P. abies*. (Image: Google Earth)

precipitation is 690 mm (1900–2008). High annual and daytime thermal ranges favor weathering processes that provide abundant material for matrix-poor debris flows with block sizes of up to 2 m (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012). A large (31 ha), but relatively flat (mean slope angle: 13°) cone has formed at the outlet of the steep main channel (mean: 23°); it is covered with a forest composed of *L. decidua* and some *P. abies*, but deposits of past debris flows remain clearly visible. The outermost segments of the cone are used for grazing and housing. The main road and the railway line intersect the cone in its lowermost part (see Fig. 4 for details).

The Wildibach torrent is known to produce debris flows at frequent intervals; however, archival records are scarce and contain information on events in 1927, 1932, 1978, and 2000 (Zimmermann et al., 1997; Valais, 2009). The debris flow of 1978 caused extensive damage on the cone and led to the construction of deflection dams and a retention basin. Reconstruction of the past activity of debris flows, using dendrogeomorphic techniques, was performed in an area of the cone (12 ha) where debris flows have obviously affected trees and where signs of anthropogenic influence are clearly absent. All features related to past debris flow activity (i.e., lobes, levees, abandoned flow paths) were mapped in the field using tape measure, compass, and inclinometer. A total of 385 trees (381 *L. decidua* and 4 *P. abies*) affected by the activity of past debris flows (i.e., injured, tilted, decapitated, or buried trees) were sampled with 803 increment cores.

4.2.3. Recommended sample size and dating criteria

Identification of years with debris-flow activity was performed using a classical expert's approach, where past events are accepted as such if a representative number of trees located next to each other or along the same flow path show simultaneous GD (Stoffel and Beniston, 2006; Bollschweiler et al., 2008b; Stoffel et al., 2008a, 2010b; Bollschweiler and Stoffel, 2010a,b). The approach is based on the experience of the investigator and does not take account of fixed thresholds (neither for the number of GD nor their intensity). Based on the expert's approach, a total of 50 debris flows could be reconstructed for the period A.D. 1623–1978 (Schneuwly-Bollschweiler et al., in review).

Based on the expert chronology, which is considered here as a reference, we modeled different sampling strategies with sample sizes (n) varying from 30 to 350 trees. For each sample size, 1000 subsets of n trees were computed so as to reduce the dependence of results on the sampling location. Thresholds from 2 to 10 GD and an It from 2 to 20% were tested and events accepted in the reconstruction as soon as both thresholds were exceeded. For each of the modeled sampling strategies and thresholds, output was compared with results from the expert chronology to quantify the amount of correctly identified (signal) and misdated (noise) events. With respective subsets of 50 and 100 trees, 21% (GD > 2, It > 4%) and 58% (GD > 2, It > 2%) of the events listed in the expert chronology are reconstructed without any noise in the reconstruction. Fig. 5 illustrates that a subset of 150 trees, with a GD > 2 and It > 2%, would enable a correct reconstruction of 78% of all events. The ratio increases slightly with a sample size of 200 trees (84%); and all events identified by the expert's approach can be dated correctly with a minimal number of 300 trees (GD > 5, It > 1.7). In terms of costs and benefits, a sample size of 150 trees can, therefore, be considered a good compromise between field efforts, laboratory analyses and the results obtained.

4.3. Landslide reconstruction

4.3.1. Introductory remarks

Several approaches have been applied in the past to date past landsliding with dendrogeomorphic techniques. Tree age may supply important hints as to the age of the oldest undisturbed tree on a landslide body and may, thus, provide minimum ages of movement (Carrara and O'Neill, 2003). Pioneering tree-ring work on landslides dates back to McGee (1893) and Fuller (1912); these pioneers used tree age to establish age and (earthquake) origin of landslides. The original field notes of McGee (1893, p. 413) are quite remarkable and state that

> Along the scarp opposite Reelfoot lake, ancient landslips with their characteristic deformation on the surface are found in numbers… Along the sides of the trenches…trees are frequently thrown out of the perpendicular. These features suggest a sudden and violent movement by which the highly unstable topographic forms of the upland scarp were in part broken down and thrown into more stable positions… The great boles two or more centuries old are inclined from root to top, though the younger trees of seventy or seventy-five years usually stand upright, and that the trunks of a century to a century and a half in age are commonly inclined near the ground, but are vertical above. (Trees thus) give a trustworthy

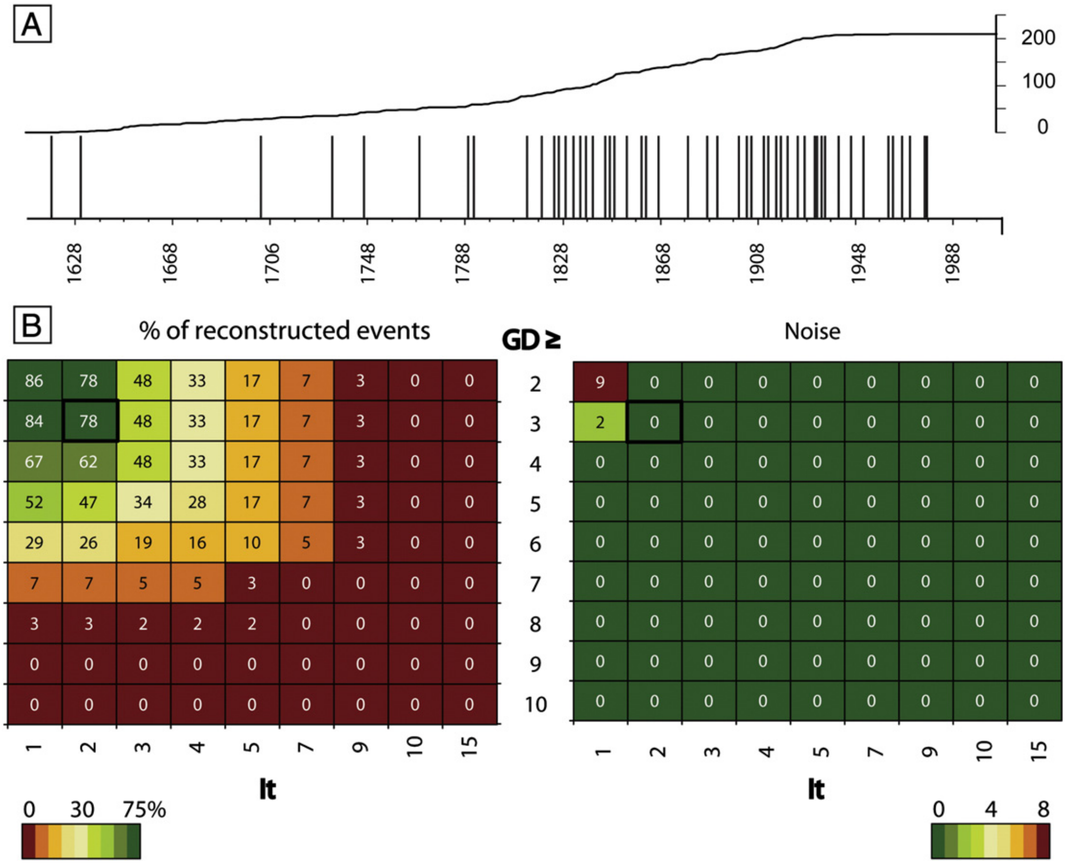

Fig. 5. (A) Identification of years with debris-flow activity using a classical expert's approach, where past events are accepted as such if a representative number of trees located next to each other or along the same flow path show simultaneous GD. Fifty debris flows have been reconstructed for the period A.D. 1623–1978. (B) Bootstrap random extraction from a subset of 150 trees, with a GD > 2 and *It* > 2%, allows correct reconstruction of 78% of events (left), without adding noise to the reconstruction (right).

> and fairly accurate date for the production of the minor topographic features a date determined by much counting of annual rings to lie between seventy-five and eighty-five or ninety years ago…

More recently, landslide reconstructions started to include GD in annual growth-ring series of trees. The first dendrogeomorphic study of a landslide body dates back to Alestalo (1971), and similar field and laboratory approaches have been used ever since in North America (Shroder, 1978; Butler, 1979b; Reeder, 1979; Hupp, 1983; Jensen, 1983; Osterkamp et al., 1986; Bégin and Filion, 1988; Williams et al., 1992; Carrara and O'Neill, 2003). In Europe, dendrogeomorphic tools were introduced much later to assess the frequency and reactivation of landslides in the French Alps (Braam et al., 1987; Astrade et al., 1998; Lopez Saez et al., 2012a,b), the Italian Apennines (Fantucci and McCord, 1995; Fantucci and Sorriso-Valvo, 1999; Stefanini, 2004), the Spanish Pyrenees (Corominas and Moya, 1999), or the Ardennes (Belgium; Van Den Eeckhaut et al., 2009). Table 3 provides an overview of past studies. The sample sizes used for the reconstruction of past landslide reactivations varied from 13 (Carrara and O'Neill, 2003) to 402 trees (Lopez Saez et al., 2012a). Yet, the number of sampled trees remained generally lower than in snow avalanche and debris-flow studies. Index value *(It)* thresholds have not been used systematically, and thresholds used exhibited important variations between 2 (Lopez Saez et al., 2012a,b, in press—a,b) and 30% (Corominas and Moya, 1999; Stefanini, 2004). Based on the data presented in Table 3, it also becomes obvious that applied *It* thresholds generally increased with decreasing sample sizes. In that sense, *It* thresholds > 10% are generally associated with small sample sizes (< 60 trees); whereas lower *It* values (with a minimum of 2%) would be used for sample sizes > 250 trees.

4.3.2. Case study site

The Pra Bellon landslide (44°25′ N., 6°37′ E.; Fig. 6) is located in the Riou-Bourdoux catchment, a tributary of the Ubaye River located on the N-facing slopes of the Barcelonnette basin (Alpes de Haute-Provence, France). The Riou-Bourdoux catchment has been considered the most unstable area in France (Delsigne et al., 2001) and is well known for its extensive mass movement activity. The history of hydrogeomorphic processes in the wider case study area has been documented extensively (Braam et al., 1987), and activity seems to date back to at least the fifteenth century when the area was almost completely deforested (Weber, 1994). Restoration activities in the Riou-Bourdoux catchment started in 1868 and are still ongoing (Flez and Lahousse, 2003). Extensive records of debris flows exist for the Pra Bellon catchment; but conversely, only one landslide has been inventoried at the study site: in spring 1971 (Delsigne et al., 2011).

The Pra Bellon landslide is 175 m long, 450 m wide (32 ha) and has a depth that varies between 4 and 9 m. Its elevation ranges from 1470 to 1750 m asl, and the volume of the landslide body has been estimated at 1.5–2 × 10^6 m^3 (Weber, 1994; Stien, 2001). The rotational landslide is a slump characterized by a 1.5-m-thick top moraine layer underlain by a weathered and unsaturated black marl layer (thickness 5–6 m), which overlies bedrock of unweathered marl (Mulder, 1991). In dry conditions, black marls are quite solid and able to absorb large quantities of water but soften considerably when wet. The area is characterized by dry and mountainous Mediterranean climate with strong interannual rainfall variability. According to the HISTALP data set (Efthymiadis et al., 2006), precipitation at the gridded point closest to the landslide body is 895 ± 154 mm y^{-1} for the period 1800–2003. Rainfall can be violent, with intensities surpassing 50 mm h^{-1}, especially during frequent summer storms. Melting of the thick snow

Table 3
Overview of past dendrogeomorphic studies of landslide activity and approaches (thresholds) used.

Author and Year	Localization	Country	Number of landslides	Species	Sample size	Period	Nb of growth disturbances	Minimal Index value	Number of landslide reactivations
McGee (1893)	Tennessee	USA	Unknown	Not provided	Not provided	1812	Not computed	Not computed	Not computed
Fuller (1912)	Mississippi	USA	Unknown	Not provided	Not provided	1811–1812	Not computed	Not computed	Not computed
Shroder (1978)	Utah	USA	1	*Picea engelmannii*, *Pinus flexilis*, *Pseudotsuga menziesii*	260	1781–1958	Not computed	4%	14
Terasme (1975)	Ontario	Canada	1	Not provided	Not provided	Unknown	Not computed	Not computed	Not computed
Reeder (1979)	Alaska	USA	1	Not provided	Not provided	Unknown	Not computed	Not computed	Not computed
Palmquist et al. (1981)	Wyoming	USA	1	Not provided	Not provided	Unknown	Not computed	Not computed	Not computed
Jensen (1983)	Wyoming	USA	1	Not provided	Not provided	Unknown	Not computed	Not computed	Not computed
Bégin and Filion (1985)	Quebec	Canada	1	*Picea abies*	52	1785–1933	Not computed	Not computed	8
Bégin and Filion (1988)	Quebec	Canada	7	*Picea abies*	Not provided	1818	Not computed	Not computed	1
Braam et al. (1987)	Alps	France	2	*Pinus uncinata*	56	1890–1980	Not computed	7–17%	24
Van Asch and Van Steijn (1991)	Alps	France	1	Not provided	65	1900–1982	Not computed	10%	15
Williams et al. (1992)	Washington	USA	4	Not provided	Not provided		Not computed	Not computed	Not computed
Fleming and Johnson (1994)	Ohio	USA	1	Not provided	Not provided	1958	Not computed	Not computed	Not computed
Astrade et al. (1998)	Alps	France	1	*Pinus sylvestris*	41	1923–1994	Not computed	10%	9
Corominas and Moya (1999)	Pyrenees	Spain	7	Not provided	250	1926–1995	Not computed	30	35
Fantucci and Sorriso-Valvo (1999)	Calabria	Italy	1	*Quercus pubescens*, *Pinus nigra*	38	1845–1995	Not computed	Not computed	1
Carrara et al. (2003)	Wyoming	USA	1	*Pseudotsuga menziesii*	13	1865	Not computed	Not computed	1
Carrara and O'Neill (2003)	Montana	USA	3	*Pseudotsuga menziesii*, *Pinus contorta*, *Pinus flexilis*, *Abies lasiocarpa*	32	1880–1992	Not computed	25%	20
Stefanini (2004)	Appenines	Italy	1	*Quercus cerris*	24	1928–1998	Not computed	30%	9
Wieczorek et al. (2006)	Virginia	USA	1	Various species	258	2003	Not computed	Not computed	1
Van Den Eeckhaut et al. (2009)	Ardennes	Belgium	1	*Fagus sylvatica*	147	1917–1998	Not computed	Not computed	25
Lopez Saez et al. (2011)	Alps	France	1	*Pinus uncinata*	79	1850–2008	159	10%	1
Lopez Saez et al. (2012a)	Alps	France	1	*Pinus uncinata*	403	1900–2010	704	2%	1
Lopez Saez et al. (2012b)	Alps	France	1	*Pinus uncinata*	223	1900–2010	355	2%	1
Šilhán et al. (2012)	Caucasus	Ukraine	1	*Pinus nigra*	48	1702–2009	150	5%	45
Lopez Saez et al. (in press—a)	Alps	France	7	*Pinus uncinata*	759	1897–2010	1298	2%	61

cover, which forms during the cold months between December and March, only adds to the effect of heavy spring rain (Flageollet, 1999). Mean annual temperature is 7.5 °C with 130 d y^{-1} of freezing (Maquaire et al., 2003). The study site is characterized by irregular topography with a mean slope angle of ~20°. Mountain pine (*Pinus mugo* ssp. *uncinata*) has a competitive advantage on these dry, poor soils (Dehn and Buma, 1999) and forms nearly homogeneous forest stands outside the surfaces affected by the scarps and recent earth slides.

4.3.3. Recommended sample size and dating criteria

To reconstruct past landslide reactivations at Pra Bellon, a total of 403 *P. uncinata* trees were sampled with 1563 increment cores, yielding a large data set of 704 GD observed in the tree-ring record. Based on an empirical threshold fixed at GD≥5 and *It*>1.7, 32 reactivation phases have been reconstructed at this site between 1910 and 2011 (Lopez Saez et al., 2012a). Because of the lack of independent archival records and the existence of the largest tree-ring sample ever retrieved from a landslide body, the event chronology reconstructed by Lopez Saez et al. (2012a) has, thus, been considered as a reference for the subsequent threshold testing.

As for the avalanche and debris-flow sites, we aimed at defining the optimal sampling strategy for which the largest number of events can be identified and where the inclusion of noise can be avoided or at least minimized. Sample sizes were varied from 30 to 350 trees, and results again obtained with 1000 iterations so as to reduce dependency of results on sampling location. We then tested thresholds from 2 to 10 GD and *It* from 2 to 30 and compared output with the results obtained by Lopez Saez et al. (2012a). Fig. 7 shows that a subset of 50 trees, with GD≥5 and *It*>1.7, will be sufficient to identify correctly 94% of the events without including noise in the reconstruction.

5. Recommendations and conclusions

In this contribution, we stress the importance of careful site selection and sampling design and call for the inclusion of varying

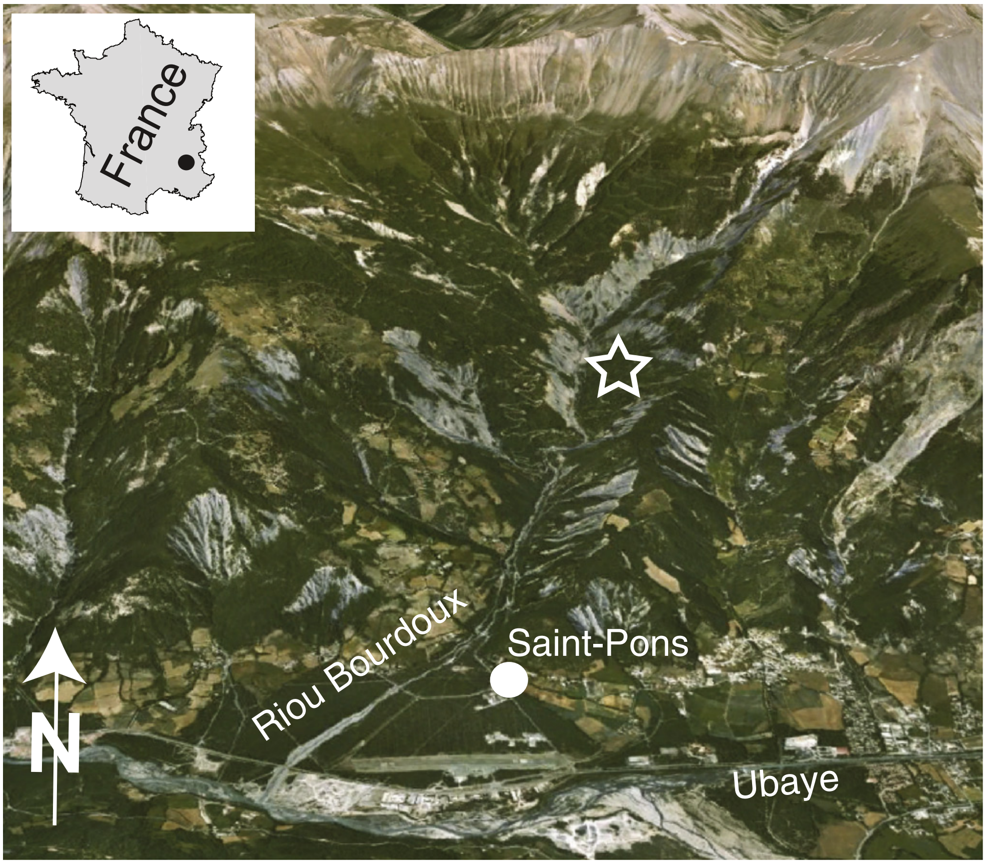

Fig. 6. The Pra Ballon landslide (44°25′ N., 6°37′ E.; star indicates location) is located in the Riou-Bourdoux catchment, a tributary of the Ubaye River (Barcelonnette basin, Alpes de Haute-Provence, France). It is 175 m long, 450 m wide (32 ha; estimated volume: $1.5–2\times10^6$ m^3), and its elevation ranges from 1470 to 1750 m asl. (Image: Google Earth)

numbers of trees and associated varying thresholds in terms of absolute (GD) and relative (*It*) numbers of trees with simultaneous growth reactions for different mass movement processes. Processes that tend to spread considerably will likely leave larger spatial footprints and will, therefore, be visible in a larger number of trees. In particular, this is the case for landslides, for which almost all major reactivations (94%) can be identified with a limited number of trees (50 specimens). Although of often similar extent in space, a slightly larger sample size (100 trees) seems appropriate to obtain reasonable results on snow avalanche sites. The difference can presumably be explained by variations in the extent of avalanches (in terms of lateral spread and reach) as a result of differing snow conditions, complex flow patterns of snow avalanches in less energetic runout zones where trees typically withstand events or by the fact that avalanche chronologies (such as the one of the Pèlerins path) will also contain data on very small events for the recent past and for the years following disasters (Corona et al., 2012). On debris-flow sites, 150 trees seem to represent an appropriate lower number of samples for a reasonable reconstruction, as the spatial footprint of debris flows will typically be much smaller than that of the aforementioned processes.

The optimal sample size for avalanches and debris flows can probably be lowered even more in the future, provided that the position of trees (e.g., fan apex, sectors along channels) and the weighting of GD (to emphasize features that are clearly associated with geomorphic activity, such as injuries or TRD) are included as further criteria in the sampling strategy. Such an addition to current approaches will also lead ultimately to the identification of sampling hotspots and presumably facilitate the selection of optimal trees (in terms of number of GD or return periods). As a further conclusion, we realize that the bootstrap random extraction calls for the definition of flexible GD and *It* thresholds and an adaptation of these values depending on the number of trees available for analysis at different periods of the past.

In any case, however, the sample size values presented above have to be seen as a guide rather than a strict rule; and sampling strategies will need to be adjusted to the field situation. In addition, and even more importantly, definitions of these values were based on the idea of cost–benefit ratios where a minimization of field efforts and a maximization of reconstructed events without noise was challenged. At the same time, however, we are fully aware that fundamental research will need to rely on larger sample sizes in the future, especially if it focuses on the validation and/or calibration of physically based mass movement models (Stoffel et al., 2006b; Ballesteros et al., 2011a,b; Corona et al., in press—a), the assessment of mass movement triggers (Schneuwly and Stoffel, 2008a; Šilhán et al., 2012), or the analysis of climate–mass movement interactions (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012).

Recent advances in dendrogeomorphic research have also demonstrated quite clearly that the selection of trees and an adequate mixture of species and age classes are fundamental for the reconstruction of well-balanced and minimally biased time series of past mass movements (Arbellay et al., 2010a; Trappmann and Stoffel, 2013; Corona et al., in press—b). In this sense, fieldwork and an appropriate sampling strategy will be key to avoid the inclusion of biases and trends, which is particularly crucial for an increased reliability of results in hazard assessment and disaster risk reduction plans, and even more fundamental for time series focusing on the impacts of climate change.

The optimization of minimum sample sizes provided above will ultimately facilitate fieldwork, render analyses and interpretation more reliable and will allow reconstruction of very reasonable time series of past mass movements with reasonable field efforts and

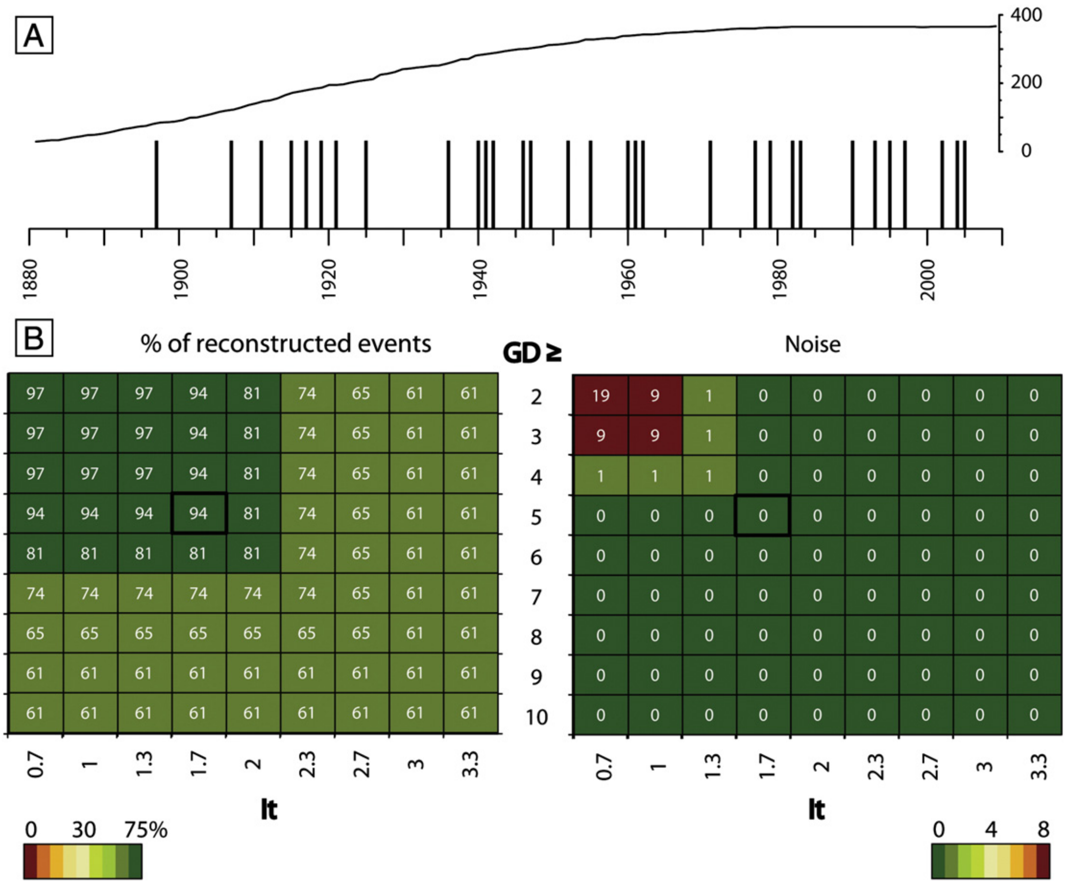

Fig. 7. (A) Landslide reactivations at Pra Bellon were initially reconstructed with 1563 increment cores sampled from 403 *P. uncinata* trees and using an empirical threshold of GD≥5 and *It*>2%, yielding 32 reactivation phases since A.D. 1910. (B) Bootstrap random extraction from a subset of 50 trees, with GD≥5 and *It*>1.7, will be sufficient to identify correctly 94% of all reconstructed events without including noise in the reconstruction.

excellent cost–benefit ratios. Based on the sample sizes identified in this study, we believe that dendrogeomorphology represents a complimentary but quite competitive source of information on past disasters and could, thus, be included in conventional risk assessments at exposed sites covered by forest and more frequently used as an invaluable source of information by practitioners and/or local authorities.

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References

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

Arbellay, E., Stoffel, M., Bollschweiler, M., 2010a. Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees. Earth Surface Processes and Landforms 35, 399–406.

Arbellay, E., Stoffel, M., Bollschweiler, M., 2010b. Wood anatomical analysis of *Alnus incana* (L.) Moench and *Betula pendula* Roth injured by a debris flow. Tree Physiology 30, 1290–1298.

Arbellay, E., Fonti, P., Stoffel, M., 2012a. Duration and extension of anatomical changes in wood structure after cambial injury. Journal of Experimental Botany 63, 3271–3277.

Arbellay, E., Corona, C., Stoffel, M., Fonti, P., Decaulne, A., 2012b. Defining an adequate sample of earlywood vessels for retrospective injury detection in diffuse-porous species. PLoS One 7, e38824.

Arbellay, E., Stoffel, M., Decaulne, A., in press. Dating of snow avalanches by means of wound-induced vessel anomalies in subarctic Betula pubescens. Boreas. http://dx.doi.org/10.1111/j.1502-3885.2012.00302.x.

Astrade, L., Bravard, J.P., Landon, N., 1998. Mouvements de masse et dynamique d'un géosystème alpestre: étude dendrogéomorphologique de deux sites de la vallée de Boulc (Diois, France). Géographie physique et Quaternaire 52, 153–166.

Baillie, M.G.L., 2008. Proposed re-dating of the European ice core chronology by seven years prior to the 7th century AD. Geophysical Research Letters 35, L15813.

Ballesteros, J.A., Stoffel, M., Bodoque, J.M., Bollschweiler, M., Hitz, O.M., Diez, A., 2010a. Changes in wood anatomy in tree rings of *Pinus pinaster* Ait. following wounding by flash floods. Tree-Ring Research 66, 93–103.

Ballesteros, J.A., Stoffel, M., Bollschweiler, M., Bodoque, J.M., Díez, A., 2010b. Flash-flood impacts cause changes in wood anatomy of *Alnus glutinosa*, *Fraxinus angustifolia* and *Quercus pyrenaica*. Tree Physiology 30, 773–781.

Ballesteros, J.A., Bodoque, J.M., Díez-Herrero, A., Sanchez-Silva, M., Stoffel, M., 2011a. Calibration of floodplain roughness and estimation of flood discharge based on tree-ring evidence and hydraulic modelling. Journal of Hydrology 403, 103–115.

Ballesteros, J.A., Eguibar, M., Bodoque, J.M., Díez-Herrero, A., Stoffel, M., Gutiérrez-Pérez, I., 2011b. Estimating flash flood discharge in an ungauged mountain catchment with 2D hydraulic models and dendrogeomorphic palaeostage indicators. Hydrological Processes 25, 970–979.

Bannan, M.W., 1936. Vertical resin ducts in the secondary wood of the *Abietineae*. New Phytologist 35, 11–46.

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

Beardsley, G.F., Cannon, W.A., 1930. Note on the effects of a mud-flow at Mt. Shasta on the vegetation. Ecology 11, 326–336.

Bégin, C., Filion, L., 1985. Analyse dendrochronologique d'un glissement de terrain dans la région du Lac à l'Eau Claire (Québec nordique). Canadian Journal of Earth Sciences 22, 175–182.

Bégin, C., Filion, L., 1988. Age of landslides along the Grande Rivière de la Baleine estuary, eastern coast of Hudson Bay, Québec (Canada). Boreas 17, 289–299.

Bekker, M.F., 2010. Tree rings and earthquakes. In: Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B.H. (Eds.), Tree Rings and Natural Hazards: A State-of-the-art. Springer, Heidelberg, New York, pp. 391–397.

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., 2010a. Changes and trends in debris-flow frequency since AD 1850: results from the Swiss Alps. The Holocene 20, 907–916.

Bollschweiler, M., Stoffel, M., 2010b. Tree rings and debris flows: recent developments, future directions. Progress in Physical Geography 34, 625–645.

Bollschweiler, M., Stoffel, M., 2010c. Variations in debris-flow occurrence in an Alpine catchment — a reconstruction based on tree rings. Global and Planetary Change 73, 186–192.

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

Bollschweiler, M., Stoffel, M., Schneuwly, D.M., Bourqui, K., 2008a. Traumatic resin ducts in *Larix decidua* stems impacted by debris flows. Tree Physiology 28, 255–263.

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

Bollschweiler, M., Stoffel, M., Vazquez Selem, L., Palacios, D., 2009. Tree-ring reconstruction of past lahar activity at Popocatepetl volcano, Mexico. The Holocene 20, 265–274.

Bollschweiler, M., Stoffel, M., Schlaeppy, R., 2011. Debris-flood reconstruction in a pre-alpine catchment in Switzerland based on tree-ring analysis of conifers and broadleaved trees. Geografiska Annaler 93, 1–15.

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

Braam, R., Weiss, E., Burrough, P., 1987. Spatial and temporal analysis of mass movement using dendrochronology. Catena 14, 573–584.

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

Butler, D.R., 1979a. Snow avalanche path terrain and vegetation, Glacier National Park, Montana. Arctic and Alpine Research 11, 17–32.

Butler, D.R., 1979b. Dendrogeomorphological analysis of flooding and mass movement, Ram Plateau, Mackenzie Mountains, Northwest Territories. The Canadian Geographer 23, 62–65.

Butler, D.R., Malanson, G.P., 1984. Transverse pattern of vegetation on avalanche paths in the northern Rocky Mountains, Montana. Great Basin Naturalist 44, 453–458.

Butler, D.R., Malanson, G.P., 1985. A history of high-magnitude snow avalanches, southern Glacier National Park, Montana, U.S.A. Mountain Research and Development 5, 175–182.

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

Butler, D., Malanson, G., Oelfke, J., 1987. Tree-ring analysis and natural hazard chronologies: minimum sample sizes and index values. The Professional Geographer 39, 41–47.

Butler, D.R., Sawyer, C.F., Maas, J.A., 2010. Tree-ring dating of snow avalanches in Glacier National Park, Montana, USA. In: Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B.H. (Eds.), Tree Rings and Natural Hazards: A State-of-the-art. Springer, Heidelberg, New York, pp. 35–46.

Cachat, J., 2000. Les carnets de Cachat le Géant: mémoires de Jean-Michel Cachat dit "Le Géant", guide demonsieur de Saussure, paysan de la vallée de Chamonix. La Fontaine de Siloé, Montmélian, France.

Carrara, P.E., 1979. The determination of snow avalanche frequency through tree-ring analysis and historical records at Ophir, Colorado. Geological Society of America Bulletin 90, 773.

Carrara, P., O'Neill, J.M., 2003. Tree-ring dated landslide movements and their relationship to seismic events in southwestern Montana, USA. Quaternary Research 59, 25–35.

Carrara, A., Crosta, G., Frattini, P., 2003. Geomorphological and historical data in assessing landslide hazard. Earth Surface Processes and Landforms 28, 1125–1142.

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

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

Casteller, A., Villalba, R., Araneo, D., Stöckli, V., 2011. Reconstructing temporal patterns of snow avalanches at Lago del Desierto, southern Patagonian Andes. Cold Regions Science and Technology 67, 68–78.

Chaubet, D., 2011. Les cahiers de l'oncle ambroise, un chamoniard "ordinaire" (1867–1942). Célèbres ou obscurs. Hommes et femmes dans leurs territoires et leur histoire, Editions du CTHS, Bordeaux, France, pp. 259–267.

Corominas, J., Moya, J., 1999. Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, eastern Pyrenees, Spain. Geomorphology 30, 79–93.

Corona, C., Rovéra, G., Lopez Saez, J., Stoffel, M., Perfettini, P., 2010. Spatio-temporal reconstruction of snow avalanche activity using tree rings: Pierres Jean Jeanne avalanche talus, Massif de l'Oisans, France. Catena 83, 107–118.

Corona, C., Lopez Saez, J., Stoffel, M., Bonnefoy, M., Richard, D., Astrade, L., Berger, F., 2012. How much of the real avalanche activity can be captured with tree rings? An evaluation of classic dendrogeomorphic approaches and comparison with historical archives. Cold Regions Science and Technology 74–75, 31–42.

Corona, C., Trappmann, D., Stoffel, M., in press—a. Parameterization of rockfall source areas and magnitudes with ecological recorders—when disturbances in trees serve the calibration and validation of simulation runs. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2013.02.001

Corona, C., Lopez Saez, J., Stoffel, M., Rovéra, G., Edouard, J.L., Berger, F., in press—b. Seven centuries of avalanche activity at Echalp (Queyras massif, southern French Alps) as inferred from tree rings. The Holocene.

Dehn, M., Buma, J., 1999. Modelling future landslide activity based on general circulation models. Geomorphology 30, 175–187.

Deline, P., 2009. Interactions between rock avalanches and glaciers in the Mont Blanc massif during the late Holocene. Quaternary Science Reviews 28, 1070–1083.

Delsigne, F., Lahousse, P., Flez, C., Guiter, G., 2001. Le Riou Bourdoux: un "monstre" alpin sous haute surveillance. Revue forestière française LIII, 527–540.

Delsigne, F., Lahousse, P., Flez, C., Guiter, G., 2011. Le Riou Bourdoux: un "monstre" alpin sous haute surveillance. Revue Forestière Française 5, 527–541.

Dickson, B.A., Crocker, R.L., 1953. A chronosequence of soils and vegetation near Mount Shasta, California; I. Definition of the ecosystem investigated and features of the plant succession. Journal of Soil Science 4, 123–141.

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

Eckert, N., Parent, E., Kies, R., Baya, H., 2009. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: application to 60 years of data in the northern French Alps. Climatic Change 101, 515–553.

Efthymiadis, D., Jones, P.D., Briffa, K.R., Auer, I., Böhm, R., Schöner, W., Frei, C., Schmidli, J., 2006. Construction of a 10-min-gridded precipitation data set for the greater alpine region for 1800–2003. Journal of Geophysical Research. http://dx.doi.org/10.1029/2005JD006120.

ETNA, 2000. Commune de Chamonix Mont Blanc, projet de Centre de secours principal près des Pélerins, étude du risque d'avalanche. Technical report.

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.

Flageollet, J., 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (southern French Alps, France). Geomorphology 30, 65–78.

Fleming, R.W., Johnson, A.M., 1994. Landslides in colluvium. U.S. Geological Survey Bulletin 2059-B (24 pp.).

Flez, C., Lahousse, P., 2003. Contribution to assessment of the role of anthropic factors and bioclimatic controls in contemporary torrential activity in the southern Alps (Ubaye valley, France). In: Roberts, N. (Ed.), The Mediterranean World, An Environmental History. Elsevier, Paris, pp. 105–118.

Fuller, M., 1912. The New Madrid Earthquake. Center for Earthquake Studies, Southeast Missouri State University, Cape Girardeau.

Germain, D., Filion, L., Hétu, B., 2005. Snow avalanche activity after fire and logging disturbances, northern Gaspé Peninsula, Quebec, Canada. Canadian Journal of Earth Sciences 42, 2103–2116.

Germain, D., Filion, L., Hétu, B., 2009. Snow avalanche regime and climatic conditions in the Chic-Choc Range, eastern Canada. Climatic Change 92, 141–167.

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

Hupp, C.R., 1983. Geo-botanical evidence of late Quaternary mass wasting in block field areas of Virginia. Earth Surface Processes and Landforms 8, 439–450.

Hupp, C.R., 1984. Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California. Environmental Geology and Water Sciences 6, 121–128.

Hupp, C.R., Osterkamp, W.R., Thornton, J.L., 1987. Dendrogeomorphic Evidence and Dating of Recent Debris Flows on Mount Shasta, Northern California. Professional Paper 1396-B. U.S. Geological Survey, Denver, CO.

Ives, J., Mears, A., Carrara, P., Bovis, M., 1976. Natural hazards in Mountain Colorado. Annals of the Association of American Geographers 66, 129–144.

Jacoby, G.C., Sheppard, P.R., Sieh, K.E., 1988. Irregular recurrence of large earthquakes along the San Andreas fault: evidence from trees. Science 241, 196–199.

Jamard, A.L., Garcia, S., Bélanger, L., 2002. L'enquête permanente sur les Avalanches (EPA). Statistique descriptive générale des événements et des sites. Université Joseph Fourrier, Grenoble, France.

Jenkins, M.J., Hebertson, E.G., 2004. A practitioners guide for using dendroecological techniques to determine the extent and frequency of avalanches. ISSW Proceedings: A Merging of Theory and Practice, Jackson, WY, pp. 423–434.

Jensen, J.M., 1983. The Upper Gros Ventre landslide of Wyoming: a dendrochronology of landslide events and possible mechanics of failure. Geological Society of America Abstracts with Programs, p. 387.

Kajimoto, T., Daimaru, H., Okamoto, T., Otani, T., Onodera, H., 2004. Effects of snow avalanche disturbance on regeneration of subalpine *Abies mariesii* forest, northern Japan. Arctic, Antarctic, and Alpine Research 36, 436–445.

Kogelnig-Mayer, B., Stoffel, M., Schneuwly-Bollschweiler, M., Hübl, J., Rudolf-Miklau, F., 2011. Possibilities and limitations of dendrogeomorphic time-series reconstructions on sites influenced by debris flows and frequent snow avalanche activity. Arctic, Antarctic, and Alpine Research 43, 649–658.

Köse, N., Aydin, A., Akkemik, Ü., Yurtseven, H., Güner, T., 2010. Using tree-ring signals and numerical model to identify the snow avalanche tracks in Kastamonu, Turkey. Natural Hazards 54, 435–449.

Lagotala, H., 1927. Etude de l'avalanche des Pèlerins (Chamonix). Technical report. Société Générale d'Imprimerie, Genève, Switzerland.

Lambert, R., 2009. Cartozonage: de la carte au zonage du risque avalanche. Neige et glace de montagne: reconstitution, dynamiques, pratique. Edytem 8, 233–237.

Larocque, S.J., Hetu, B., Filion, L., 2001. Geomorphic and dendroecological impacts of slushflows in central Gaspe Peninsula (Quebec, Canada). Geografiska Annaler, Series A: Physical Geography 83, 191–201.

Laxton, S.C., Smith, D.J., 2008. Dendrochronological reconstruction of snow avalanche activity in the Lahul Himalaya, Northern India. Natural Hazards 49, 459–467.

Leone, S., 2006. Les Populations de haute montagne face aux contraintes naturelles. Les vallées de Chamonix et Vallorcine (1730–1914). Ph.D. Thesis. Université Pierre Mendès France. Grenoble, France, 687 pp.

Lopez Saez, J., Corona, C., Stoffel, M., Gotteland, A., Berger, F., Liébault, F., 2011. Debris-flow activity in abandoned channels of the Manival torrent reconstructed with LiDAR and tree-ring data. Natural Hazards and Earth System Science 11, 1247–1257.

Lopez Saez, J., Corona, C., Stoffel, M., Schoeneich, P., Berger, F., 2012a. Probability maps of landslide reactivation derived from tree-ring records: Pra Bellon landslide, southern French Alps. Geomorphology 138, 189–202.

Lopez Saez, J., Corona, C., Stoffel, M., Astrade, L., Berger, F., Malet, J.-P., 2012b. Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: the Bois Noir landslide, southeast French Alps. Landslides 9, 189–203.

Lopez Saez, J., Corona, C., Stoffel, M., Berger, F., in press—a. High-resolution fingerprints of past landsliding and spatially explicit, probabilistic assessment of future reactivations: Aiguettes landslide, southeastern French Alps. Tectonophysics. http://dx.doi.org/10.1016/j.tecto.2012.04.020.

Lopez Saez, J., Corona, C., Stoffel, M., in press—b. Climate change increases the frequency of snowmelt-induced landslides in the French Alps, Geology.

Lugon, R., Stoffel, M., 2010. Rock–glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. Global and Planetary Change 73, 202–210.

Malik, I., Owczarek, P., 2009. Dendrochronological records of debris flow and avalanche in a mid-mountain forest zone (Eastern Sudetes–Central Europe). Geochronometria 34, 57–66.

Maquaire, O., Malet, J.P., Remaître, A., Locat, J., Klotz, S., Guillon, J., 2003. Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette basin, south east France. Engineering Geology 70, 109–130.

Mattheck, C., 1993. Design in der Natur. Reihe Ökologie. : Rombach Wissenschaft, 1.

May, C.L., Gresswell, R.E., 2004. Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA. Geomorphology 57, 135–149.

Mayer, B., Stoffel, M., Bollschweiler, M., Hübl, J., Rudolf-Miklau, F., 2010. Frequency and spread of debris floods on fans: a dendrogeomorphic case study from a dolomite catchment in the Austrian Alps. Geomorphology 118, 199–206.

McAuliffe, J.R., Scuderi, L.A., McFadden, L.D., 2006. Tree-ring record of hillslope erosion and valley floor dynamics: landscape responses to climate variation during the last 400 yr in the Colorado Plateau, northeastern Arizona. Global and Planetary Change 50, 184–201.

McGee, W.J., 1893. A fossil earthquake. Geological Society of America Bulletin 4, 411–414.

Moya, J., Corominas, J., Pérez Arcas, J., Baeza, C., 2010. Tree-ring based assessment of rockfall frequency on talus slopes at Solà d'Andorra, eastern Pyrenees. Geomorphology 118, 393–408.

Mulder, H., 1991. Assessment of Landslide Hazard. Ph.D. Thesis, Faculty of Geographical Sciences, University of Utrecht, Netherlands, 149 pp.

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

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

Muntán, E., García, C., Oller, P., Martí, G., García, A., Gutierrez, E., 2009. Reconstructing snow avalanches in the southeastern Pyrenees. Natural Hazards and Earth System Science 9, 1599–1612.

Osterkamp, W.R., Hupp, C., Blodgett, J.C., 1986. Magnitude and frequency of debris flows, and areas of hazard on Mount Shasta, California. Professional Paper 1396-C. U.S. Geological Survey, Denver, CO (21 pp.).

Osterkamp, W.R., Hupp, C.R., Stoffel, M., 2012. The interactions between vegetation and erosion: new directions for research at the interface of ecology and geomorphology. Earth Surface Processes and Landforms 37, 23–36.

Owczarek, P., 2010. Talus cone activity recorded by tree-rings of Arctic dwarf shrubs: a study case from SW Spitsbergen, Norway. Geologija 52, 34–39.

Palmquist, R.C., Cloud, T.A., Jensen, J., 1981. Landslide history, middle reach of the Gros Ventre River Valley. Wyoming: National Geographic Society Final Report, grant no. 2134-80 (16 pp.).

Pederson, G.T., Reardon, B.A., Caruso, C.J., Fagre, D.B., 2006. High resolution tree-ring based spatial reconstructions of snow avalanche activity in Glacier National Park, Montana, USA. ISSW Proceedings, Telluride, CO, pp. 436–443.

Pfiffner, O.A., 2009. Geologie der Alpen. Haupt, Bern, Stuttgart, Wien.

Potter, N., 1969. Tree-ring dating of snow avalanche tracks and the geomorphic activity of avalanches, northern Absaroka Mountains, Wyoming, Boulder, CO. Special Paper 123. Geological Society of America, Washington D.C., pp. 141–165.

Procter, E., Bollschweiler, M., Stoffel, M., Neumann, M., 2011. A regional reconstruction of debris-flow activity in the Northern Calcareous Alps, Austria. Geomorphology 132, 41–50.

Procter, E., Stoffel, M., Schneuwly-Bollschweiler, M., Neumann, M., 2012. Exploring debris-flow history and process dynamics using an integrative approach on a dolomitic cone in western Austria. Earth Surface Processes and Landforms 37, 913–922.

Rayback, S.A., 1998. A dendrogeomorphological analysis of snow avalanches in the Colorado Front Range, USA. Physical Geography 502–515.

Reardon, B.A., Pederson, G.T., Caruso, C.J., Fagre, D.B., 2008. Spatial reconstructions and comparisons of historic snow avalanche frequency and extent using tree rings in Glacier National Park, Montana, U.S.A. Arctic, Antarctic, and Alpine Research 40, 148–160.

Reeder, J.W., 1979. The dating of landslides in Anchorage. Alaska—A Case for Earthquake Triggered Movements: Geological Society of America Abstracts with Programs, 11, p. 501.

Salzer, M.W., Hughes, M.K., 2007. Bristlecone pine tree rings and volcanic eruptions over the last 5000 yr. Quaternary Research 67, 57–68.

Santilli, M., Pelfini, M., 2002. Dendrogeomorphology and dating of debris flows in the Valle del Gallo, Central Alps, Italy. Dendrochronologia 20, 269–284.

Savi, S., Schneuwly-Bollschweiler, M., Bommer-Denns, B., Stoffel, M., Schlunegger, F., in press. Geomorphic coupling between hillslopes and channels in the Swiss Alps. Earth Surface Processes and Landforms.

Schaerer, P.A., 1972. Terrain and vegetation of snow avalanche sites at Rogers Pass, British Columbia. In: Slaymaker, O., McPherson, H.J. (Eds.), Mountain Geomorphology: Geomorphological Processes in the Canadian Cordillera. Tantalus Research Ltd., Vancouver BC, pp. 215–222.

Schneuwly, D.M., Stoffel, M., 2008a. Tree-ring based reconstruction of the seasonal timing, major events and origin of rockfall on a case-study slope in the Swiss Alps. Natural Hazards and Earth System Science 8, 203–211.

Schneuwly, D.M., Stoffel, M., 2008b. Changes in spatio-temporal patterns of rockfall activity on a forested slope — a case study using dendrogeomorphology. Geomorphology 102, 522–531.

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

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

Schneuwly-Bollschweiler, M., Stoffel, M., 2012. Hydrometeorological triggers of periglacial debris flows in the Zermatt valley (Switzerland) since 1864. Journal of Geophysical Research 117, F02033.

Schneuwly-Bollschweiler, M., Corona, C., Stoffel, M., in review. How to improve dating quality and reduce noise in tree-ring based debris-flow reconstructions. Quaternary Geochronology.

Shroder, J., 1978. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. Quaternary Research 9, 168–185.

Šilhán, K., Pánek, T., Hradecký, J., 2012. Tree-ring analysis in the reconstruction of slope instabilities associated with earthquakes and precipitation (the Crimean Mountains, Ukraine). Geomorphology 173–174, 174–184.

Smith, L., 1973. Indication of snow avalanche periodicity through interpretation of vegetation patterns in the North Cascades, Washington. Methods of Avalanche Control on Washington Mountain Highways. : Third Annual Report. Washington State Highway Commission Department of Highways, Olympia, WA, pp. 55–101.

Sorg, A., Bugmann, H., Bollschweiler, M., Stoffel, M., 2010. Debris-flow activity along a torrent in the Swiss Alps: minimum frequency of events and implications for forest dynamics. Dendrochronologia 28, 215–223.

St. George, S., Nielsen, E., 2002. Hydroclimatic change in southern Manitoba since A.D. 1409 inferred from tree rings. Quaternary Research 58, 103–111.

Stefanini, M., 2004. Spatio-temporal analysis of a complex landslide in the northern Apennines (Italy) by means of dendrochronology. Geomorphology 63, 191–202.

Stefanini, M.C., Ribolini, A., 2003. Dendrogeomorphological investigations of debris-flow occurence in the Marittime Alps (northwestern Italy). In: Rickenmann, D., Chen, C.L. (Eds.), Debris-flow Hazard Mitigation: Mechanisms, Prediction, and Assessment. Millpress, Rotterdam, pp. 231–242.

Stien, D., 2001. Glissements de terrains et enjeux dans la vallée de l'Ubaye et le pays de Seyne. Rapport RTM, Barcelonnette, France . (218 pp.).

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

Stoffel, M., 2010. Magnitude–frequency relationships of debris flows—a case study based on field surveys and tree-ring records. Geomorphology 116, 67–76.

Stoffel, M., Beniston, M., 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophysical Research Letters 33, L16404.

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

Stoffel, M., Bollschweiler, 2009. Tree-ring reconstruction of past debris flows based on a small number of samples — possibilities and limitations. Landslides 6, 225–230.

Stoffel, M., Hitz, O.M., 2008. Snow avalanche and rockfall impacts leave different anatomical signatures in tree rings of *Larix decidua*. Tree Physiology 28, 1713–1720.

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

Stoffel, M., Wilford, D.J., 2012. Hydrogeomorphic processes and vegetation: disturbance, process histories, dependencies and interactions. Earth Surface Processes and Landforms 37, 9–22.

Stoffel, M., Schneuwly, D., Bollschweiler, M., Lièvre, I., Delaloye, R., Myint, M., Monbaron, M., 2005a. Analyzing rockfall activity (1600–2002) in a protection forest—a case study using dendrogeomorphology. Geomorphology 68, 224–241.

Stoffel, M., Lievre, I., Monbaron, M., Perret, S., 2005b. 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, M.A., Raetzo, H., Gärtner, H.W., Monbaron, M., 2005c. 400 years of debris flow activity and triggering weather conditions: Ritigraben VS, Switzerland. Arctic, Antarctic, and Alpine Research 37, 387–395.

Stoffel, M., Bollschweiler, M., Hassler, G.-R., 2006a. Differentiating past events on a cone influenced by debris-flow and snow avalanche activity — a dendrogeomorphological approach. Earth Surface Processes and Landforms 31, 1424–1437.
Stoffel, M., Wehrli, A., Kühne, R., Dorren, L.K.A., Perret, S., Kienholz, H., 2006b. Quantifying the protective effect of mountain forests against rockfall using a 3D simulation model. Forest Ecology and Management 225, 113–122.
Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Maître, G., 2008a. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. Global and Planetary Change 60, 222–234.
Stoffel, M., Bollschweiler, M., Leutwiler, A., Aeby, P., 2008b. Large debris-flow events and overbank sedimentation in the Illgraben torrent (Valais Alps, Switzerland). Open Geology Journal 2, 18–29.
Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B., 2010a. Tree Rings and Natural Hazards: A State-of-the-art. Springer, Heildelberg, New York.
Stoffel, M., Bollschweiler, M., Widmer, S., Sorg, A., 2010b. Spatio-temporal variability in debris-flow activity: a tree-ring study at Geisstriftbach (Swiss Alps) extending back to AD 1736. Swiss Journal of Geoscience 103, 283–292.
Stoffel, M., Bollschweiler, M., Beniston, M., 2011. Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences — potential future evolutions. Climatic Change 105, 263–280.
Stoffel, M., Casteller, A., Luckman, B.H., Villalba, R., 2012. Spatiotemporal analysis of channel wall erosion in ephemeral torrents using tree roots — an example from the Patagonian Andes. Geology 247–250.
Stoffel, M., Corona, C., in review. Dendroecological dating of (hydro-)geomorphic disturbance in trees. Tree-Ring Research.
Strunk, H., 1991. Frequency distribution of debris flows in the Alps since the Little Ice Age. Zeitschrift für Geomorphologie NF 71–81.
Strunk, H., 1997. Dating of geomorphological processes using dendrogeomorphological methods. Catena 31, 137–151.
Szymczak, S., Bollschweiler, M., Stoffel, M., Dikau, R., 2010. Debris-flow activity and snow avalanches in a steep watershed of the Valais Alps (Switzerland): dendrogeomorphic event reconstruction and identification of triggers. Geomorphology 116, 107–114.
Terasme, J., 1975. Dating of landslide in the Ottawa river valley by dendrochronology — a brief comment. Mass wasting. Proceedings, 4th Guelph Symposium on Geomorphology, pp. 153–158.
Timell, T.E., 1986. Compression Wood in Gymnosperms. Springer, Berlin.
Trappmann, D., Stoffel, M., 2013. Counting scars on tree stems to assess rockfall hazards: a low effort approach, but how reliable? Geomorphology 180–181, 180–186.
Valais, 2009. Archival records of past debris flows and related phenomena. Unpublished database, Canton of Valais, Switzerland.
Van Asch, T., Van Steijn, H., 1991. Temporal patterns of mass movements in the French Alps. Catena 18, 515–527.
Van Den Eeckhaut, M., Muys, B., Van Loy, K., Poesen, J., Beeckman, H., 2009. Evidence for repeated re-activation of old landslides under forest. Earth Surface Processes and Landforms 34, 352–365.
Weber, D., 1994. Research into earth movements in the Barcelonnette basin. In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community: Final Report 1, pp. 321–336 (Brussels, Belgium).
Wieczorek, G.F., Eaton, L.S., Yanosky, T.M., Turner, E.J., 2006. Hurricane-induced landslide activity on an alluvial fan along Meadow Run, Shenandoah Valley, Virginia (eastern USA). Landslides 3, 95–106.
Wilkerson, F.D., Schmid, G.L., 2003. Debris flows in Glacier National Park, Montana: geomorphology and hazards. Geomorphology 55, 317–328.
Williams, P., Jacoby, G., Buckley, B., 1992. Coincident ages of large landslides in Seattle Lake Washington. Geological Society of America Abstract with Programs, p. 90.
Yoshida, K., Kikuch, S., Nakamura, F., Noda, M., 1997. Dendrochronological analysis of debris flow disturbance on Rishiri Island. Geomorphology 20, 135–145.
Zimmermann, M., Mani, P., Gamma, P., 1997. Murganggefahr und Klimaänderung—ein GIS-basierterAnsatz. vdf Hochschulverlag ETH Zürich.