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Spatial and temporal occurrence of past debris flows in the Valais Alps - results from tree-ring analysis

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Table of contents

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Abstract

Debris flows are common mass-movement processes in most mountainous regions of the world, where their unpredictable and sudden occurrence represents a major threat to transportation corridors and settlements. Increased anthropogenic activity in regions exposed to debris-flow risk renders a detailed hazard assessment inevitable. However, archival data on past events remains scarce and, most of the time, fragmentary. Similarly, tree-ring analyses have been used only exceptionally to investigate past debris-flow activity. It is therefore the aim of this PhD thesis to reconstruct debris-flow frequencies for different torrents within the Valais Alps (Switzerland) using dendroecological methods in order to (i) contribute to the systematic acquisition of data on past events for hazard assessments, and (ii) to reconstruct the spatial extent and behavior of previous events. Also, the extension of tangential rows of resin ducts (TRD) was assessed in trees injured by debris-flow activity in order to improve knowledge regarding growth reactions of impacted trees.

In the first paper, 28 injuries from 8 European larches (*Larix decidua* Mill.) wounded during debris-flow activity in the Feergraben (Simplon region, Valais Alps) were investigated. The aim of the study was to assess the onset of TRD after wounding, as well as their vertical and tangential extensions. Consequently, 182 stem discs were prepared for analysis. This study represents the first fundamental research on the vertical and tangential extension of TRD in trees that have been impacted by a geomorphic process under natural conditions. As the trees were injured in October 2000 and November 2004, i.e. after the end of the local growing season, TRD could only be observed in the earlywood cell layers of the new growth ring. The vertical extension of TRD averaged 74 cm, but was much greater above rather than below the injury. At the height of the wound, TRD were present in 18% of the circumference remaining vital after the impact. In addition, a certain delay in the onset of the reaction could be observed with distance from the centre of the impact. Therefore, increment cores should be sampled close to the wound in future studies in order to avoid dating mistakes.

For the reconstruction of past debris-flow events in two catchments located in Val Ferret (Valais Alps, Switzerland), a total of 556 increment cores from 278 heavily affected European larches, Norway spruces (*Picea abies* (L.) Karst.) and Scots pines (*Pinus sylvestris* L.) were sampled from the cones of Reuse de Saleinaz and Torrent de la Fouly. Tree-ring analyses allowed reconstruction of 39 events for the period 1743 to 2003 at Reuse de Saleinaz. Along the debris-flow channel of the Torrent de la Fouly, 30 events were reconstructed for between 1862 and 2003. Although the catchments and channels of the two torrents evince considerable differences in geology and morphology, debris-flow frequencies are very similar with, on average, one event every eight years for the period reconstructed. In both catchments, material is apparently readily available and the triggering and occurrence of events thus seems to be transport- rather than weathering-limited.

The aim of the third study was to assess spatio-temporal patterns of past debris-flow activity on the cone of the Bruchji torrent (Blatten b. Naters, Valais). Based on a detailed geomorphic map (scale 1:1000), 401 obviously disturbed European larches and Norway spruces were sampled. In total, 960 growth disturbances identified in the samples allowed assessment of 40 event years for the period 1867-2005. The combination of tree-ring analysis with geomorphic mapping allowed identification of eleven previously active debris-flow channels. In addition, five patterns of spatial behavior of past events could be assessed. While older events preferentially affect trees in the western part of the cone, the flow regime apparently changed during the mid-1930s towards the eastern part of the cone.

In the last part of the study, two different dendro-ecological approaches were combined for the assess-ment of past debris-flow activity. Classical dating of growth disturbances with dendrogeomorphological methods allowed reconstruction of 49 events between AD 1782 and 2005. The spatial extent of events was determined by a positioning of disturbed trees on the geomorphic map. For sectors where survivor trees were absent, the oldest post-event trees were sampled and their age assessed counting the number of growth rings. Tree rings were added when the pith was absent on the increment core and to account for missing rings at sampling height. As a result, we were able to approximate the real age of trees with reasonable accuracy. The coupling of two different dendroecological approaches – dendrogeomorphological event reconstruction and assessment of germination dates of successor trees – allowed estimation of the minimum time elapsed since the last debris-flow activity for 23 of 29 channels on the cone. The time elapsed since the last event seems to increase with distance from the current channel.

In conclusion, this PhD thesis provides new insights into the possibilities and limitations of tree-ring analyses in debris-flow research. The onset, as well as the tangential and vertical extension of TRD, could, for the first time, be assessed in trees impacted by debris flows. In addition, frequencies of past events could be reconstructed for four torrents in the Valais Alps. 10-year frequencies indicate times of high torrential activity in the past, especially during the warm-wet period between 1916 and 1925. In contrast, a decrease in the number of events can be observed since 1996. However, it needs to be said that a part of this decrease in frequency should be considered as being the result of anthropogenic interventions in the channels, rather than the effect of changing climatic conditions. While this thesis provides valuable data for hazard assessment, reliable data on the magnitude of past events remains scarce. Consequently, further research needs to determine not only changes in the frequency, but also the influence of a changing climate on the magnitude of future events.

Keywords: *debris flow, tree ring, dendrogeomorphology, growth disturbance, frequency, spatial extension, tangential rows of traumatic resin ducts, vertical extent, axial extent, hazard assessment*

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Zusammenfassung

Murgänge sind in den meisten Berggebieten der Welt verbreitete Massenbewegungen, deren plötzliches und unvorhersehbares Auftreten eine Bedrohung für Transportwege und Siedlungen darstellt. Durch eine Ausbreitung der menschlichen Aktivitäten in Gebiete, die dem Einfluss von Murgängen ausgesetzt sind, ist eine detaillierte Gefahrenbeurteilung unumgänglich. Archivdaten zu vergangenen Ereignissen sind jedoch selten und meistens lückenhaft. Jahrringanalysen wurden bisher ebenfalls nur ausnahmsweise für die Untersuchung von vergangener Murgangaktivität eingesetzt. Das Ziel dieser Studie war es deshalb, Murgangfrequenzen für verschiedene Untersuchungsgebiete mit dendroökologischen Methoden zu erarbeiten, um zur systematischen Datenerfassung für Gefahrenbeurteilungen beizutragen. Zusätzlich wurden die räumliche Ausdehnung und räumliches Verhalten von Ereignissen rekonstruiert. Die Ausbreitung von traumatischen, tangentialen Harzkanalreihen (TRD) in von Murgängen verletzten Bäumen wurde ebenfalls untersucht, um die Kenntnisse über Wachstumsreaktionen betroffener Bäume zu verbessern.

In der ersten Studie wurden 28 Verletzungen von acht Lärchen (*Larix decidua* Mill.) untersucht, welche infolge Murgangaktivität im Feergraben (Simplongebiet, Walliser Alpen) verursacht wurden. Ziel der Untersuchung war, das erste Einsetzen sowie die vertikale und tangentiale Ausbreitung von TRD nach einer Verletzung zu bestimmen. Dazu wurden insgesamt 182 Stammscheiben für die Analysen vorbereitet. Diese Studie stellt die erste Arbeit dar, welche die vertikale und tangentiale Ausbreitung von TRD in Bäumen untersucht, welche durch einen geomorphologischen Prozess und unter natürlichen Bedingungen verletzt wurden. Da die Bäume im Oktober 2000 und November 2004 verletzt wurden, also ausserhalb der lokalen Wachstumsperiode, konnten die ersten TRD erst in den Frühholz-Zellreihen des neuen Jahrringes beobachtet werden. Die vertikale Ausdehnung der TRD betrug im Durchschnitt 74 cm, war jedoch oberhalb der Verletzung deutlich ausgeprägter als unterhalb. Auf der Höhe der Verletzung waren TRD in 18% des nach der Verletzung vital bleibenden Bereichs des Umfangs vorhanden. Daneben konnte eine gewisse Verzögerung beim Einsetzen der ersten TRD mit zunehmender Distanz vom Zentrum der Wunde beobachtet werden. Aus diesem Grund sollten bei künftigen Untersuchungen Bohrproben nahe bei der Verletzung gezogen werden, um Fehler in der Datierung zu vermeiden.

Für die Rekonstruktion vergangener Murgangereignisse in zwei Einzugsgebieten des Val Ferret (Walliser Alpen, Schweiz) wurden auf den Kegeln der Reuse de Saleinaz und des Torrent de la Fouly 556 Bohrproben von 278 stark betroffenen Lärchen, Fichten (*Picea abies* (L.) Karst.) und Föhren (*Pinus sylvestris* L.) gezogen. Jahrringuntersuchungen erlaubten die Rekonstruktion von 39 Ereignissen auf dem Kegel der Reuse de Saleinaz zwischen 1743 und 2003. Entlang der Murrinne des Torrent de la Fouly konnten 30 Ereignissen zwischen 1862 und 2003 rekonstruiert werden. Obwohl die geologischen und morphologischen Eigenschaften im Einzugsgebiet und im aktuellen Gerinne sehr unterschiedlich sind, bestehen kaum Unterschiede in der Murgangfrequenz: In beiden Wildbächen traten Murgänge demnach in der rekonstruierten

Zeitspanne durchschnittlich mindestens einmal alle acht Jahre auf. In beiden Einzugsgebieten steht offensichtlich ausreichend Material für die Auslöung von Murgängen zur Verfügung und die Auslösung und das Auftreten von Ereignissen dürfte daher eher transport- als verwitterungslimitiert sein.

Das Ziel der dritten Untersuchung war es, räumlich-zeitliche Muster vergangener Murgangaktivität auf dem Kegel des Bruchjis (Blatten b. Naters, Wallis) aufzuzeigen. Basierend auf einer detaillierten geomorphologischen Karte (Massstab 1:1000) wurden 401 offensichtlich gestörte Lärchen und Fichten beprobt. Durch die Datierung von 960 Wachstumsstörungen konnten 40 Ereignisjahre zwischen 1867 und 2005 rekonstruiert werden. Durch die Verknüpfung der Jahrringdaten mit jenen der geomorphologischen Karte konnten elf ehemalige Rinnen auf dem Kegel identifiziert werden. Zusätzlich wurden fünf Muster räumlicher Aktivität vergangener Murereignisse aufgezeigt. Während die älteren Ereignisse vornehmlich Bäume im westlichen Teil des Kegels betrafen, haben sich Murgänge während der 1930er-Jahre in den östlichen Teils des Kegels verlagert.

Im letzten Artikel wurden zwei unterschiedliche dendroökologische Ansätze für die Rekonstruktion vergangener Muraktivität kombiniert. Durch die klassische Datierung von Wachstumsstörungen mit dendrogeomorphologischen Methoden konnten auf dem Kegel des Grosse Grabe (Mattertal, Walliser Alpen) 49 Ereignisse zwischen 1782 und 2005 bestimmt werden. Die räumliche Ausbreitung der Ereignisse konnte durch die Positionierung der geschädigten Bäume auf der geomorphologischen Karte rekonstruiert werden. In den Sektoren, in welchen keine Bäume ein Ereignis überlebt haben und neue Bäume auf den Ablagerungen aufwuchsen, wurden die ältesten "Post-Event"-Bäume beprobt und ihr Alter durch das Zählen der Jahrringe ermittelt. Die Anzahl fehlender Jahrringe, die teilweise durch das Verfehlen des Baummarks während der Beprobung oder durch die Beprobung oberhalb des Wurzelanlaufs auftraten, wurde abgeschätzt und im Einzelfall dem errechneten Alter hinzugefügt, um so den Keimungszeitpunkt der Bäume so genau wie möglich zu bestimmen. Die Kombination der beiden Ansätze – dendrogeomorphologische Ereignisrekonstruktion und Bestimmung des Alters von Pionierbäumen – erlaubte eine Abschätzung des minimalen Zeitrahmens, der seit dem letzten Ereignis verstrichen ist, für insgesamt 23 der 29 Murrinnen auf dem Kegel. Es fällt auf, dass die Zeit seit dem letzten Ereignis mit wachsender Distanz von der heutigen Rinne stetig zunimmt.

Abschliessend kann festgehalten werden, dass diese Dissertation neue Erkenntnisse zu den Möglichkeiten und Grenzen von Jahrringanalysen in der Murgangforschung liefert. Das Auftreten und die tangentiale und vertikale Ausbreitung von TRD in von Murgängen betroffenen Bäumen konnte erstmals aufgezeigt werden. Daneben wurden Frequenzen vergangener Ereignisse für vier Wildbäche in den Walliser Alpen rekonstruiert. Dekadenfrequenzen deuten darauf hin, dass die Muraktivität vor allem während der warm-feuchten Phase von 1916 bis 1925 überdurchschnittlich hoch war. In Gegensatz dazu konnte seit 1996 eine klare Abnahme in der Anzahl Ereignisse festgestellt werden, die jedoch teilweise auch durch bauliche Massnahmen in den Rinnen verursacht wurde. Während die vorliegende Arbeit wichtige Grundlagen für die Gefahrenbeurteilung in mehreren Wildbäche liefert, fehlen zuverlässige Angaben zur Grösse vergangener Ereignisse weiterhin. Hier sind weitere Studien nötig, um nebst den Veränderungen in der Frequenz auch den Einfluss des sich ändernden Klimas auf die Magnitude künftiger Ereignisse abschätzen zu können.

Schlüsselwörter: *Murgang, Jahrring, Dendrogeomorphologie, Wachstumsstörung, Frequenz, räumliche Ausbreitung, Traumatische Harzkanalreihen, vertikale Ausbreitung, axiale Ausbreitung, Gefahrenbeurteilung*

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CHAPTER A

GENERAL INTRODUCTION

1 Introduction

1.1 Background

Debris flows [1] are widespread phenomena in Alpine regions where they repeatedly cause damage to the infrastructure or even provoke loss of life. Transportation corridors are often exposed to the devastating effects of debris flows in mountain torrents as well (e.g., BWG, 2002; Habersack & Krapesch, 2006; Jomelli *et al.*, 2007). Over the last 20 years, debris-flow and flooding activity has caused more than 20 casualties and damage amounting to several billions of Swiss Francs in the Swiss Alps alone. Due to its high-energy topography, the canton of Valais is particularly exposed to such events and has been repeatedly affected in the past decades, for example in 1987 (e.g., VAW, 1992; Rickenmann & Zimmermann, 1993), 1993 (e.g., Röthlisberger, 1994) and 2000 (e.g., BWG, 2002).

Destructive debris-flow and flooding events affecting major parts of the Swiss Alps – as the ones mentioned above – have been documented extensively and analyzed. In contrast, data on smaller, more isolated or older events is scarce or even completely inexistent. As a result, there is an important lack of knowledge on events prior to 1987, and on smaller events in isolated catchments for almost all torrents in the Swiss Alps.

Federal regulations in Switzerland require cantonal authorities to compile hazard maps and restrict development on hazard-prone terrain (Raetzo *et al.*, 2002). Therefore, assessment of hazards and risks and consequent planning of adequate countermeasures are of crucial importance. The federal authorities have thus developed a three-step procedure for the analysis of natural hazards (BWW, 1997; Raetzo *et al.*, 2002): As a first step, the hazard needs to be identified, and maps are produced showing the different phenomena identified in the field. Next, the magnitude or intensity, as well as the temporal occurrence of the process, needs to be determined. This is the basis for the production of hazard maps. Based on these hazard maps, land use has to be properly planned and, if necessary, risk management strategies, such as the design of protective countermeasures, have to be integrated. More details on the actual state, as well as the advances in landslide risk management in Switzerland, have been documented by Lateltin *et al.* (2005).

As a result of the legal requirements and the lack of information on past events and process dynamics, knowledge of the different mass-movement processes occurring in the Swiss Alps needs to be improved, so as to obtain reliable fundamentals for the production of hazard maps and thus the design of protection measures (ARE, 2003). A solid database of flow properties and the spread of material on deposition surfaces is also needed to enable modeling of mass-movement processes at the study-site level.

Similarly, there has been much debate on the existence of an increase in the frequency of disastrous debris-flow and flooding events over the past few years. With projected greenhouse warming (e.g., Christensen & Christensen, 2007), there are indications that, not only might the frequency of events be changing, but also the magnitude and seasonality of debris-flow and flooding events may be increasing (e.g., Milly *et al.*, 2002; Beniston, 2006). However, reliable data covering sufficiently long periods in the past is scarce and the effect of changing climatic conditions on mass-movement processes remains largely unknown.

[1] In this PhD thesis, the term „debris flow“ is used in its larger sense including all flow processes between sediment-charged flooding and debris flow in its strict sense (see Chapter A.2).

1.2 Aims of the study

The present PhD thesis therefore aims at reconstructing previous debris-flow activity in selected channels of the Valais Alps (Switzerland) that repeatedly produce debris flow. Using the study of tree-ring series, this thesis wishes to extend and densify the existing database used to analyze and assess natural hazards. At the same time, the different studies included in this thesis will also improve our knowledge of the process in general and its behavior during individual events. In addition, spatial patterns of previous events will be identified in order to determine sectors where material could actually leave the channel, thus resulting in overbank sedimentation and the re-activation of abandoned channels. Finally, the thesis will also contribute to the current discussion on the influence of changing climatic conditions on debris-flow activity.

The above objectives and questions will be addressed using conventional dendrogeomorphological approaches, such as the analysis of increment cores and cross-sections of disturbed trees. In addition, novel approaches will be employed and there will be a special focus on the appearance and extension of tangential rows of traumatic resin ducts within the stem. Similarly, germination dates of post-event trees will be used in order to indicate the minimum ages of deposits. So far, this approach has mainly been used in glacier forefields in order to date glacial deposits, but has not been applied for the assessment of the minimum ages of debris-flow cones.

1.3 Structure of the thesis

The thesis starts with a general introduction (Chapter A) containing basic information on the debris-flow process and on dendrogeomorphology. A summary of the methods used is provided in Chapter A.3, and an overview on the localization of the different study sites is given in Chapter A.4.

The main part of this thesis is composed of four papers: The first paper (Chapter B) contains fundamental results on the vertical and tangential extension of tangential rows of traumatic resin ducts as they occur after the impact of debris flows. In the second paper (Chapter C), the occurrence of debris-flow frequencies is described for two torrents located in the same valley, but affected by different geological settings. In Chapter D, the reconstruction focuses on the spatial behavior of past events and, indirectly, the spread of debris-flow material on the cone. In the fourth paper (Chapter E), minimum ages are assessed for trees growing on a cone so as to determine, approximately, the last occurrence of debris-flow activity in previously active channels.

An overall discussion and conclusion of the main findings (Chapter F), as well as three appendices (Chapter G), complement this work. Appendix F.1 contains a paper, co-written by the author of this PhD thesis, on the differentiation of debris-flow and snow avalanche activity on a cone influenced by both processes. In the other two appendices, pictures are provided of the different study sites and of the samples used in Chapter B. An overall bibliography (Chapter H) and a short curriculum vitae complete this thesis.

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2 Debris-flow process

2.1 Definition and classification

The first scientific study of a debris flow goes back to Stiny (1910) who described a flood in a mountain torrent and the consequent sudden increase of the amount of sediment carried by the flow. He concluded that the initial mixture changed into a viscous mass consisting of water, soil, sand, gravel, rocks and wood, flowing like lava. In his classic work, Johnson (1970) defined the debris-flow process as a gravity-induced mass movement, being intermediate between a landslide and flooding, and having its own mechanical characteristics. Varnes (1978) described debris flows as rapid mass movements consisting of granular solids, water and air, moving as a viscous flow.

The impressive characteristics of debris flows have been well described by Johnson & Rodine (1984, p. 257): "A wall of boulders, rocks of all sizes and oozing mud suddenly appears around the bend in a canyon preceded by a thunderous roar. As the boulder-choked wall passes, the channel remains filled with a debris-laden torrent of mud and boulders clanking and grinding together. The debris flows across an alluvial fan, engulfing structures and cars in its path, covering roads, fields and pastures with a blanket of muck, and slowly coming to a stop as the debris spreads in a lobate form with steep terminal snout and margins".

However, there is much dispute on the term "debris flow", as different terminologies and classifications of mass movements are used in the "flow" category (e.g., Varnes, 1978; Cruden & Varnes, 1996; Hungr *et al.*, 2001; Jakob, 2005; see Table A2.1). In this study, we provide lists and definitions for debris flow, debris flood or hyper-concentrated flow, mud flow and debris avalanche, based on the classification by Hungr *et al.* (2001).

The term **"debris flow"** can be used in its larger sense, meaning a specific phase of a landslide during which flowage of coarse material (debris) is occurring (Cruden & Varnes, 1996). It includes all processes between sediment-charged flooding and debris flow in its strict sense (Hungr, 2005). In its strict sense, the term "debris flow" means a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel (Hungr, 2005). Debris flows (in this strict sense) are usually considered to contain more than 50% of particles larger than sand size (Varnes, 1978).

A **"debris flood"** is a very rapid surging flow of water, heavily charged with debris, in a steep channel (Hungr, 2005). The term **"hyperconcentrated flow"** describes more or less the same phenomenon and was introduced by Beverage & Culberson (1964), who drew attention to its transitional behavior between sediment-charged flooding and debris flow. The distinction between hyperconcentrated flow and debris flow depends on the sediment concentration (Costa & Jarret, 1981; Pierson, 2005). Hungr (2005) differentiated between debris flow and debris flood on the observed or potential peak discharge of an event. In debris floods, the discharge is limited to 2-3 times that of a major flood and its impact is therefore relatively limited. In contrast, debris flows produce extremely large peak discharges spontaneously by means of surge growth processes (e.g., Pierson, 1980; Hungr, 2000), and have therefore a much higher destructive potential.

The term **"mud flow"** describes a very rapid to extremely rapid flow of saturated plastic debris in a channel, involving a significantly greater water content relative to the source material (Hungr, 2005). Mudflows are composed predominantly of silt, with some clay and fine sand (Pierson, 2005). Some authors used the term for relatively fine-grained debris flows occur-

Material	Water content	Special condition	Terminology
debris	saturated	established channel increased water content	debris flow
mud	at or above liquid limit	fine-grained debris flow	mud flow
debris	free water present	flood	debris flood
debris	partly - or fully- saturated	no established channel relatively shallow, steep source	debris avalanche

Table A2.1 *Classification of flow type landslides (simplified after* Hungr *et al. 2001).*

ring on rapidly eroding semi-arid slopes in sedimentary rocks and on volcanoes (Blackwelder, 1928; Crandell, 1957; Bull, 1964).

"Debris avalanches" are, in contrast, very rapid to extremely rapid shallow flows of partially- or fully-saturated debris on a steep slope, without confinement in an established channel (Hungr, 2005).

However, there is a continuum between all of these processes and a strict delimitation and classification is not always possible. Therefore, the term "debris flow" is used in its larger sense in this study and includes all flow-like mass-movement phenomena between sediment-charged flooding and debris flow in its strict sense.

2.2 Predisposition and triggering of debris flows

Prerequisites for the occurrence of debris flows are steep slopes, availability of debris, high pore pressure and a loss of consistency of the material after initial movement (Blijenberg, 1998). Generally, the area of debris-flow initiation is located on a steep slope, ranging between 20° and 45°. On slopes with an angle below 20°, the potential energy may not be sufficient to initiate a debris flow. On the other hand, on slopes steeper than 45°, the debris accumulation is normally too small for the release of a flow (Hungr, 2005). Sources of debris include deposits of gravitational mass-movement processes, colluvial gully fills, channel bedload material, zones of weathered or altered rocks, residual soils, headwalls and side slopes of steep gullies, talus deposits, steep unconsolidated moraines, man-made fills, and similar accumulations of unstable or erodible material (e.g., Hungr, 2005; Zimmermann & Haeberli, 1992; Rickenmann & Zimmermann, 1993).

Takahashi (1981) described two main locations for the initiation of debris flows. On one hand, they can be triggered on steep and often weakly consolidated talus slopes that meet the required predispositions, or in the contact zone of a rock wall and a steep talus slope. Similarly, debris flows can start as rigid translational slides on slopes that liquefy (Iverson *et al.*, 1997; Gabet & Mudd, 2006). On the other hand, debris flows can start in mountain torrents or rock couloirs filled with debris.

When the conditions for initiation are met, debris flows can be triggered in various ways. Rapid infiltration of prolonged intense rainfall, causing soil saturation and a temporary increase in pore-water pressure, is generally believed to be the mechanism by which most debris flows are generated during rainstorms (Iverson, 2000). The soil becomes saturated and destabilizes superficial deposits on steep slopes (Savage & Baum, 2005). However, long-duration rainfall with moderate intensity may also lead to triggering of debris flows. The close relationship between rainfall and debris-flow initiation, as well as threshold values for the triggering of debris flows, has been widely analyzed and documented in the literature (e.g., Caine, 1980; Innes, 1983; Wilson *et al.*, 1993; Wilson & Wieczorek, 1995). Similarly, rapid snowmelt can cause the initiation of debris flows; in extreme cases as an exclusive triggering process, or more commonly in combination with rainfall (Wieczorek & Glade, 2005).

However, debris flow may also initiate without the influx of water due to rainfall or snowmelt. Temporary damming in the channels (bank sliding, build-up of debris on the bed with subsequent failure) may provoke the initiation of a debris flow (Aulitzky, 1984). The breakout of glacier lakes (GLOF; Haeberli, 1983; Clague & Evans, 2000) can cause debris flows as well. Similarly, vibrations induced by earthquakes (Martinez *et al.*, 1999), volcanic eruptions (Pierson, 1992) or loading forces by snow avalanches or other mass movements (Bovis & Dagg, 1987; Marui *et al.*, 1997; Sassa, 1985; Selby, 1993; Sassa *et al.*, 1997) can trigger debris flows.

Recurrence intervals of debris flows are not only controlled by rainfall frequencies, as sediment availability must be considered as well. Therefore, channel recharge rates play an important role in the release as well as on the magnitude of debris-flow events in channels (Jakob *et al.*, 2005). Channels in weathering-limited basins typically recharge at rates controlled by rock weathering and disintegration, whereas transport-limited basins typically contain large volumes of readily mobilizable glacial, colluvial or volcanic material. Consequently, transport-limited basins tend to produce debris flows more readily whenever a climatic threshold is exceeded (Jakob *et al.*, 2005).

2.3 Transport and flow behavior

Once triggered, the rapid initial landslide may continue downslope in a flow-like motion following pre-existing channels. However, debris flows tend to build their own channels as well, as levees form at the lateral boundaries of the flow. As a result, they move down slopes and across unobstructed surfaces in almost any direction (Costa, 1984).

Debris flows commonly move in distinct waves or surges, separated by a watery intersurge flow. Such surges are characterized by a front mainly composed of boulders (Pierson, 1980, 1986). The main body of the surge is a finer mass of liquefied debris and the tail is a dilute, turbulent flow of sediment-charged water. A typical bouldery front and fine-grained tail of a debris flow is illustrated in Figure A2.1.

In fine-grained debris flows, the lack of boulders tends towards a more laminar flow behavior behind a turbulent front (Davies, 1986; Takahashi, 1991). Loading of loose material from the bed and banks in the flow path may increase the volume of the flow (Hungr, 2005), and erosion in the channel bed may destabilize the lateral bank. The banks may respond immediately and trigger shallow landslides directly into the body of the surge, or may release the mass subsequently, thus providing material for incorporation into a following surge or event (Hungr *et al.*, 2005).

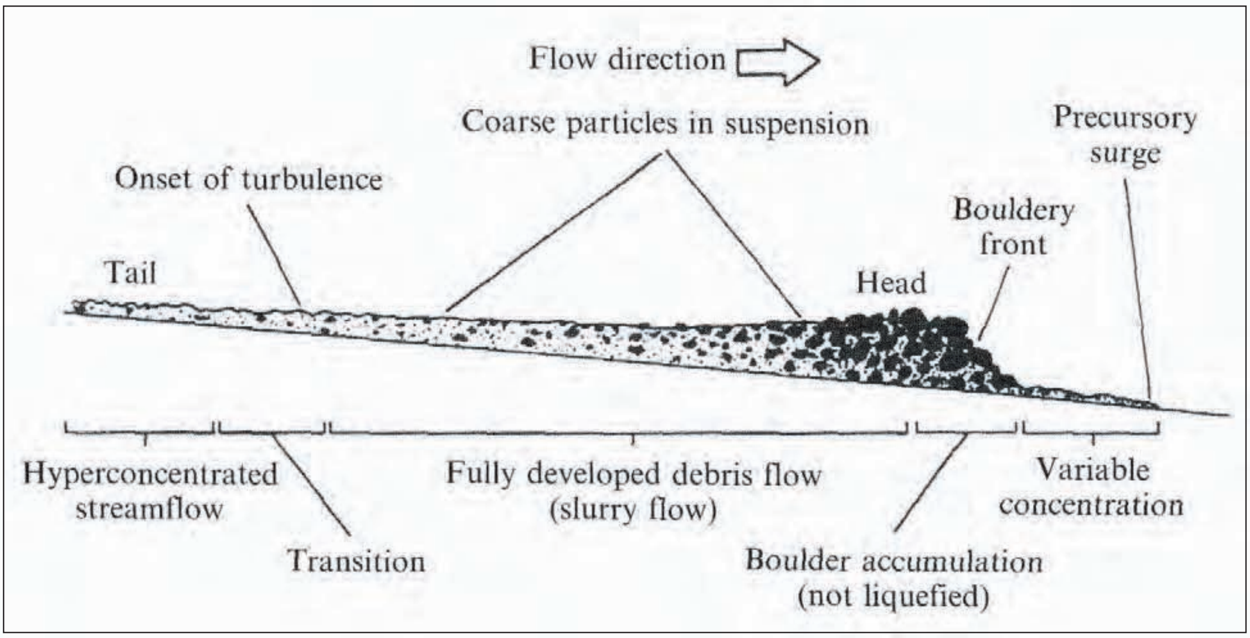

Fig. A2.1 *Representation of a typical debris-flow surge with a bouldery front (Pierson, 1986).*

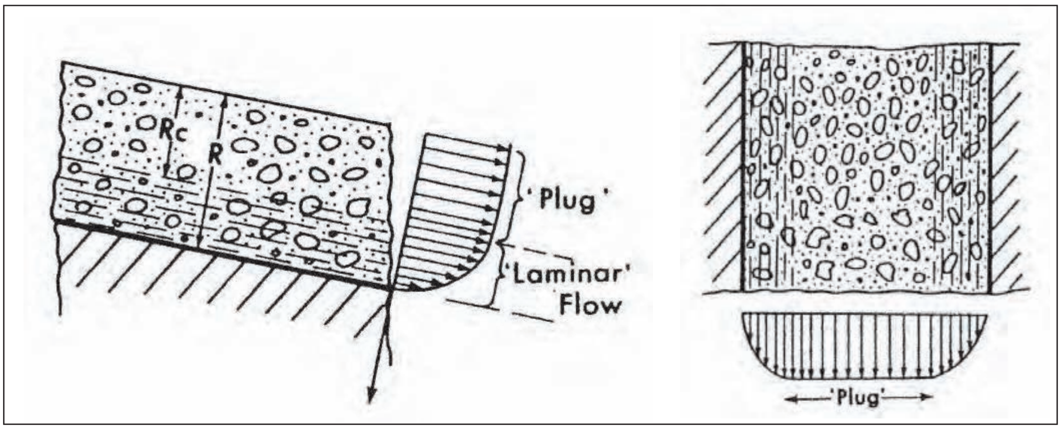

Fig. A2.2 *Profiles through a debris-flow mass and representation of the flow velocities. In the middle of the flow a rigid "plug" forms, whereas velocities are considerably decreasing at the borders of the mass (after* JOHNSON & RODINE, *1984).*

The velocity of debris flows varies with the characteristics of its flow and ranges from 0.5 to about 20 m s^{-1} (COSTA, 1984). However, the velocity in a flow is not evenly distributed. In the centre of the mass, a rigid "plug" is formed and flows with an almost constant velocity. According to JOHNSON & RODINE (1984), this "plug" generally occupies more than half of the diameter of the channel. In contrast, at the sides of the "plug", the velocity of the debris-flow mass considerably decreases and the flow behavior becomes more laminar (Fig. A2.2).

2.4 DEPOSITION

Deposition of debris-flow material starts once the slope angle or the water content decreases below a certain level (MAJOR & IVERSON, 1999). Deposition normally occurs throughout the movement of the flow, as the velocity of the mass is slower at the margins of the flowing mass and where boulders are pushed to the sides. The boulders form elongated levees (Fig. A2.3) of coarse material along the flow path of the debris flow (COSTA, 1984). These levees normally show a slight orientation of the particles, with the largest boulders found on the external side of the levee (VAN STEIJN, 1988).

Pore-fluid pressure of the debris-flow mass decreases and leads to a complete halt in the movement and subsequent deposition of material (MAJOR & IVERSON, 1999). At first, velocities at the debris-flow front slow down, the front then steepens to form a lobate deposit (HUNGR, 2005; Fig. A2.4). The material behind the front is either blocked in the channel or continues its way by leaving the channel and redirecting the flow, thus leading to the formation of distributary channels (HUNGR, 2005).

As a result of this deposition process, coarse debris-flow material usually forms large deposits in the upper part of debris-flow cones. In the distal part of cones, finer material and smaller forms are normally deposited (HUNGR, 2005). However, many debris-flow deposits are reworked by water flow following a debris-flow event. Repeated debris-flow activity with formation of temporary channels and deposition of lobate deposits leads to the formation of typical debris-flow cones.

Fig. A2.3 *(a) Debris-flow channel with two generations of lateral levees. The dashed red lines indicate the levees deposited by a recent event that occurred in a pre-existing channel. Signs of previous events can be identified by an older generation of levees (dashed black lines). (b) Two adjacent debris-flow channels with their lateral levees.*

Fig. A2.4 *(a) Debris-flow lobe formed with fine-grained material. Part of the water transported in the mass was evacuated after movement of the coarse fraction stopped, as can be seen in the lower part of the picture. (b) Front of a debris-flow lobe composed of boulders (photo courtesy of Igor Lièvre, used with permission)*

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3 Debris flows and tree rings

3.1 Principles of Dendrochronology

Dendrochronology is based on the fact that trees growing in the temperate regions form distinct annual growth rings. During spring and early summer, conifer trees form large tracheids with thin cell walls (earlywood cells), whereas smaller cells with thicker walls are formed at the end of the growing season in late summer and early autumn (latewood cells; Schweingruber, 1996). Due to the smaller cell size and the larger cell walls, latewood cells have a smaller lumen and therefore have a much darker appearance.

The size of each tree ring is influenced by biotic as well as by abiotic factors. Biotic factors include the genetic makeup as well as the ageing of trees and are individual for each species and each tree. Abiotic factors include e.g., light, temperature, water, nutrient supply or influence of strong wind and are more or less common for all trees growing at a specific site (Schweingruber, 1996).

Therefore, trees growing at the same site will record the same environmental impacts and fluctuations (e.g., temperature or precipitation) in their tree-ring series. This similarity in relative ring widths allows accurate dating of tree-ring series of unknown age. The method used for the absolute dating of wood is called "cross-dating" and allows the construction of long tree-ring series by overlapping the the inner parts of younger trees with the outer parts of older trees (Figure A3.1; Schweingruber, 1983).

Apart from the use of tree rings for pure dating purposes in dendroarcheology, the information contained in the growth sequences have been used repeatedly to retrieve information from the environment of the tree or the stand analyzed (dendroecology; Bräuning, 1995). Dendrogeomorphology represents one of the subfields of dendroecology and tree-ring series are used to study earth-surface processes such as debris flows, rockfall, snow avalanches or landslides.

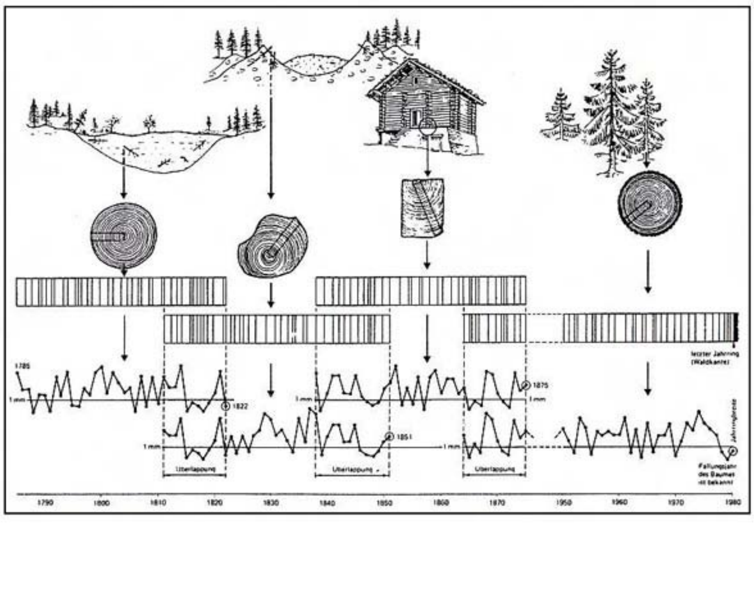

Fig. A3.1 *Cross-dating of tree-ring series of unknown age from houses or moraines with younger series from living trees illustrated with the raw data as seen on the cross-sections as well as in the form of measured ring-width series (*Schweingruber*, 1983).*

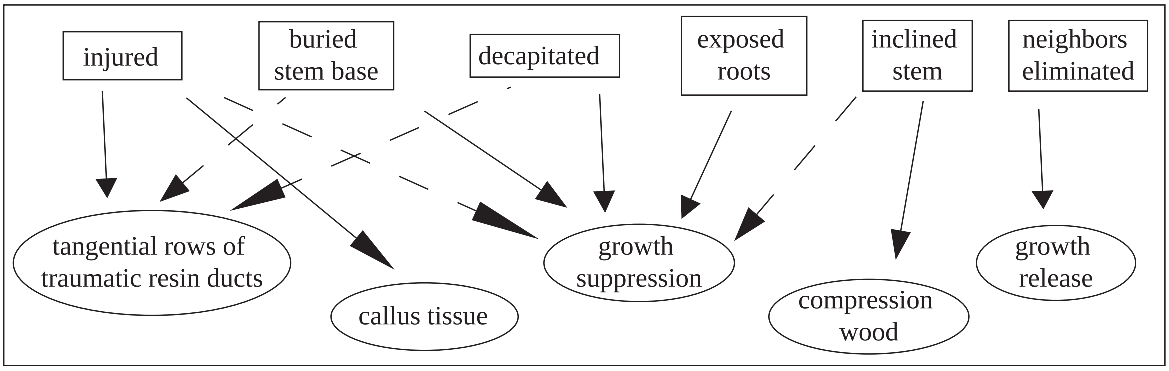

Fig. A3.2 *Different types of events on trees by debris flows (squares) and the related growth reaction (ovals). Solid lines represent common reactions to impacts; dashed lines indicate less frequent growth reactions.*

3.2 Influence of debris-flows on trees and their reactions to the impact

The analysis of geomorphic processes through the study of growth anomalies in tree-ring series is called dendrogeomorphology (Alestalo, 1971). Tree-ring analyses of geomorphic processes are based on the concept of "process – event – response" as defined by Shroder (1978). A mass movement, such as debris flows, represents the ***process***. When the geomorphic process impacts a tree ***(event)***, the latter will react to this intrusive event with a characteristic growth ***response***. Figure A3.2 provides an overview of the different events that can impact upon a tree and the resulting growth reactions.

In the following sections, the different types of events caused by debris flows, as well as the responses of trees are presented.

Injuries (wounds)

Any kind of material (e.g., rocks, boulders or trunks) transported in a debris-flow mass can cause injuries to the stems of trees growing in, or close to, the flow path. In the injured area, the dividing cambium cells can be destroyed and tree rings thus fail to form here (Schweingruber, 1996). From the edges of the injury, cambium cells start to overgrow continuously the wound by the production of callus tissue (Sachs, 1991; Larson, 1994). In addition, tangential rows of traumatic resin ducts (TRD) are formed on both sides of the injury (e.g., Fahn *et al.*, 1979; Nagy *et al.*, 2000; Stoffel & Perret, 2006).

As TRD are normally formed directly after the impact, the position of their first occurrence within the tree ring can be used to date the season of the event (Stoffel *et al.*, 2005a; Stoffel & Beniston, 2006). Depending on the force of the impact and/or

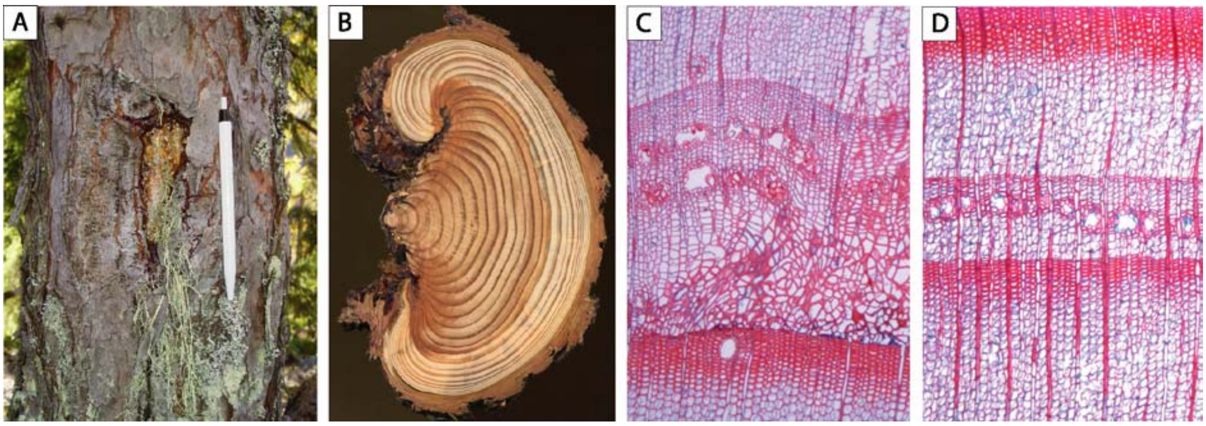

Fig. A3.3 *(a) Injured stem of a European larch. (b) Stem disc of an injured tree. Overgrowth starts from both sides of the injury. (c) Callus tissue as observed in the overgrowing wood. (d) Tangential rows of traumatic resin ducts in the vicinity of an injury.*

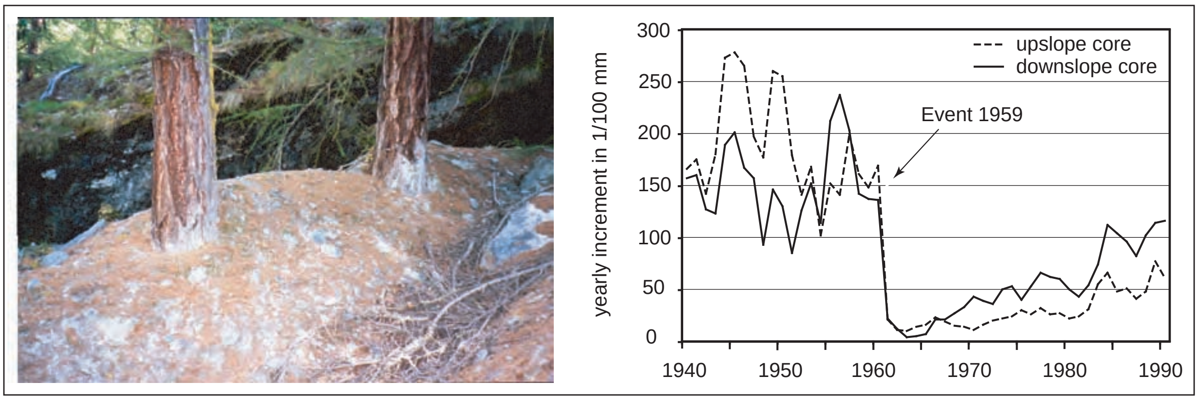

Fig. A3.4 (a) Trees with a buried stem base (photo courtesy of Dominique Schneuwly, used with permission). (b) After partial burial, trees respond with a distinct suppression.

the importance of the injury, decreased growth can be observed in the years succeeding the impact as well. Figure A3.3 shows macroscopic views of an injury in a stem and how a tree overgrows this injured part. In addition, microscopic illustrations are provided showing callus tissue and TRD.

Buried stem base

Debris-flow material can deposit around the stem base of trees affected by the mass movement. Growth in trees with a buried stem base is normally reduced, as the supply with water and nutrients is (temporarily) limited (Fig. A3.4; LaMarche 1966; Hupp *et al.*, 1987). According to Strunk (1997) working in the Dolomites, the maximum burial depth tolerated by Norway spruce (*Picea abies* (L.) Karst.) is between 1.6 and 1.9 m, depending on the material of the debris flow. Similarly, trees with buried stem bases may produce adventitious roots close to the new ground surface (Strunk, 1997).

Decapitation

Smaller trees may lose their crowns due to the impact of rocks and boulders transported in the debris-flow mass. In bigger trees, decapitation may occur as well, but it normally happens due to sinusoidal propagation of shockwaves in the stem as a result of impacts close to ground level ("hula-hoop" effect; see Dorren & Berger, 2006). Trees react to decapitation by distinct growth suppression in the years following the impact. In order to recover, one or several lateral branches will try to take the lead and thus replace the broken crown (Fig. A3.5), resulting in a "candelabra" tree morphology (Butler & Malanson, 1985; Shroder & Butler, 1987). In addition, the shock of the impacting material may also provoke the formation of TRD.

Exposure of roots

Debris-flow surges passing down a channel can also cause erosion in the channel bed or on its banks. As a result, roots of trees growing on the banks may be exposed after such an event (Figure A3.6).

Fig. A3.5 Branches take the lead and form a new crown after the loss of their apex resulting from geomorphic events (photo courtesy of Dominique Schneuwly, used with permission).

Fig. A3.6 Erosive debris-flow events in the channel lead to partial exposure of the root system of this tree. It will react to this new situation with growth suppression in the years after the event.

Again, water and nutrient supply will be limited in following years, resulting in growth suppression in the tree-ring series (LaMarche, 1968; Carrara & Carroll, 1979; McAuliffe *et al.*, 2006).

Inclination of stem

Unilateral pressure of the debris-flow mass can also lead to inclination of the stem. In order to regain its vertical position, conifers form compression wood on the downslope side of the stem (Clague & Souther, 1982; Giardino *et al.*, 1984; Braam *et al.*, 1987). In the tree-ring series, eccentric growth can be observed after such a tilting event. On the downslope side of the stem, tree rings become considerably wider compared to the upslope side, and the cell walls of the tracheids are much more important (Timell, 1986; Shroder, 1980). In addition, growth suppression can be observed if the tree was heavily impacted, especially on the upslope side of the stem. Figure A3.7 shows a tree that has been inclined by a geomorphic event; the onset of compression wood in the downslope sample is illustrated as well as eccentric growth identified in the tree-ring series.

Elimination of neighboring trees

Extremely devastating debris flows are capable of eliminating parts of forest stands. Trees growing next to the cleared surface will benefit from better growth conditions (i.e. more light, water and nutrients) and react by a growth release (Fig. A3.8; Schweingruber, 1996; Strunk, 1997).

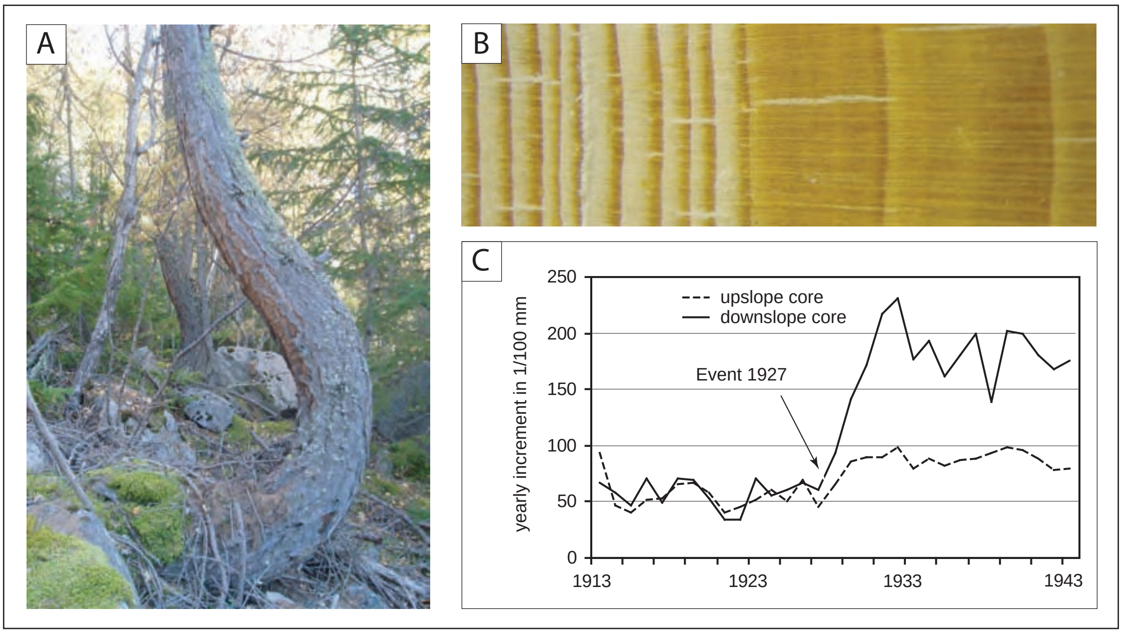

Fig. A3.7 (a) The stem of this tree was inclined by a geomorphic event. (b) On the downslope side of the stem, compression wood is formed (photo courtesy of Dominique Schneuwly, used with permission). (c) In the tree-ring series, eccentric growth can be observed after the impact.

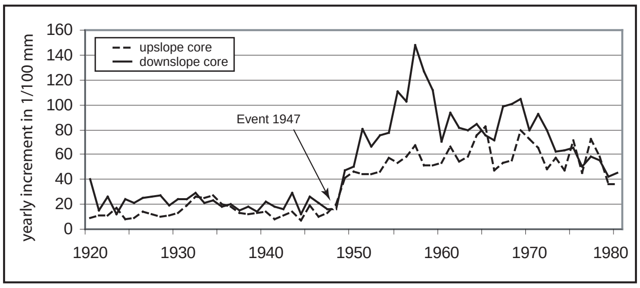

Fig. A3.8 *Partial elimination of a forest stand by a mass-movement event. Neighboring trees will benefit from better growth conditions and react by a growth release.*

3.3 Methods in dendrogeomorphology

3.3.1 Geomorphic mapping

For a dendrogeomorphological study whose object is to reconstruct previous debris-flow activity, field analyses need to start with a detailed overview of the processes present in order to exclude the influence of other geomorphic processes (e.g., rockfall or snow avalanche activity), as these events would falsify the results from subsequent tree-ring analyses.

Dendrogeomorphological studies of debris-flow cones normally start with mapping of all the geomorphic features existing on the present-day cone surface. In this thesis, special focus was addressed to features of previous debris-flow events, such as abandoned channels, levees and lobate deposits. Due to the presence of forest growth on the cones, as well as the shielding effect of high mountains, GPS devices could not be used. Therefore, mapping was based on detailed field measurements using a compass, a tape measure and an inclinometer. In this study, debris-flow cones were mapped on a scale of 1:1'000, meaning that all features larger than 1 m could potentially be included on the map.

Buildings or bridges present on official topographic sheets were used as fixed points for

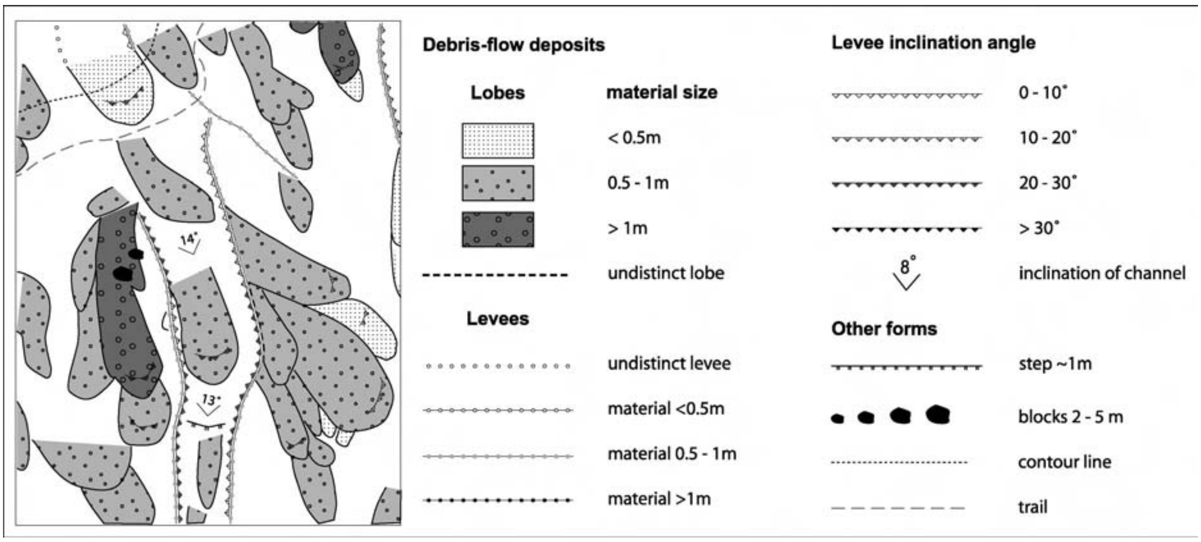

Fig. A3.9 *Illustration of a geomorphic map showing channels, levees and lobate deposits.*

the accurate mapping of previously active debris-flow channels and deposits. The most important characteristics of debris-flow features measured in the field were their direction and inclination. Slope angles and the height of levees bordering the channels were assessed as well. Lobate deposits were delineated with several cross profiles in order to assess their form, height, orientation and inclination. In addition, block sizes of all deposits were noted. Further features present on the current-day cone surface, such as large blocks or anthropogenic interventions, were included on the map as well.

In the lab, distances measured in the field were recalculated using the following formula:

a * cos ß = b

with **a** representing the distance measured in the field, **ß** the slope angle and **b** the resulting distance as seen on the map.

The illustration of the geomorphic map was obtained using Adobe Illustrator 9.0 (Fig. A3.9) and served as a basis for the sampling strategy.

3.3.2 Sampling methods and strategy

Based on the geomorphic map, trees were selected that showed obvious signs of disturbance by previous debris-flow events (see Chapter A.3.2). The sampling of these trees was done by felling with a handsaw or chainsaw, depending on the diameter of the tree-stems. The advantage of sampling entire trees is the amount of information present on cross-sections that can be prepared from all desired positions in the stem. However, analyzing entire stems is very time-consuming and transport of samples from the (remote) study sites to the lab can be a problem as well. In addition, the method is not applicable for sampling of entire forest stands. Finally, felling of trees is normally not possible in protection forests.

The second sampling method, which is more appropriate for the analysis of entire forest stands, is the extraction of increment cores (Grissino-Mayer, 2003). An increment borer with a length of 40 cm and a diameter of 6 mm is turned into the stem of the tree, and a core with 5 mm diameter extracted. Figure A3.10 illustrates the two sampling methods.

As it appears more difficult to identify growth disturbances on increment cores, as opposed to stem discs, special attention needs to be taken with the sampling position on the tree. In this study, decapitated trees, trees with exposed root systems or trees with buried stem bases were sampled as close to the ground as possible to obtain the largest number of tree rings possible. Two cores were normally extracted from these trees, one in the direction of the impact, and another one on the opposite side of the stem. In the case of tilted stems, two cores were extracted at the height of the angle-change, one on the upslope side, and another on the downslope side, where the presence of compression wood was expected. Finally, sampling of trees with

Fig. A3.10 *Sampling methods used in this study included the felling of trees with a chainsaw (left) or the extraction of cores with increment borers (right).*

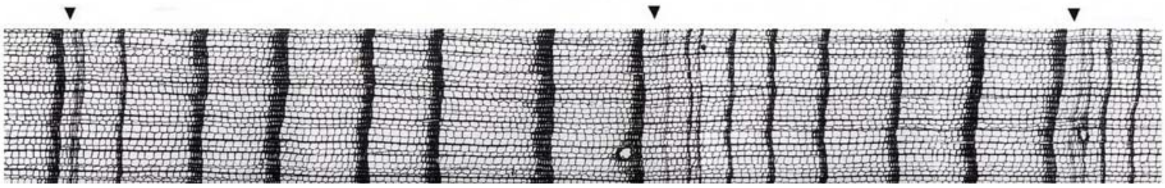

Fig. A3.11 Outbreaks of larch budmoth are identified in the tree-ring series in the form of narrow tree rings with almost no latewood (see arrows; adapted after SCHWEINGRUBER*, 2001)*

visible injury included the extraction of at least three cores. Two samples were taken from the lateral edges of the injury where signs of the impact were visible in the tree-ring series, but where no rings were missing due to abrasion. In addition, one more sample was taken from the opposite side of the stem.

The samples were then labeled and stored in a receptacle for transport, and the position of each tree sampled was marked on the geomorphic map. Further data noted for the sampled trees included a description of the nature of the disturbance, determination of its position within the deposits, stem diameter at breast height (DBH), position of the cores sampled, tree height and information on neighboring trees.

3.3.3 Sample preparation, counting of tree rings, skeleton plots and ring–width measure ments

Increment cores were glued onto a wooden support, with special attention being made to the direction of the wood fibers, which needed to be vertical to allow further analysis (ISELI & SCHWEINGRUBER, 1989). Increment cores and stem discs were then sanded or prepared with a cutter. White chalk powder was sometimes applied to the samples in order to fill the cells and thus increase the visibility of tree-ring characteristics under the stereomicroscope (ISELI & SCHWEINGRUBER, 1989).

Tree rings were then counted, starting from the outermost ring which represents the year of sampling (e.g. 2005). Thereafter, increment cores and cross-sections were analyzed visually, and rings with particular growth characteristics noted on skeleton plots (SCHWEINGRUBER *et al.*, 1990). Special attention was focused on extremely narrow, as well as large, tree rings. In addition, all changes in the wood structure, such as tangential rows of traumatic resin ducts, callus tissue or compression wood were noted on the skeleton plots. This method primarily assists the cross-dating of samples by identifying false or missing rings. Similarly, characteristic years present in a large number of samples (i.e. pointer years; SCHWEINGRUBER *et al.*, 1990) can be identified. In European larch trees (*Larix decidua* Mill.), outbreaks of larch budmoth (*Zeiraphera diniana Gn.;* Fig. A3.11) occur at more or less regular intervals, and are identified in the tree-ring series as very narrow rings with almost no latewood (WEBER, 1997; BALTENSWEILER & RUBLI, 1999). The inclusion of larch budmoth chronologies for the study sites is crucial in order to avoid misinterpretation of growth suppression in trees impacted by debris flows.

In a subsequent step, ring widths were measured using a LINTAB positioning table coupled to a Leica stereomicroscope (Fig. A3.12). In this study, the software used for the measurement of the ring width is called TSAP (Time Series Analyses and Presentation; RINNTECH, 2007). This program also allows representation of measured tree-ring series, as well as cross-dating and quality checks of the growth curves. Ring widths were measured with an accuracy of 1/100 mm.

Fig. A3.12 LINTAB positioning table coupled to a Leica stereomicroscope and TSAP software was used for the measurement of tree-ring width.

3.3.4 Building a reference chronology

In undisturbed trees (i.e. trees that have not been affected by geomorphic events), growth suppressions and releases are driven by climate or the influence of insect outbreaks. Trees belonging to the same species and growing at the same site are considered to be benefiting or suffering from the same environmental conditions and are thus supposed to show the same growth patterns in their tree-ring series. The general growth patterns of one species at a specific site can be summarized in a reference chronology (Cook & Kairiukstis, 1990; Schweingruber, 1996). Within this study, at least 15 undisturbed trees were sampled per species with two increment cores each. Samples were taken perpendicular to the slope in order to avoid the influence of compression wood.

Increment cores were prepared and measured as described for the disturbed samples. In a succeeding step, mean curves were constructed for each tree and standardized with 11-year moving average so as to eliminate the influence of long-term trends such as ageing (Cook & Kairiukstis, 1990). In addition, the mean curve of every tree was then indexed. Trees with abnormal growth features were eliminated before an overall mean curve was constructed with the remaining trees. As not all trees included in the reference chronology have the same age, their number decreases the further back the curve goes in time. The reference curve ends as soon as it consists of less then five trees. Figure A3.13 illustrates the indexation and standardization procedures applied to the raw growth curves of a reference tree.

3.3.5 Dating events in tree-ring series

For the identification of growth reactions resulting from debris-flow activity, tree-ring series of the disturbed trees were compared with the growth curves of the reference chronology. This procedure allows identification of abrupt changes in growth, such as suppression or release. Other reactions testifying to disturbance by debris flows include the onset of compression wood in tilted stems, injuries and callus tissue after wounding as well as TRD. In the case of TRD and callus tissue, the intra-annual position of the disturbance was noted, in addition to the year of the event.

As certain growth reactions can be provoked by influences other than geomorphic, it is important to consider the relative number of trees showing reactions in a specific year (Shroder, 1978; Butler *et al.*, 1987). In this study, no fixed index value has been defined for the consideration of an event year.

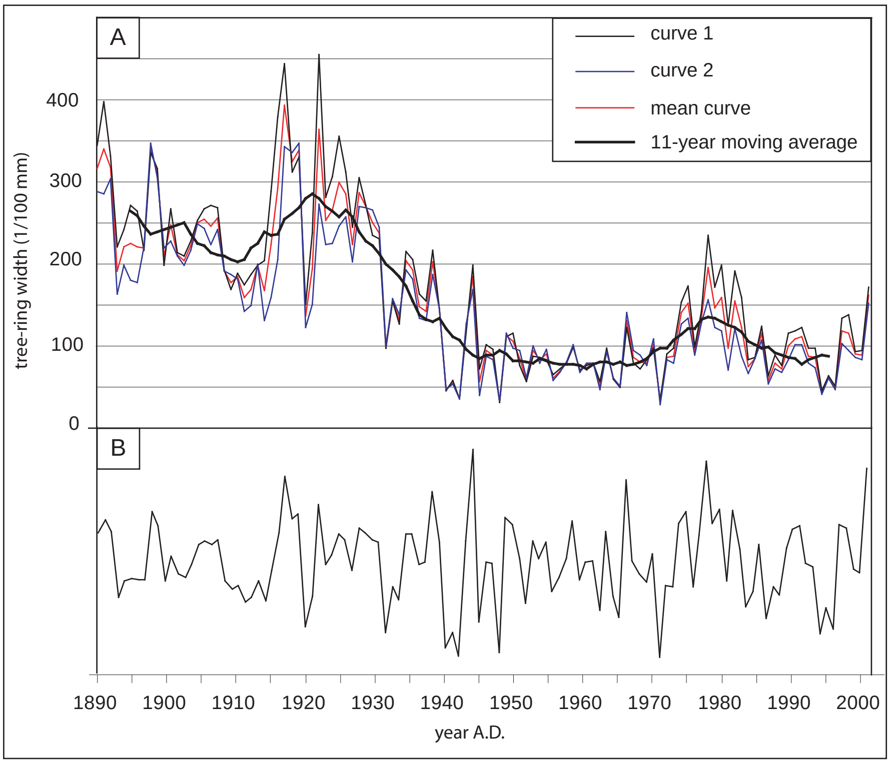

Fig. A3.13 *(a) The mean curve of an individual tree of the reference chronology is constructed from the two growth curves and standardized with a 11-year moving average. (b) Growth curve of the same tree after indexation and standardization.*

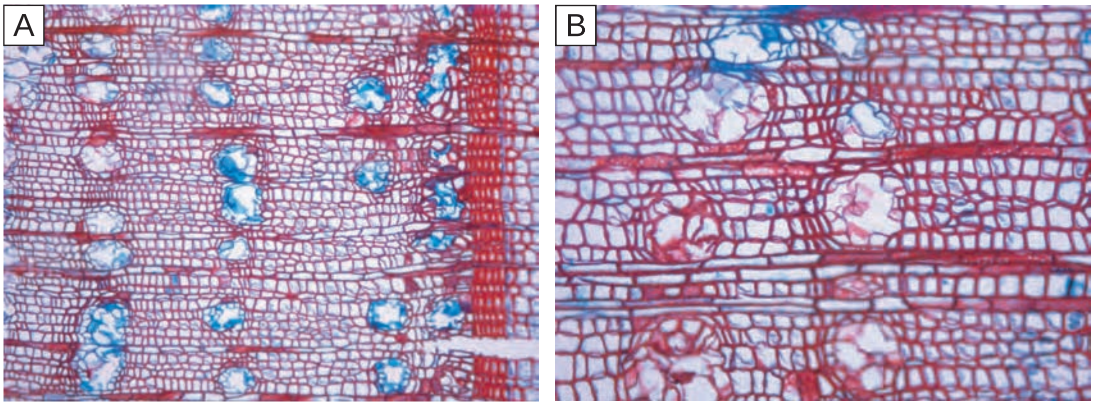

Fig. A3.14 *Micro-cuts of a tree ring with multiple rows of traumatic resin ducts (magnifications: a: 100x; b: 200x).*

In contrast, the strength of the signal, the number of trees with signals as well as their distribution on the cone were taken into account for dating past events. In case reactions were not significant, they were not considered, and no event was dated for that year in question.

3.3.6 Preparation of micro-cuts

Micro-cuts are helpful as soon as further analyses, such as the intra-annual position of callus tissue or TRD within the tree ring, need to be identified (Schweingruber, 1990). In a first step, wooden blocks of the most interesting segments were cut off with a knife from the rest of the sample. Micro-cuts with a thickness of approximately 10 x 10^{-6} m were then prepared using a Reichert sliding microtome. The cuts were then immersed with javel water in order to remove the cell contents, and rinsed with water before they were stained with a 1% safranin and astrablue solution. Afterwards, the cuts were again rinsed, this time with water, 75% alcohol, absolute alcohol and xylol. In a final step, the cuts were fixed onto slides with Canada balm and dried in an oven at 60° C for 12 hours. Figure A3.14 shows micro-cuts of a tree ring with tangential rows of traumatic resin ducts.

3.4 Research on debris flows using tree rings – a state of the art

In **North America**, dendrogeomorphological analyses of debris flows were introduced by Hupp (1984), Hupp *et al.* (1987) and Osterkamp & Hupp (1987), who reconstructed magnitudes and frequencies of previous events in several creeks on Mount Shasta (northern California) since AD 1580. They were also able to attribute the formation of terraces along the creeks to individual events. An overview of tree-ring analysis and recent applications of the method in North America is provided by Wiles *et al.* (1996). More recently, May & Gresswell (2004) assessed spatial patterns of debris-flow activity as well as recurrence intervals in 125 headwater basins in the Oregon Coast Range. In addition, they determined different types of debris-flow cones and deposits. The same authors (May & Gresswell, 2003) calculated sediment and wood accumulation in channels by identifying the moment of last activity in channels with dendrochronological methods. Wilkerson & Schmid (2003) investigated debris flows in the Glacier National Park (Montana) to define the geomorphology of, and hazards posed by, such events. Finally, Jakob *et al.* (2005) used tree-ring analysis for the assessment of past frequencies and stress that channel recharge rates are a crucial prerequisite for the formation of future debris flows.

In **Asia**, dendrogeomorphological investigations were conducted with living and dead (buried) trees on the head of a debris-flow cone to determine the debris-flow frequency of a channel on Rishiri Island (Yoshida *et al.*, 1997).

In **Europe**, debris-flow research based on tree-ring data started with the studies of Strunk (1989, 1991, 1995, 1997), who reconstructed frequencies back to the 16th century and who focused on the occurrence of adventitious roots. Stefanini & Ribolini (2003) investigated five debris-flow cones in the Maritime Alps Massif (Cuneo province, Northwest Italy) with tree rings, and assessed the frequency of events. Dendrogeomorphological analysis in combination with radiocarbon dating allowed the reconstruction of debris-flow histories for the late Holocene in the Valle del Gallo in Northern Italy (Sondrio province; Santilli & Pelfini, 2002).

In **Switzerland**, Baumann & Kaiser (1999) reconstructed a 500-year debris-flow chronology for the Multetta cone (Tschierv, Grisons) through analysis from living trees as well as the excavation of buried stems. Stoffel *et al.* (2005b) reconstructed debris-flow events on the Ritigraben cone (Grächen, Valais) with dendrogeomorphological methods and compared their results with data on floods in neighboring catchments to define triggering weather conditions for the last four centuries. Tree-ring data from the Ritigraben torrent were also used to assess changes in the seasonality of debris-flow events and to identify potential changes in the frequency or magnitude in a future greenhouse climate (Stoffel & Beniston, 2006). Most recently, debris-flow deposits were dated on the cone (32 ha; Stoffel *et al.* (2007) so as to create the basis for the first tree ring-based magnitude-frequency analysis.

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4 Study sites

Fieldwork for the present PhD thesis was conducted on six sites in the Valais Alps (Southern Switzerland). An overview of the different study sites is provided in Figure A4.1. The first study (Chapter B) was undertaken on the fluvial terrace of the Laggina and Feergraben torrents (shown with an L on the map). In the second study (Chapter C), analyses were performed on the Reuse de Saleinaz (S) and Torrent de La Fouly (F) cones. A third study (Chapter D) was made on the cone of the Bruchji torrent (Br), and the field work of the last investigation (Chapter E) was performed on the cone of the Grosse Grabe (G). The fieldwork for the paper presented in the appendix (Chapter G1) was conducted on the Birchbach cone (Bi; Lötschental).

Details of the individual study sites are provided in the relative chapters. Pictures illustrating the characteristics of the study sites are shown in Appendix G.3.

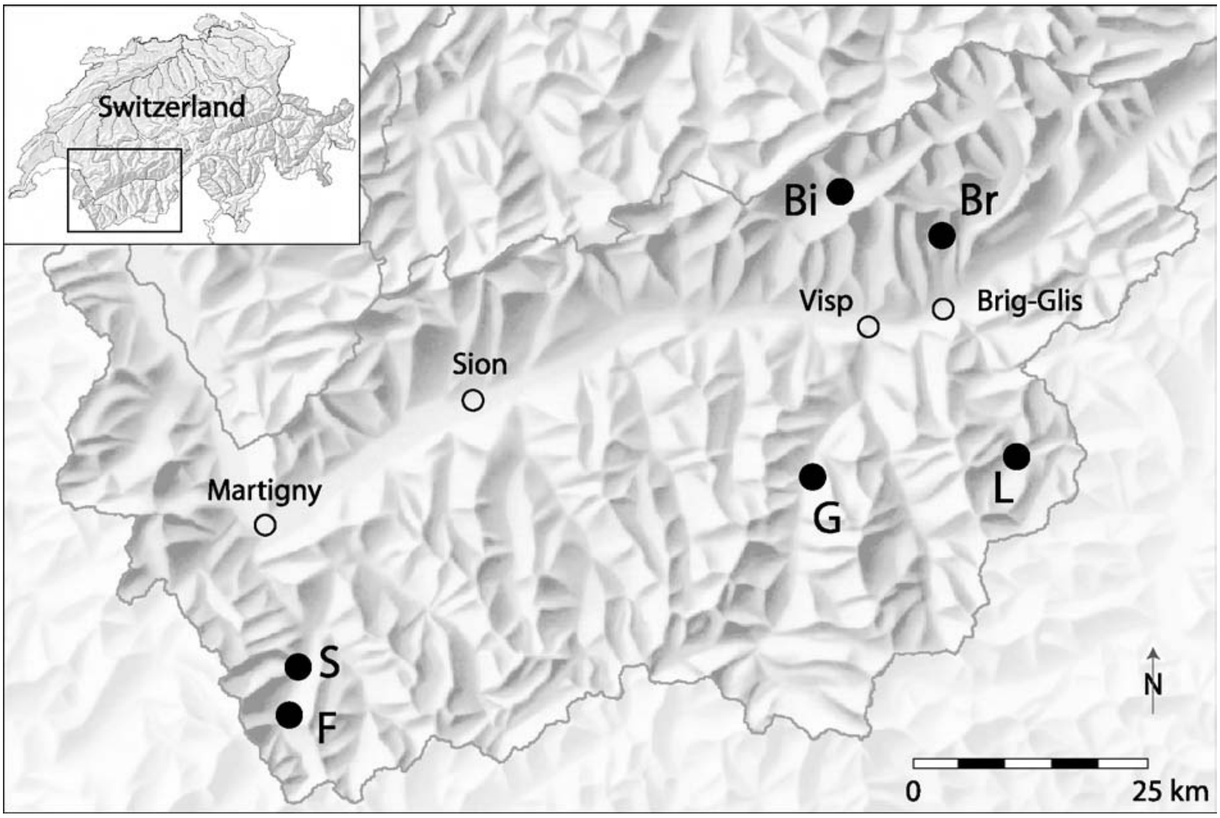

Fig. A4.1. Study sites of this PhD thesis are located in the Valais Alps (southern Switzerland): L = Laggina; S = Reuse de Saleinaz; F = Torrent de La Fouly; Br = Bruchji; G = Grosse Grabe; Bi = Birchbach (map © 2007 Swisstopo).

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CHAPTER B

Traumatic resin ducts in *Larix decidua* stems impacted by debris flows

Traumatic resin ducts in *Larix decidua* stems impacted by debris flows

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"Traumatic resin ducts in *Larix decidua* stems impacted by debris flows"

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Abstract

Following mechanical injury, stems of many conifers produce tangential rows of traumatic resin ducts (TRDs), the distribution of which has been used to date geomorphic events. However, little is known about how far TRD formation extends tangentially and axially from the point of injury or what the time course of TRD appearance is. We analyzed 28 injuries in eight *Larix decidua* Mill. tree stems resulting from debris flows in October 2000 and November 2004. Injuries occurred outside the period of cambial activity, and TRD formation occurred in the first layers of the growth ring formed in the year following that of injury. The axial extent of TRD formation averaged 74 cm and was greater above the injury than below it. At the height of the wound center, TRDs extended horizontally to a mean of 18% of the stem circumference excluding that portion where the cambium had been destroyed. In subsequent growth rings, TRDs, if present, were confined mainly to the height of the center of injury. Both the vertical and horizontal extent of TRD formation was related to the injury size. Within growth rings, the position of TRD formation changed with increasing distance from the wound progressing from early earlywood to later portions of the growth ring.

Keywords

axial extension, dendrogeomorphology, European larch, injury, onset of traumatic resin ducts, tangential extension

1. Introduction

Debris flows on steep hillsides are fast-flowing mixtures of water, gas, soil and rock (Varnes, 1978) that can cause tree stem abrasion, bending, burial or breakage. Growth responses to such impacts, which include compression wood formation (Clague & Souther, 1982; Timell, 1986; Braam *et al.* 1987; Fantucci & Sorriso-Valvo, 1999), reduced growth (LaMarche, 1968; Strunk 1997) and multiple leader formation (Butler & Malanson, 1985; Mattheck, 1991), have been used to date geomorphic events (e.g., Baumann & Kaiser, 1999; May & Gresswell, 2004; Stoffel *et al.* 2005a; Bollschweiler & Stoffel 2007).

In many conifers, mechanical damage to stems results in the formation of tangential rows of traumatic resin ducts (TRDs; LePage & Bégin, 1996; Stoffel & Perret, 2006). In several studies, the presence and distribution of TRDs have been used to date past debris flows (Stoffel & Beniston, 2006; Bollschweiler *et al.* 2007; Stoffel, 2007). There is uncertainty, however, about the timing and the vertical and horizontal distribution of TRD formation following stem injury. This information is crucial for determining the appropriate sampling strategy for tree-ring analysis based on nondestructive increment core sampling.

Widely scattered resin ducts are a common feature in stems of trees of the genus Larix (Bannan, 1936). In contrast, TRD formation in the developing secondary xylem is observed only after insect or fungal attack, fire damage or mechanical wounding (e.g., Thomson & Sifton, 1925; Fahn *et al.*, 1979; Nagy *et al.*, 2000; Langenheim, 2003; Hudgins *et al.*, 2004). When a portion of the cambium has been destroyed, resin ducts normally form within the current growth ring in tangential series close to the wound and occasionally also in succeeding rings (Bannan, 1936). The formation of TRDs represents a nonspecific defense response to injury that compartmentalizes the wood (Berryman, 1972; Tippett *et al.*, 1982; Shigo 1984).

A tree's response to wounding normally begins shortly after injury. If wounding occurs during the period of cambial activity, resin ducts differentiate in the developing secondary xylem within 4 to 28 days following injury (Nagy *et al.*, 2000; Franceschi *et al.*, 2002; Luchi *et al.*, 2005). Fahn *et al.* (1979), who studied *Cedrus libani* A. Rich. trees growing in a Mediterranean climate in the Northern Hemisphere, observed that TRDs are always formed in the year of the disturbance if the wounding occurs between April and October. They also observed that wounding in November may occasionally lead to a brief resumption of cambial activity during which time a few short TRDs are formed. In contrast, TRDs were not formed until the following growing season if the disturbance occurred between December and March. Similarly, Bannan (1936) concluded that the characteristics and the amount of tissue formed in response to wounding vary with the circumstances of the injury. The most extensive development of ducts was observed following injury during the growing season. If injury occurred during dormancy, TRD formation did not take place or occurred to only a limited extent in the next season's growth ring. Likewise, Franceschi *et al.* (2002) observed that TRD formation in *Picea abies* (L.) Karst. trees following methyl jasmonate treatment was much weaker when treatment occurred late in the growing season than when it occurred in spring.

According to Bannan (1936), TRDs may extend several centimeters above and below a stem wound, although remaining narrowly confined in the horizontal dimension. Franceschi *et al.* (2002) observed that in *P. abies* treated with methyl jasmonate, a ring of TRDs formed in the treated area, but was rarely more than 5 cm above the treated sector and never beyond 15 cm from the wound. Luchi *et al.* (2005) observed TRDs in Pinus nigra Arn. up to 12 cm from sites of inoculation with *Diplodia scrobiculata* or *Spahaeropsis sapinea*. Experiments with *Pinus pinea* L. show that decapitation significantly increases the number of TRDs to a distance of 10 cm below the point of stem severance (Lev-Yadun, 2002). In contrast, there is little information on the tangential extension of TRD formation after wounding. It appears that the number and size of ducts decreases with distance from the wound (Fahn *et al.*, 1979) and that their arrangement becomes more dispersed (Bannan, 1936). Moore (1978) concluded that responses in broad-leaved trees can extend tangentially up to 20 cm from the impact site. Thus, there is, at present, only limited knowledge about the axial and tangential distribution of TRDs in tree stems after wounding. Furthermore, most studies have been on juvenile plants or based on treatments with hormones or fungi, or on decapitated trees.

In this study, we focused on the presence of TRD bordering wounds in adult *Larix decidua* Mill. trees injured by debris-flow events of known date, and sought to determine the vertical and horizontal extent of induced TRD formation and the time course of TRD appearance following injury. We analyzed 182 stem discs from eight L. decidua trees with a total of 28 injuries.

2. Materials and Methods

2.1 Study site

The study site (46°11' N, 8°05' E) is located 8 km south of the Simplon Pass (Valais Alps, Switzerland). The forest stand is situated at 1220 m a.s.l. on a fluvial terrace and is primarily composed of European larch (*L. decidua*). Vegetation is influenced by debris flows and flooding in the Feergraben and Laggina creeks that traverse the terrace. Between October 14 and 15, 2000, intense precipitation in the Valais Alps caused debris-flow events in the Feergraben, when trees were impacted during the transport of large amounts of solid material. Another debris flow, on November 2, 2004, caused further damage. The debris included boulders up to 0.5 m in diameter.

Phenological data at the study site were obtained in 1976, when growth of L. decidua started around May 16, latewood formation commenced on July 17 and growth ceased on October 9 (Müller, 1980). It can thus be assumed that earlywood formation at this site lasts from around mid-May to mid-July and that latewood tracheids develop between mid-July and early to mid-October. Cambial activity ceases between mid-October and mid-May. Mean annual temperature at the study site is about 5 °C, and mean annual rainfall totals 1216 mm (MeteoSwiss, 2007).

2.2 Field collection and sample preparation

Formation and extension of TRDs after wounding was observed in eight *L. decidua* trees visibly damaged by either the 2000 or the 2004 debris flows or both. Tree characteristics are given in Table B2.1. The bases of some trees growing in the levees of the creeks were buried by material originating from previous debris flows. To permit analysis of all injuries, such partially buried stems were excavated before the trees were felled. Stem injuries were located by height above the root collar, and their vertical and horizontal extent of the injuries recorded. Trees were then cut into segments about 10 cm long, with the first cross section taken at the root collar. Additional sections were taken around the upper and lower boundaries of the wounds.

In the laboratory, stem sections were dried and polished with 400-grit sandpaper, and the tree rings counted. To investigate changes in the position of TRDs within the growth rings, sections

Tree	Age (years)	DBH (cm)	Tree height (m)	Injuries (no.)	Event years	Samples (no.)	*L* (cm)
A	48	19.5	14	4	2000, 2004	18	258
B	54	9	15	3	2000, 2004	30	324
C	54	7	14	3	2000	18	200
D	42	6	6.5	5	2000, 2004	27	234
E	44	15	14	2	2000	16	249
F	42	12	5	5	2000, 2004	24	273
G	41	5	14	5	2000	30	287
H	48	13	12	1	2000	19	268
Mean	46.63	10.81	11.81	3.50		22.75	261.63
Total				28		182	

Table B2.1 *Descriptive parameters of the Larix decidua trees chosen for analysis. The height of trees is relative to the present-day ground line. Abbreviation: DBH, diameter at breast height; and L, total length of the samples.*

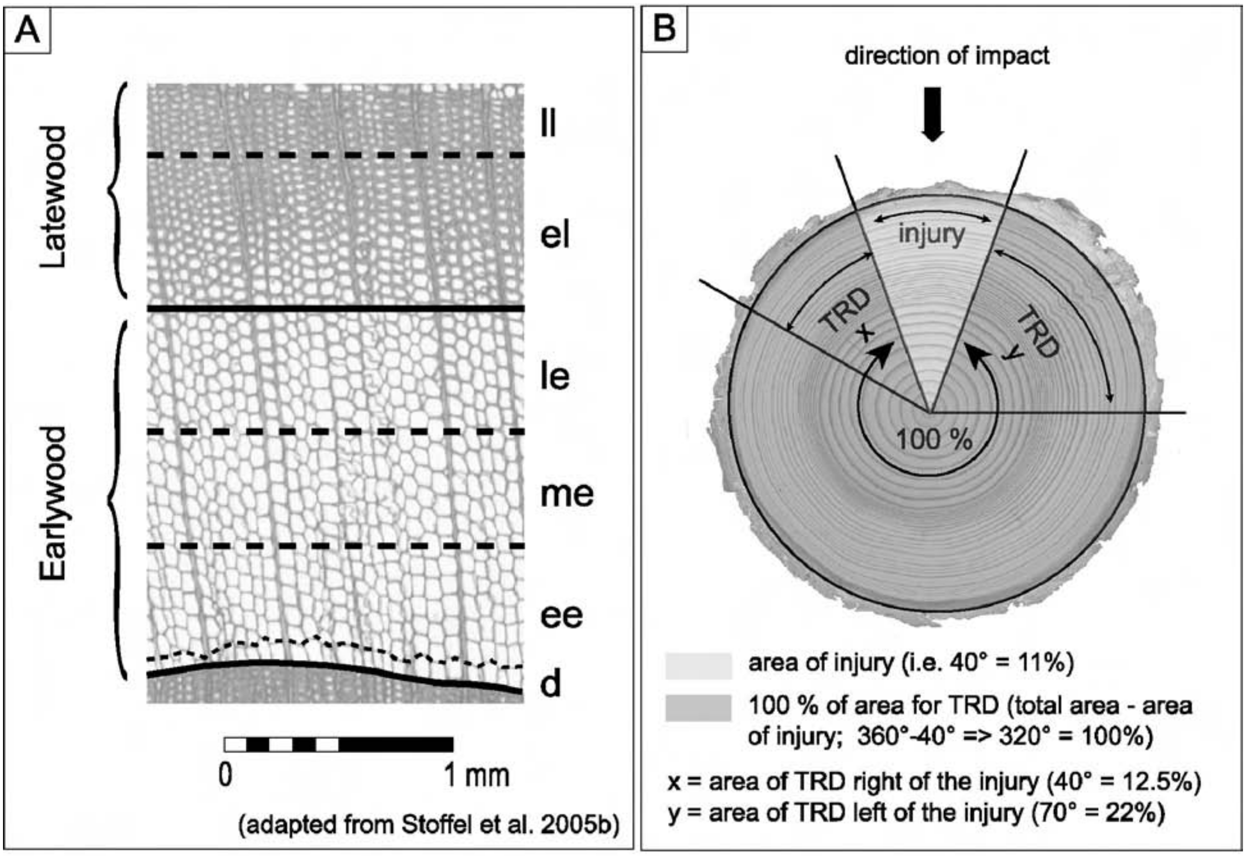

***Fig. B2.1** (a) Subdivision of Larix decidua tree rings according to the time of formation: the first formed cell layer in which TRD formation usually occurs as the result of injury during the dormant season (d), early (ee), middle (me) and late (le) earlywood as well as early (el) and late (ll) latewood. (B) The relative tangential extent of traumatic resin ducts (TRDs) at the wound height takes account of the area available for resin duct formation and the absence of cambial activity in the injured segment. The portion of the ring with cambial activity thus represents 100% of the surface where TRDs can theoretically form.*

for microscopic examination were prepared from some samples, as described by Clark (1981) and Schweingruber (1978).

2.3 Analytical procedures

To identify the location of TRDs, growth rings were subdivided according to time of formation as follows: the first formed cell layer (in which TRD formation usually occurs as the result of an injury during the dormant season) (d), early (ee), middle (me) and late earlywood (le), and early (el) and late (ll) latewood (Figure B2.1a).We noted the first occurrence of TRDs after an impact as well as the position of TRDs in subsequent years.

To determine the axial extent of TRDs formed after an impact, samples above and below each injury were examined. In addition, the total axial extent of the TRDs was assessed. This represents the total distance between the upper- and the lowermost cross-sections with TRDs and includes the length of the injury (Figure B2.2).

The tangential extent of TRD formation was assessed at the height of the center of each injury (H_c) by measuring the distance between the wound boundary and the farthest point at which TRDs occurred. This distance is given as a percentage of the ring circumference at H_c, excluding that portion where the cambium had been destroyed (Figure B2.1b). The maximal tangential extent of TRDs in samples from above and below the injury was also determined. We recorded the tangential extent of TRD formation at distances of 10, 30, 50 and 70 cm above the top as well as 10, 30 and 50 cm below the bottom of each injury. We focused mainly on the first year after injury. (i.e., 2001 and 2005), but tree rings of all subsequent years with TRDs were also analyzed. In the succeeding years, we concentrated on assessment of tangential distribution at H_c.

Pearson product-moment correlations (r) were calculated for the factors influencing the formation and extension of TRDs. We also present and discuss linear regressions between both the axial and tangential extent of TRD formation and various injury parameters.

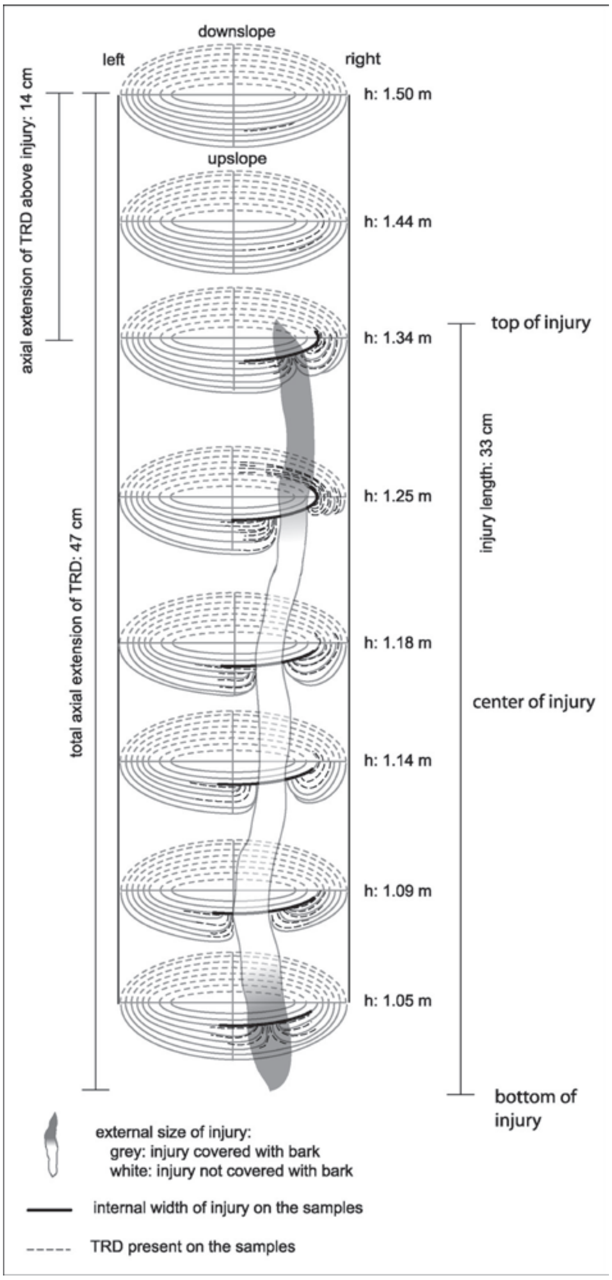

Fig. B2.2 *Schematic view of a Larix decidua stem with an open wound (No. D-03) and traumatic resin ducts (TRD) bordering the injury. In this example, the axial extension of TRD above the injury amounts to 14 cm.*

3. Results

3.1 TRD position within annual growth rings

Analysis of 182 cross sections from eight trees led to the identification of 28 injuries: 23 the result of debris flows in October 2000; five the result of debris flows in November 2004 (Table B3.1). In 25 cases, damaged trees formed at least one tangential row of TRDs. In the remaining three cases, no TRDs were formed in tissue adjacent to the injury.

Wounding occurred in mid-October 2000 and in early November 2004, which was, in both cases, after cambial activity had ceased. Traumatic resin duct formation in response to injury occurred during the following growing season. In 23 of 25 cross sections located at H_c, TRDs were observed in either the first (17 cases) or the next four cell layers (6 cases) of the new growth ring (Table B3.2). In one case, TRD formation occurred in the latewood of the growth ring formed in the year after injury, and in another case, TRD formation occurred in the earlywood formed in the second year after injury. Although, the first formed TRDs were usually located in the first cell layers of the new growth ring, in approximately half of all cases, the location of TRD formation migrated, with increasing horizontal and vertical distance from the site of injury, to the middle or late earlywood or the latewood (Figure B3.1). In five stems, multiple rows of ducts were formed within a single growth ring.

3.2 Axial extent of TRD

In the first year after disturbance, total axial extent of TRDs reached up to 320 cm and had a mean vertical extent of 78 cm (Table B3.2). Extent above the top and below the bottom of the injury averaged 43 and 14 cm, respectively, although in four cases, TRDs occurred neither above nor below the injury boundaries. In seven cases, TRDs formed at and above the injury, but not below it, and in four cases, TRDs formed below the injury but not above it. Downward propagation of TRDs was sometimes limited by the root collar. In the growth rings formed in the second and subsequent year after injury, TRD formation was limited axially mainly to the vicinity of the wound. In the second and fifth growth ring

Injury	L (cm)	$\%L$	H_{LB} (cm)	H_{center} (cm)	H_{UB} (cm)	W_{OS} (cm)	W_{IS} (cm)	W_R (%)	Area (cm^2)	Radial position (°)	Year
A-01	12	0.9	13	19	25	2	3	4.5	41	330	2004
A-02	25	1.8	62	74	87	2	2	3	47	280	2000
A-03	15	1.1	77	84	92	1	2	1	9	160	2000
A-04	14	1	96	103	110	9	6	11	97	220	2000
B-01	16	1.1	5	13	21	4	6	8	48	350	2000
B-02	58	3.9	58	87	116	11	15	24	437	130	2000
B-03	5	0.3	164	166	169	1	2	3	4	275	2004
C-01	18	1.3	36	45	54	6	9	25	113	100	2000
C-02	32	2.3	76	92	108	3	4	11	77	110	2000
C-03	7	0.5	138	141	145	1	1	3	5	20	2000
D-01	21	3.2	52	62	73	4	5.5	29	115	330	2000
D-02	8	1.2	76	80	84	3.5	4	19	29	200	2000
D-03	24	3.7	102	114	126	3	4	18	68	320	2000
D-04	4	0.6	11	13	15	2	4	18	18	340	2004
D-05	7	1.1	51	54	58	2.5	3	11	17	350	2004
E-01	44	3.1	20	42	64	9	7	10	235	290	2000
E-02	32	2.3	86	102	118	6	8	8	129	350	2000
F-01	20	4	19	29	39	1	2	3	25	350	2000
F-02	13	2.6	108	114	121	5	9	19	93	230	2000
F-03	27	5.4	114	127	141	7	8	20	204	50	2000
F-04	4	0.8	43	45	47	2	2	3	5	330	2004
F-05	61	12.2	157	187	218	6	9	18	414	20	2000
G-01	29	2.1	0	15	29	5	8	38	208	60	2000
G-02	21	1.5	89	99	110	3	5	22	73	100	2000
G-03	6	0.4	97	100	103	2	3	11	10	210	2000
G-04	72	5.1	117	153	189	2	2.5	14	158	340	2000
G-05	6	0.4	130	133	136	2	3	14	13	170	2000
H-01	18	1.5	162	171	180	3	4	10	68	160	2000
Mean	22	2.8	77	88	99	4	5	14	99		
Min	4	0.4	0	13	15	1	1	1	4		
Max	72	12	164	187	218	11	15	38	437		
SD	18	2	49	50	53	3	3	9	113		

***Table B3.1** Characteristics of the 28 injuries identified in eight Larix decidua trees. Column headings:* L*, vertical extent of injury; %*L*, *L *as a percent of total stem length;* H_{LB}, H_{center} *and* H_{UB}, *height from root collar to the lower boundary, the center and the upper boundary of the stem injury, respectively;* W_{OS}, *injury width measured on the stem surface;* W_{IS}, *injury width measured in the horizontal plane across the surface of the wound (see Figure 1B);* W_R, *relative width of injury calculated as shown in Figure 1B; Area, the wound surface calculated from internal width and length; Radial position, position of injury is relative to the upslope position (0°); SD, standard deviation.*

formed after injury, TRDs were observed beyond the axial limits of the injury in only seven and four cases, respectively.

3.3 Tangential extent of TRD

In the case of 25 impact injuries resulting in TRD formation, the TRDs formed at Hc were distributed tangentially over a mean of 19% of the stem circum- ference, excluding that portion where the cambium had been destroyed, and extending in one case to more than half the circumference of the tree (Table 3.3).

Figure 4 shows the variation with height in the tangential distribution of TRDs. Tangentially, TRDs were most widely distributed at H_c, decreasing to 5% of the stem circumference with viable cambium 50 cm above H_c and to less than 1% at 50 cm below H_c. In subsequent years, the tangential distribution of TRDs decreased to a median value of about 10% and a maximum of 50% of the undamaged stem circumference at H_c. In about one third of the wounds, TRDs were evident in only those segments of the secondary xylem overgrowing the wound.

Traumatic resin ducts were formed for a mean period of 2.6 years (SD ± 1.8) after injury, with no TRDs being formed after the first year following injury in eight cases, whereas, in the remaining 17 cases, they were formed in each of the subsequent four years.

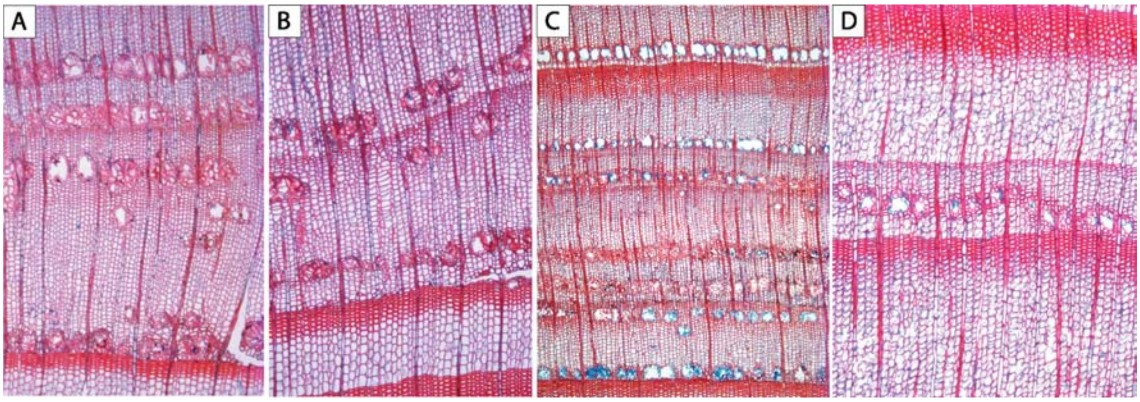

Fig. B3.1 *A wounded Larix decidua stem, showing the formation of traumatic resin ducts (TRDs) at (A) the beginning of the new tree ring or (B) within the first five cell layers. (C) Multiple rows of TRDs formed in the years following wounding in October 2000. (D) Tangential migration of TRDs within the tree ring.*

Injury	SA (cm^2)	*L* (cm)	H_c (cm)	Location of TRD onset	Axial extent of TRDs (cm)										
					Year 1			Year 2		Year 3		Year 4		Year 5	
					Total	hi+	hi–	hi+	hi–	hi+	hi–	hi+	hi–	hi+	hi–
A-01	41	12	19	d	161	149	0	0	0	0	0	0	0	0	0
A-02	47	25	74	d	79	37	17	0	0	0	0	0	0	0	0
A-03	9	15	84	d	130	91	24	0	0	0	0	0	0	0	0
A-04	97	14	103	d	139	84	41	0	0	0	0	0	0	0	0
B-01	48	16	13	ee	49	24	9	0	0	0	9	0	9	0	0
B-02	437	58	87	d	320	230	32	24	13	24	13	24	13	24	13
B-03	4	5	166	ee	5	0	0	0	0	0	0	0	0	0	0
C-01	113	18	45	ee	63	16	29	0	0	0	0	0	0	0	0
C-02	77	32	92	ee	54	11	11	0	0	0	0	0	0	0	0
C-03	5	7	141	–	0	0	0	0	0	0	0	0	0	0	0
D-01	115	21	62	ee	51	0	30	0	42	0	0	0	0	0	0
D-02	29	8	80	ee	8	0	0	0	0	0	0	0	0	0	0
D-03	68	24	114	ee	42	10	8	0	8	0	8	0	0	0	0
D-04	18	4	13	–	0	0	0	0	0	0	0	0	0	0	0
D-05	17	7	54	–	0	0	0	0	0	0	0	0	0	0	0
E-01	235	44	42	ee	261	202	15	0	0	0	0	0	0	0	0
E-02	129	32	102	d	167	135	0	0	0	0	0	0	0	0	0
F-01	25	20	29	d	81	19	42	0	0	0	0	0	0	0	0
F-02	93	13	114	d	63	50	0	12	0	12	0	12	0	12	0
F-03	204	27	127	d	80	0	53	13	12	25	12	25	12	25	12
F-04	5	4	45	ll	65	19	42	0	0	0	0	0	0	0	0
F-05	414	61	187	d	125	64	0	24	0	24	0	24	0	24	0
G-01	208	29	15	d	41	12	0	0	0	0	0	0	0	0	0
G-02	73	21	99	d	40	19	0	0	0	0	0	0	0	0	0
G-03	10	6	100	d	17	11	0	0	0	0	0	0	0	0	0
G-04	158	72	153	d	78	0	6	0	0	0	0	0	0	0	0
G-05	13	6	133	d	13	0	7	0	0	0	0	0	0	0	0
H-01	68	18	171	d	63	20	25	20	0	0	0	0	0	0	0
Mean	99	22	88		78	43	14	3	3	3	2	3	1	3	1
Min	4	4	13		0	0	0	0	0	0	0	0	0	0	0
Max	72	72	187		320	230	53	24	42	25	13	25	13	25	13
SD	113	18	50		77	63	17	8	8	8	4	8	4	8	3

Table B3.2 *Axial extent of traumatic resin ducts (TRDs) in growth rings formed 1 to 5 years after injury for all injuries analyzed in eight Larix decidua trees (A–H). Abbreviations: SA, surface area of the injury; L, vertical extent of injury; Hc, height from the root collar to the center of injury; d, dormant period; ee, early earlywood; ll, late latewood; hi+, axial extension of TRDs above the top of the injury; hi–, axial extension of TRDs below the bottom of the injury; and SD, standard deviation.*

Injury	SA (cm^2)	L (cm)	H_c (cm)	Tangential extent of TRDs											
				Year 1								Year 2	Year 3	Year 4	Year 5
				At H_c	+10	+30	+50	+70	–10	–30	–50				
A-01	41	12	19	47	39	31	25	17	0	0	0	0	0	0	0
A-02	47	25	74	6	11	6	0	0	11	6	0	9	3	6	0
A-03	9	15	84	18	11	6	6	6	8	0	0	11	3	3	6
A-04	97	14	103	19	14	14	6	0	6	0	0	8	5	3	11
B-01	48	16	13	33	31	47	6	0	0	0	0	8	15	5	5
B-02	437	58	87	56	28	8	6	6	44	3	0	31	26	37	33
B-03	4	5	166	6	0	0	0	0	0	0	0	0	0	0	0
C-01	113	18	45	19	3	0	0	0	33	19	0	19	9	28	13
C-02	77	32	92	3	3	0	0	0	14	0	0	14	8	11	9
C-03	5	7	141	0	0	0	0	0	0	0	0	3	3	3	3
D-01	115	21	62	22	0	0	0	0	28	22	0	25	23	47	27
D-02	29	8	80	7	0	0	0	0	0	0	0	15	0	0	0
D-03	68	24	114	22	17	0	0	0	17	0	0	22	34	19	14
D-04	18	4	13	0	0	0	0	0	0	0	0	24	0	0	0
D-05	17	7	54	0	0	0	0	0	0	0	0	0	0	0	0
E-01	235	44	42	13	42	17	17	17	3	0	0	20	8	5	5
E-02	129	32	102	39	22	22	25	31	0	0	0	8	20	5	9
F-01	25	20	29	31	11	0	0	0	19	6	6	0	0	0	0
F-02	93	13	114	21	22	17	14	0	0	0	0	19	22	12	10
F-03	204	27	127	25	36	0	0	0	44	25	28	17	10	12	3
F-05	4	45	46	14	0	0	0	6	0	0	0	0	0	0	
F-05	414	61	187	36	58	17	19	0	0	0	0	22	25	15	14
G-01	208	29	15	16	31	0	0	0	0	0	0	4	0	4	0
G-02	73	21	99	7	31	0	0	0	0	0	0	7	18	14	0
G-03	10	6	100	6	17	0	0	0	0	0	0	0	0	0	0
G-04	158	72	153	24	0	0	0	0	14	0	0	39	27	13	6
G-05	13	6	133	6	0	0	0	0	17	0	0	0	0	0	0
H-01	68	18	171	17	19	18	17	3	14	13	0	2	6	9	3
Mean	99	22	88	19	16	7	5	3	10	3	1	12	9	9	6
Min	4	4	13	0	0	0	0	0	0	0	0	0	0	0	0
Max	72	72	187	47	58	31	25	31	44	25	28	39	34	47	33
SD	113	18	50	15	16	12	8	7	13	7	5	11	11	12	8

Table B3.3 *Tangential extent of traumatic resin duct (TRD) formation (% of circumference with undamaged cambium) at the height of the center of injury (H_c) in growth rings formed 1 to 5 years after injury for all injuries analyzed in the eight* Larix decidua *trees. For Year 1, TRD extent is also given for the indicated vertical distances (cm) above the top (+) and below the bottom (–) of the injury. Abbreviations: SA, surface area of injury; and L, vertical length of injury.*

4. Discussion

We analyzed 182 stem discs from eight *Larix decidua* trees injured by debris flows in October 2000 or November 2004, or both, i.e., after the end of the local growing period. Traumatic resin ducts were observed in the growth ring formed in the year following injury in the case of 25 of the 28 injuries, which is in agreement with observations of Bannan (1936), Fahn *et al.* (1979) and Cruickshank *et al.* (2006).

In almost one third of the samples taken at the center of the injury, TRD formation extended radially across a number of cell layers within a single tree ring. The location of TRD formation migrated radially to later formed cell layers with increasing distance from the wound. Changes in the radial position of ducts with distance from the center of the injury were described by Bannan (1936), but his observations concerned only changes in position relative to the upper and lower boundaries of the wound. Such variation in position of TRD formation is consistent with dependence on a slowly propagating signal. Krekling *et al.* (2004) stated that, in Norway spruce, the signal propagates about 2.5 cm day–1 in the axial direction. In our samples, we found no significant influence of injury size, length, width or height on the migration in the site of TRD formation.

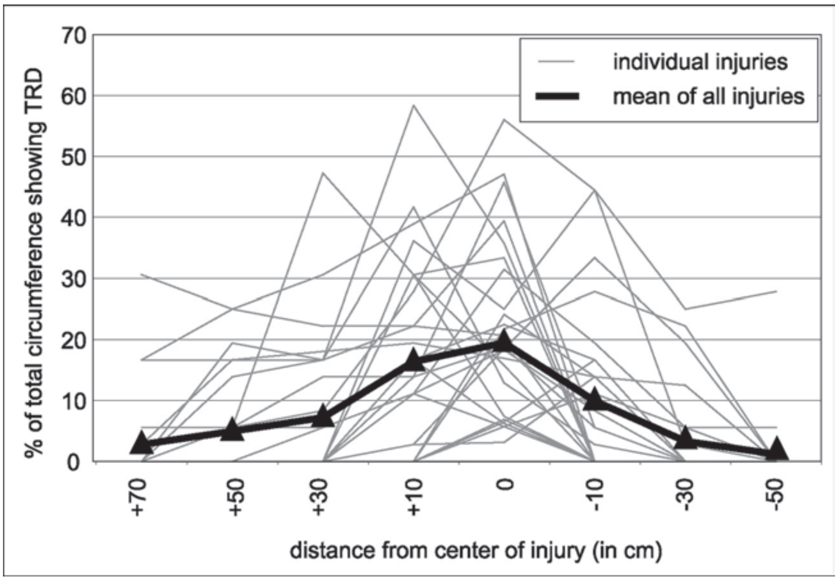

Fig. B3.2 *Tangential extent of traumatic resin ducts (TRDs) at different heights in the stem of Larix decidua trees. The extent is greatest at the height of the center of the injury (H_c) and decreases above (+) and below (–).*

We observed a mean total axial extension of TRDs of over 78 cm, with ducts present 43 cm above and 14 cm below the extent of injury (Table B3.2). Previous studies report axial extensions ranging from 5 cm (Franceschi *et al.* 2002) to 10 cm (Lev-Yadun, 2002) or 12 cm (Luchi *et al.,* 2005). Fahn *et al.* (1979) showed that TRDs form over greater distances above wounds than below wounds. In these other studies, trees reacted to an artificial stimulus in the form of hormones or decapitation. Therefore, the much larger axial spread of TRDs that we observed might be explained by the difference in stimulus and the high impact energies involved. During debris flows, trees may be struck violently by rocks and boulders and severely shaken (Dorren & Berger, 2006; Stoffel, 2007). Debris flows also cause deeper wounds than the artificial impacts that have been induced in laboratory experiments (Moore, 1978).

Total axial extent of TRDs seemed to be influenced by injury size (Table B4.1), because the largest total axial extension of TRDs as well as the largest maximum extension above the area of impact were associated with the largest injuries. This observation is consistent with the findings of Fahn *et al.* (1979), who reported a correlation between wound size and number of TRDs. In our study, the axial extent of TRDs below the injury was independent of injury area, length or width (Pearson product-moment correlations of < 0.3).

In the first tree ring formed after an impact, tangential extent of TRDs at H_c varied greatly among

Parameter	Description	Parameter									
		1	2	3	4	5	6	7	8	9	10
1	Injury area		0.82	0.50	0.75	0.68	0.54	0.12	0.49	0.50	0.65
2	Injury length	0.82		0.27	0.75	0.59	0.41	0.08	0.40	0.55	0.65
3	Injury width	0.50	0.27		0.26	−0.02	−0.11	−0.19	0.00	0.30	0.54
4	Injury as % of stem length	0.75	0.75	0.26		0.32	0.14	0.15	0.38	0.38	0.54
5	TRD distribution, vertical total	0.68	0.59	−0.02	0.32		0.95	0.08	0.40	0.55	0.65
6	TRD distribution, vertical above	0.54	0.41	−0.11	0.14	0.95		0.14	0.56	0.25	0.25
7	TRD distribution, vertical below	0.12	0.08	−0.19	0.15	0.08	0.14		0.35	0.07	0.05
8	TRD distribution, tangential 1 year center of injury	0.49	0.40	0.00	0.38	0.40	0.56	0.35		0.14	0.37
9	Number of years in which TRDs formed	0.50	0.55	0.30	0.38	0.55	0.25	0.07	0.14		0.66
10	TRDs in following years	0.65	0.65	0.54	0.54	0.65	0.25	0.05	0.37	0.66	

Table B4.1 *Pearson product-moment correlation coefficients for the injury parameters (area, length, width) and the vertical as well as axial extensions of traumatic resin ducts (TRDs) ($n = 28$) in cross sections of Larix decidua stems.*

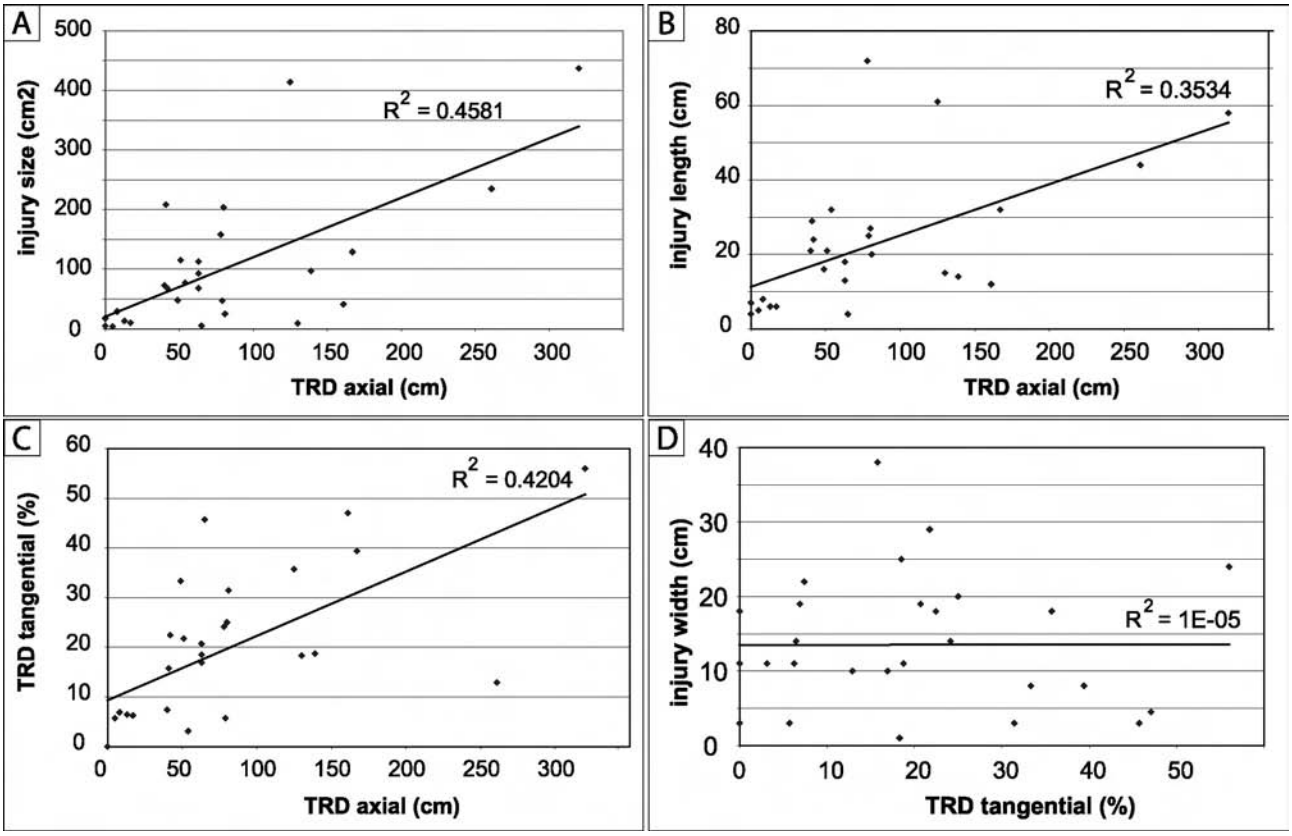

Fig. B4.1 *Linear regressions for: (A) axial extent of traumatic resin ducts (TRDs) and injury size; (B) axial extension of TRDs and injury length; (C) axial extent of TRDs and tangential extent of TRDs; (D) tangential extent of TRDs and injury width in a Larix decidua stem.*

samples. Although no TRDs were observed in 10% of the samples, 50% of the total circumference of the tree ring showed TRDs in other samples. The tangential extent of TRDs in the first year following injury showed a significant correlation with injury size (Table B4.1). Furthermore, the tangential spread of TRDs was more closely correlated with the length of an injury than its width ($r = 0.40$ and < 0.01, respectively).

Linear regressions (Figures B4.1a and B4.1b) indicated a relationship between the axial extent of TRD formation and injury size (area and length). Similarly, it appears that the tangential and axial extents of TRD formation are positively correlated (Figure B4.1c). Injury width did not influence the tangential extent of TRD formation (Figure B4.1d).

The occurrence of TRDs in the tree rings following injury was restricted by the time elapsed between the injury event in October 2000 (23 injuries) or November 2004 (5 injuries) and the felling of the trees in August 2005. From the cross sections showing wounds as a result of the October 2000 event, we observed that, in more than two thirds of the cases (16 injuries), TRDs were formed in all years following the injury. Therefore, it was impossible to determine for how many years after injury new TRDs are formed.

Our observations on the axial and tangential distribution of TRDs following stem injury have a direct bearing on sampling strategies for dendrogeomorphological studies. Because tree-ring analysis in protection forests (designated to protect adjacent property from the impact of geomorphic processes) is normally limited to the extraction of increment cores, positioning of cores around the wound is critical. Our results indicate that immediately above the injury, TRDs are present over a large portion of the stem circumference, and are, therefore, easily detected. However, TRD formation above H_c may be delayed relative to that at H_c. Given that the onset of TRD formation higher up in the stem starts only in late earlywood or even latewood cell layers of the tree ring formed in the year following the impact event (e.g., 2001), the disturbance would have been misdated and attributed to a non-existent summer 2001 debris flow. Thus, it appears preferable to extract cores from either side of the injury, where the delay in TRD formation with distance from the wound is more limited.

Even in this case, however, absolute dating precision cannot be guaranteed, as the tangential spread of TRDs was greater in the fourth year than in the year following the October 2000 event in eight cross sections. Thus, if an increment core had been extracted where TRDs were formed in the fourth, but not the first, year after injury, the injury would have been misdated. For these reasons, at least two cores should be extracted from different locations as close to the wound as possible and data from several trees should be compared.

The information obtained in this study raises new questions about the dating of past geomorphic events. In particular, it remains to be determined when TRD formation is initiated after wounding by debris flows occurring during the growth period.

Acknowledgements

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CHAPTER C

RECONSTRUCTION OF DEBRIS-FLOW FREQUENCIES

Reconstruction of debris-flow frequencies

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"Debris flows on forested cones - reconstruction and comparison of frequencies in two catchments in Val Ferret, Switzerland"

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Abstract

Debris flows represent a major threat to infrastructure in many regions of the Alps. Since systematic acquisition of data on debris-flow events in Switzerland only started after the events of 1987, there is a lack of historical knowledge on earlier debris-flow events for most torrents. It is therefore the aim of this study to reconstruct the debris-flow activity for the Reuse de Saleinaz and the La Fouly torrents in Val Ferret (Valais, Switzerland). In total, 556 increment cores from 278 heavily affected *Larix decidua* Mill., *Picea abies* (L.) Karst. and *Pinus sylvestris* L. trees were sampled. Trees on the cone of Reuse de Saleinaz show an average age of 123 years at sampling height, with the oldest tree aged 325 years. Two periods of intense colonization (the 1850s–1880s and the 1930s–1950s) are observed, probably following high-magnitude events that would have eliminated the former forest stand. Trees on the cone of Torrent de la Fouly indicate an average age of 119 years.

As a whole, tree-ring analyses allowed assessment of 333 growth disturbances belonging to 69 debris-flow events. While the frequency for the Reuse de Saleinaz study site comprises 39 events between AD 1743 and 2003, 30 events could be reconstructed at the Torrent de la Fouly for the period 1862–2003. Even though the two study sites evince considerably different characteristics in geology, debris-flow material and catchment morphology, they apparently produce debris flows at similar recurrence intervals. We suppose that, in the study region, the triggering and occurrence of events is transport-limited rather than weathering-limited.

1. Introduction

Debris flows are fast flowing mixtures of water, gas and debris of different size, ranging from silt to boulders with diameters of several meters (Varnes, 1978). Depending on the composition of the material and the amount of water, individual surges can occur in the form of sediment-charged flooding or debris flows sensu stricto with very low water content and rigid flow behavior (Hungr, 2005). These flows generally occur during periods of intense rainfall (Caine, 1980; Corominas & Moya, 1999; Chen et al., 2006), rapid snowmelt (Wieczorek & Glade, 2005), a combination of these two triggering factors, or the breakout of a glacier lake (GLOF; Clague & Evans, 2000). Initiation of debris flows requires a sufficient amount of loose rock and soil deposits (Bovis & Jakob, 1999), steep slope, and a large supply of water (Wilson & Wieczorek, 1995). Once triggered, the material generally follows pre-existing channels and erodes their banks and beds (Bollschweiler et al., 2005) or deposits lateral levees on its way, where no erosion takes place. As soon as the slope angle or the water content of the mass decreases, the movement is stopped and material deposited in the form of terminal lobes (Major & Iverson, 1999). Repeated debris-flow activity at the same site leads to the formation of a debris-flow cone (Rapp & Nyberg, 1981; Takahashi, 1991; Hungr, 1995; Wilkerson & Schmid, 2003; Stoffel et al., 2006a).

Trees growing on cones can be repeatedly affected by debris flows and react to such disturbances with growth anomalies. As a consequence, tree-ring records have repeatedly been used to identify the earlier occurrence of debris flows (Santilli & Pelfini, 2002; May & Gresswell, 2004; Stoffel & Beniston, 2006). Spatial patterns of debris-flow events have been assessed through the coupling of geomorphic mapping with tree-ring analyses (Bollschweiler et al., 2007). In a similar way, the magnitude of events has been approximated by means of dendrogeomorphological methods (Strunk, 1997; Baumann & Kaiser, 1999; Van Steijn, 1996). Finally, Stoffel et al. (2005b) compared reconstructed debris-flow events with flooding data in neighboring rivers and lakes in order to investigate triggering weather conditions.

The aim of this study is to provide an overview of debris-flow activity in a Swiss Alpine valley through (i) the assessment of growth disturbances in trees growing on two debris-flow cones, (ii) a determination of events in the two torrents, (iii) the reconstruction of debris-flow frequencies and (iv) an illustration of the spatial activity of torrents during single events. In a final section, we discuss the reconstructed frequencies with archival data on flooding and debris flows in neighboring torrents.

2. Study sites

The Val Ferret has a surface of 115 km^2 and is located in south-western Switzerland. The valley shares a border to the south with Italy and to the west with France (Fig. C2.1a). Except for its northern part, the valley is surrounded by high summits, with the highest elevation attaining 3,901 m a.s.l. at Aiguille de l'Argentinière. The western slopes of the valley belong to the Mont Blanc Massif (Fig. C2.2) and are built of Paleozoic granite and intermittent bands of rhyolites (Labhart, 2004). The eastern slopes are located in geologically complex terrain, with the predominant upper units belonging to the Sion-Courmayeur zone (Mesozoic age) and the lower ones to ultrahelvetic layers of Jurassic age. The predominant rocks are flysch, black schists, calcareous schists and quarzites (Burri *et al.*, 1992; Burri & Marro, 1993).

The **Reuse de Saleinaz** (Fig. C2.1b; Table C2.1) is located in the western part of Val Ferret close to the village of Praz de Fort; its geology is dominated by the granites of the Mont Blanc Massif. The catchment area has a size of 2,135 ha and extends from 3,901 m a.s.l. (Aiguille de l'Argentinière) to the apex of the depositional cone of the Reuse de Saleinaz torrent at about 1400 m a.s.l. The upper part of the catchment is dominated by the Saleinaz and the Orny glaciers. The torrent originating at the Saleinaz glacier has its source at 2,760 m a.s.l. and reaches the debris-flow cone after 1.5 km. The torrent descending from the Orny glacier has its source at 2,640 m a.s.l. and merges with the waters descending from the Saleinaz glacier at 1593 m a.s.l. Predominant rock sizes in the torrent are generally >20 cm and smaller fractions are comparably scarce. The depositional cone of the

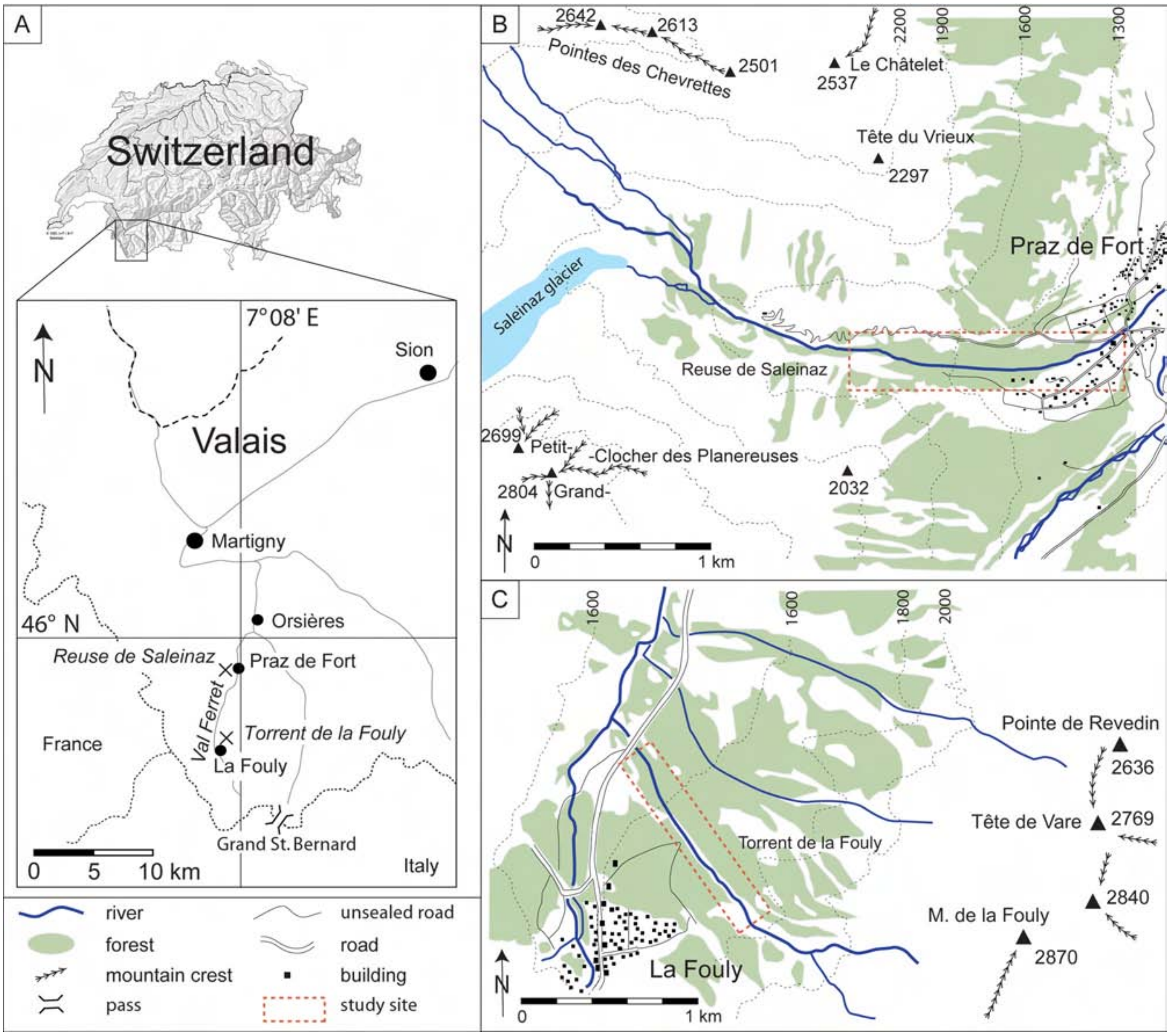

Fig. C2.1 *(a) The two study sites are located in Val Ferret, south-western Swiss Alps. (b) The Reuse de Saleinaz catchment is located west of the village of Praz de Fort in the northern part of the valley. The map shows the catchment area with the Saleinaz glacier and the torrent's tributaries. (c) The sketch map of the Torrent de la Fouly shows the large debris-flow cone and the short distance between the catchment area and the cone's apex.*

torrent has an average slope angle of 7° and extends from 1400 m a.s.l. to 1150 m a.s.l., with a surface of 81 ha. The cone is covered with European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Anthropogenic influence on the cone is more pronounced on its southern side where deposits have been removed for housing construction.

Apart from a small forest stretch located close to the torrent, the stand was eliminated for grazing activity over the past centuries. In contrast, the northern part of the cone is completely forested and human influence is non-existent, except for a road crossing the forest. In its lowermost part, debris-flow deposits were removed and the cone was reshaped for the construction of houses of the village of Praz de Fort in the 20th century. The area selected for analysis comprises both sides of the currently active torrent channel. South of the torrent, the entire stand was investigated. In the northern part, only trees located between the currently active channel and the road were chosen for analysis, as rockfall strongly influences tree growth close to the adjacent slope. Similarly, the uppermost part of the cone was omitted because of snow avalanche activity. For the

	Reuse de Saleinaz	Torrent de la Fouly
altitudinal range of the cone (m a.s.l.)	1150–1400	1500–1740
cone area (ha)	81	109.5
altitudinal range of the catchment (m a.s.l.)	1150–3901	1500–2870
catchment area (ha)	2135	113
geology	Mont Blanc Massif (granite, rhyolite, gneiss)	Sion-Courmayeur zone (flysch, schist, quarzite)
predominant block size	0.2–2 m	max. 0.5 m

Table C2.1 *Characteristics of the two study sites.*

Reuse de Saleinaz, six debris-flow events (1920, 1928, 1945, 1991, 1992 and 1993) are known in local archives (Rey & Saameli, 1997).

The **Torrent de la Fouly** (Fig. C2.1c; Table C2.1) is located in the eastern part of Val Ferret, and its geology dominated by the Sion-Courmayeur zone. The catchment has a size of 113 ha and there are no glaciers. The highest point of the catchment is Mont de la Fouly at 2,870 m a.s.l. Material in the catchment is heavily fractured and readily available for the entrainment of debris flows. Two channels start at an elevation of about 2,100 m a.s.l. They merge at 1846 m a.s.l. and reach the apex of the cone after a distance of only 250 m. The debris-flow cone extends for 110 ha and has an average slope angle of 9°. The cone apex is located at 1740 m a.s.l. and the lower limit of the cone is at 1500 m a.s.l. where the Torrent de la Fouly flows into the Dranse river. The Dranse river influences neither the debris-flow cone nor the village of La Fouly. The forest stand on the cone consists mainly of *L. decidua* and *P. abies*. The village of La Fouly was built over the last few centuries on the debris-flow cone and occupies the distal parts of its surface towards the south. Within this study, trees were selected on both sides of the channel (20 m on each side). Farther away from the currently active channel, trees were normally too young and did not show any signs of past debris-flow activity. Archival data on past events are scarce, with only two debris-flow events recorded in 1991 and 1996 (Rey & Saameli, 1997).

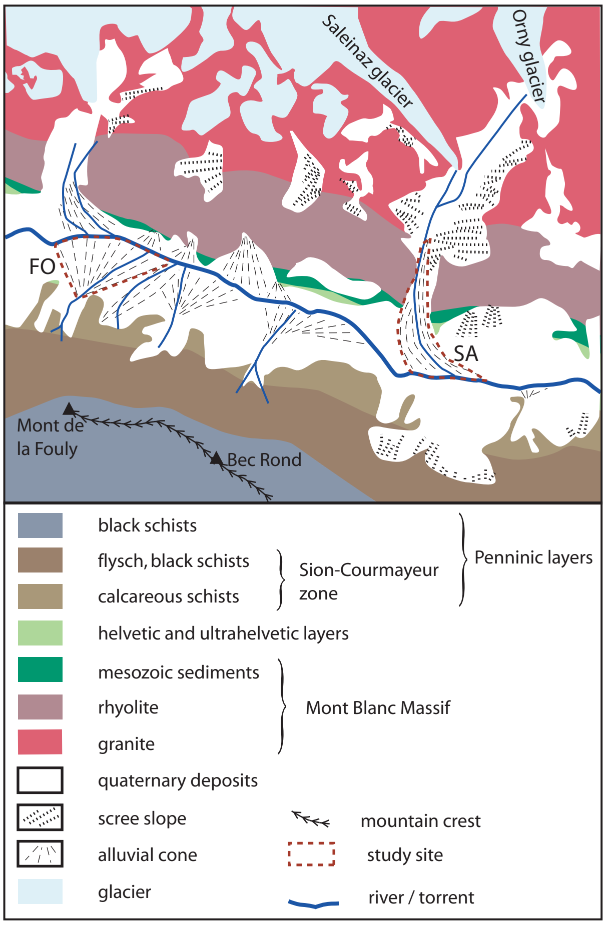

Fig. C2.2 *Simplified geological map of Val Ferret. The debris-flow cones of two study sites Reuse de Saleinaz (SA) and Torrent de la Fouly (FO) are indicated by the red dotted line.*

3. Material and methods

3.1 Field methods

In a first step, a detailed geomorphic map on a scale of 1:1000 was established representing all forms related to debris-flow activity such as levees, lobes and previously active channels (Gaillard, 2006). This map served as a basis for the sampling strategy of trees growing in the deposits and obviously influenced by previous debris-flow events.

The basic assumption in dendrogeomorphological analysis is that a geomorphic event can be reflected in a tree's annual ring growth (Shroder, 1980; Giardino *et al.*, 1984). Debris flows can affect

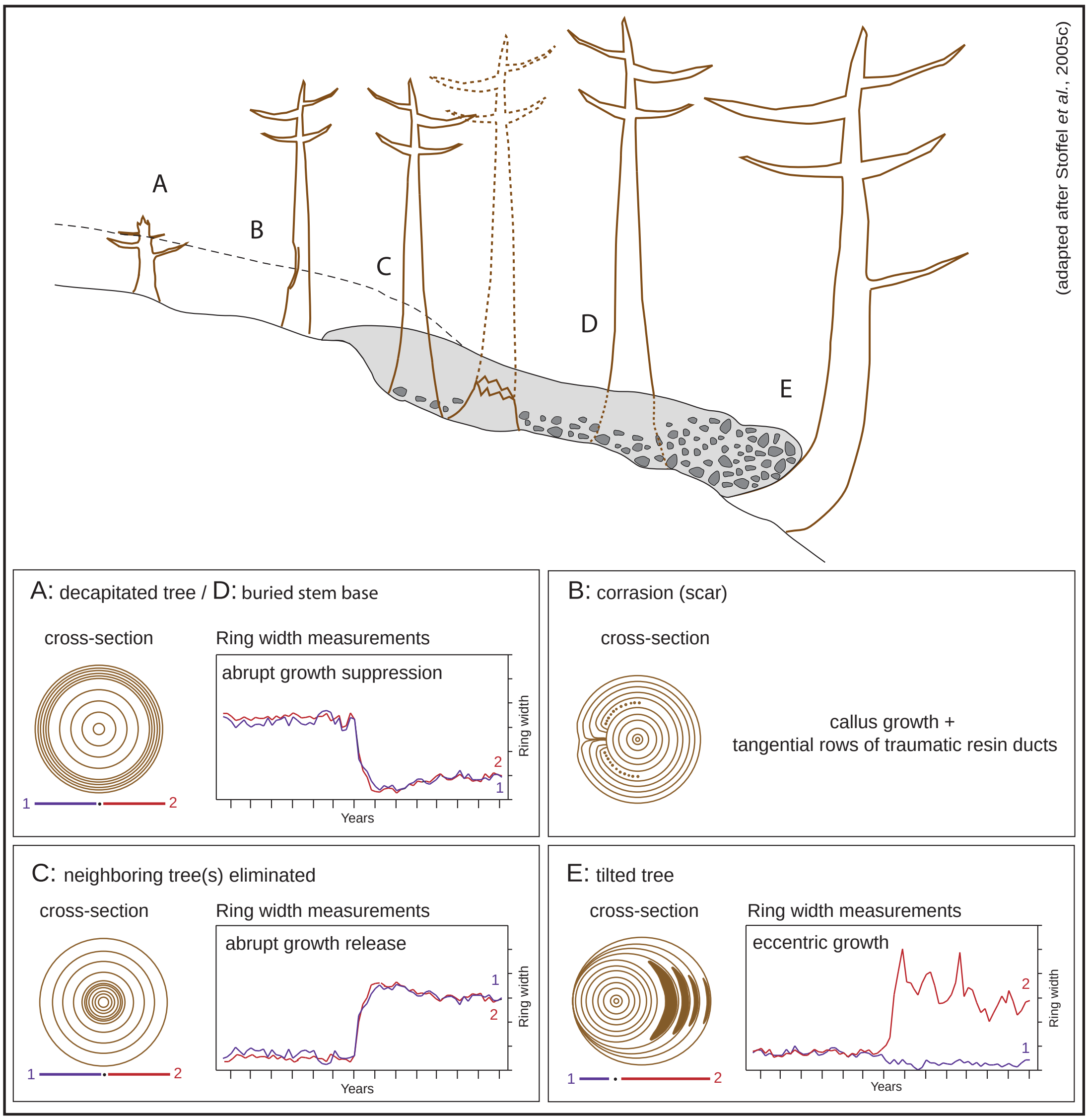

Fig. C3.1 *Types of growth disturbances of trees affected by a debris-flow event.*

trees in different ways (Schweingruber, 1996, 2001; Fig. C3.1): 1) A passing surge can cause abrasion at the tree stem. The tree reacts to this type of disturbance with changes in its cell structure and the formation of callus tissue as well as tangential rows of traumatic resin ducts (TRD; Stoffel *et al.*, 2005a, c; Perret *et al.*, 2006). 2) The unilateral pressure of the flow can lead to the inclination of the stem and the formation of compression wood on the downslope side of the trunk (Braam *et al.*, 1987; Fantucci & Sorriso-Valvo, 1999; Stefanini, 2004). 3) The material of a debris flow can also bury the stem base, thus causing growth suppression (Strunk, 1997). 4) Similarly, trees may be decapitated by rocks or boulders transported in the debris-flow mass and react to such an impact with candelabra growth. 5) A distinct decrease in ring width can be observed in the years following the event. The elimination of neighboring trees can result in a growth release in the survivor trees (Strunk, 1997).

Within this study, we normally extracted two increment cores from each tree that presented evidence of debris-flow damage. The cores were taken according to the morphology of the stem: a) trees with scars were sampled close to the edges of the wound and on the downslope side of the stem; b) cores from tilted trees were taken at the height of the inclination and on the opposite side; c) decapitated trees or trees with a buried stem base were cored as close to the ground as possible. The position of each tree was marked precisely on the geomorphic map.

At **Reuse de Saleinaz**, 228 trees were sampled, namely 148 *L. decidua*, 31 *P. abies* and 49 *P. sylvestris*. At **Torrent de la Fouly**, only 50 trees were sampled: 42 *P. abies* and 8 *L. decidua* trees.

In addition to the disturbed trees sampled on the cone, we selected undisturbed *L. decidua* and *P. abies* trees from a nearby forest stand, which showed no signs of debris-flow activity or other geomorphic processes. Reference chronologies were built so as to obtain information on "normal" (i.e. climate-driven) growth conditions at the two locations (Cook & Kairiukstis, 1990). For both study sites, at least 15 trees per species were sampled.

3.2 Laboratory methods

In the laboratory, samples were analyzed following the procedure described by Bräker (2002). Individual working steps included the sanding of increment cores and measurement of tree-ring widths using a LINTAB measuring device and TSAP software (Time Series Analysis and Presentation; Rinntech, 2007). Growth curves of disturbed trees were crossdated with the corresponding reference chronology so as to identify missing or faulty tree rings (Schweingruber, 1996). Tree samples were then analyzed visually using a binocular. Anatomical changes such as TRD, the onset of reaction wood or callus tissue were noted on skeleton plots (Schweingruber *et al.,* 1990), before growth curves were compared to the reference chronology in order to determine the beginning of growth suppression or release.

The age structure of the stands was assessed by means of the age of the selected trees. Since trees were not cored at the stem base and piths were not always present, the age structure does not reflect inception or germination dates of trees, but provides an appropriate image of the age distribution of the trees sampled. At Reuse de Saleinaz, an interpolation of tree age was produced in order to obtain a reasonable spatial illustration of the age distribution of trees. At Torrent de la Fouly, the number of sampled trees was too small for interpolations.

	Reuse de Saleinaz	Torrent de la Fouly
mean	123	119
minimum	40	37
maximum	325	238
STDEV	73	43

Table C4.1 *Statistics on tree ages (in years) for the two study sites.*

Events were defined by assessing the growth disturbances in the samples, their position within the debris-flow deposits as well as the spatial distribution of all trees showing growth disturbances (GD) in the same year. For all events, a map of the spatial distribution of affected trees was created. The position of all trees showing GD to a specific event was precisely marked on the geomorphic map so as to gain an idea on the spatial pattern of past debris-flow events.

Finally, the reconstructed debris-flow frequencies of Reuse de Saleinaz and Torrent de la Fouly were compared with each other as well as with archival data on debris-flow and flooding events in neighboring torrents (Rey & Saameli, 1997).

4. Results

4.1 Age structure of the stands

The mean age at sampling height of the trees cored at **Reuse de Saleinaz** is 123 years: *L. decidua* trees are normally older, with an average age of 158, while *P. abies* trees show, on average, 128 tree rings at sampling height. *P. sylvestris* trees are, in general, younger with only 90 increment rings on average. The age distribution within the stand is illustrated in Figure C4.1a and proves to be quite heterogeneous. The oldest trees are located on the central part of the cone and north of the currently active channel; they reveal an age of 325 years (Table C4.1). In contrast, trees in the upper part of the cone are of much younger age, ranging from 50 to 60 years. Trees growing in the southern sectors of the cone show a similar pattern: the oldest trees can again be identified in the central part of the cone with ages reaching up to 250 years; trees in the upper part are much younger, with ages of about 100 years. It can be seen clearly from Figure C4.1b that the cone was actively colonized between 1850 and 1880 as well as between 1930 and 1950.

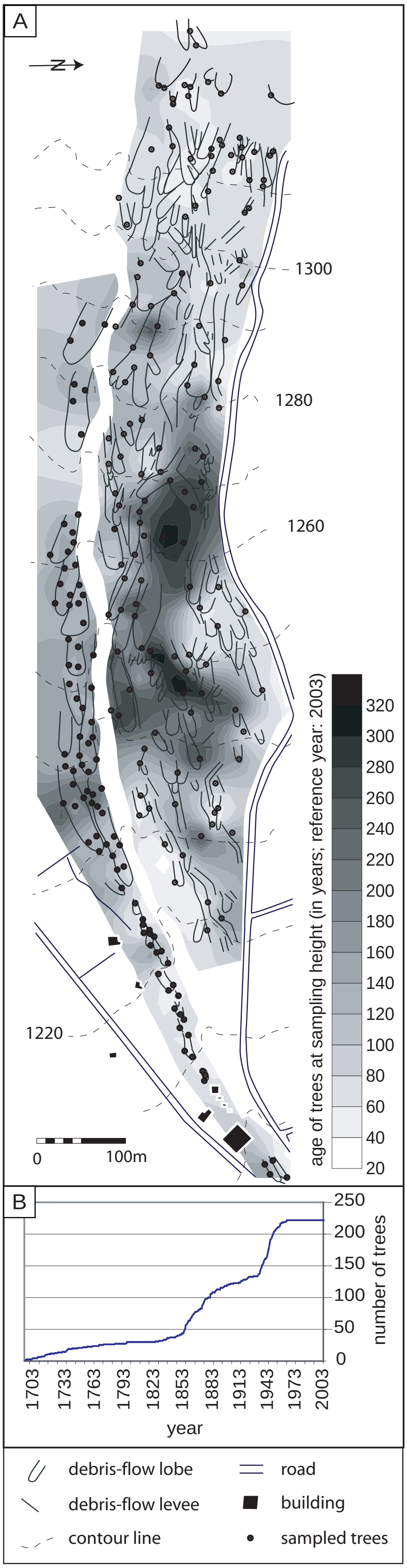

Fig. C4.1 (left) (a) Age structure of the forest stand on the cone of the Reuse de Saleinaz. The oldest trees are located on the central part of the cone, whereas trees on the eastern sectors are rarely older than 60 years. The oldest tree reached sampling height in AD 1678. (b) Number of trees cored present in a given year.

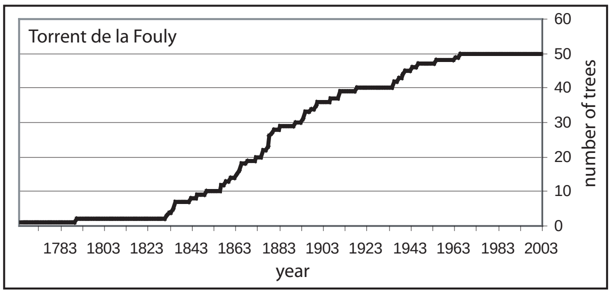

***Fig. C4.2** Age structure of the trees sampled at Torrent de la Fouly. The oldest tree reached sampling height in AD 1765.*

At **Torrent de la Fouly**, the mean age of trees is 119 years. Again, *L. decidua* trees proved to be the much older here with a mean age of 148 years. In contrast, *P. abies* trees counted, on average, only 113 tree rings. The oldest tree sampled indicates an age at sampling height of 238 years, but only two trees are older than 170 years. The age distribution of all trees shows a regular increase in the number of trees, without any obvious period with higher germination rates (Fig. C4.2). The spatial age distribution indicates that the oldest trees can be found on the uppermost part of the cone.

4.2 Dating of past debris-flow events

In total, 333 growth disturbances (GD) were assessed in the 278 trees sampled at the two study sites. Table C4.2 provides an overview of the different GD identified, as well as the absolute and the relative numbers for each type of disturbance. At both study sites, tangential rows of traumatic resin ducts (TRD) represent the GD that could most frequently be identified on the increment cores with 82% and 65% of all reactions. While compression wood was only rarely assessed at Reuse de Saleinaz (3%), it was more commonly identified in the samples collected at Torrent de la Fouly with 13% of all GD. Growth suppression was used to date past debris-flow events in 9% (Reuse de Saleinaz)

	Reuse de Saleinaz		Torrent de la Fouly		Total	
	no.	%	no.	%	no.	%
tangential rows of traumatic resin ducts	208	82	52	65	260	78
growth suppression	22	9	13	16	35	11
growth release	13	5	4	5	17	5
compression wood	7	3	10	13	17	5
injuries	3	1	1	1	4	1
Total	253	100	80	100	333	100

Table C4.2 *Growth disturbances (GD) assessed in the 556 Larix decidua Mill., Picea abies (L.) Karst. and Pinus sylvestris L. samples. For both study sites as well as the entire sampling, the number (no.) as well as the percentages (%) are indicated.*

and 16% (Torrent de la Fouly) of samples, whereas growth release amounted to 5% of samples at both study sites. Injuries could, in contrast, only rarely be identified on the increment cores.

Figure C4.3 provides characteristic examples for the dating of a debris-flow event. The *L. decidua* tree illustrated in Figure C4.3a is located in a debris-flow lobe in the lowermost part of the Reuse de Saleinaz cone and was partially buried by debris-flow material. Its growth curves show distinct growth suppression following a disturbance in 1991. The *P. abies* tree illustrated in Figure C4.3b grows in the front of a terminal lobe on the Torrent de la Fouly cone. It was tilted in 1962 and reacted to this disturbance with the formation of compression wood. The growth of this tree was strongly eccentric after 1962, as it produced much wider year rings on its downslope side than on the upslope side in the years following the event.

4.3 Reconstructed debris-flow frequencies at Reuse de Saleinaz and Torrent de la Fouly

The analysis of the 253 GD identified in the 456 tree-ring series sampled at **Reuse de Saleinaz** allowed identification of 39 debris-flow events, with the oldest event dated to AD 1743 (Fig. C4.4a). The number of events dated to the period 1743–1850 is rather limited, with evidence of only six debris flows. Thereafter, the frequency becomes much higher with 33 events reconstructed between 1868 and 2003. From the data, it also appears that periods with repeated debris-flow activity are followed by phases with little or almost no activity. Such a clustering of events is especially obvious in the 1870s, the early 1920s or the 1970s. As far as the six debris-flow events recorded in the local archives are concerned, four of them could be recognized in this study through dendrogeomorphological methods. In contrast, tree-ring records did not show any GD for the events that occurred in 1992 and 1993.

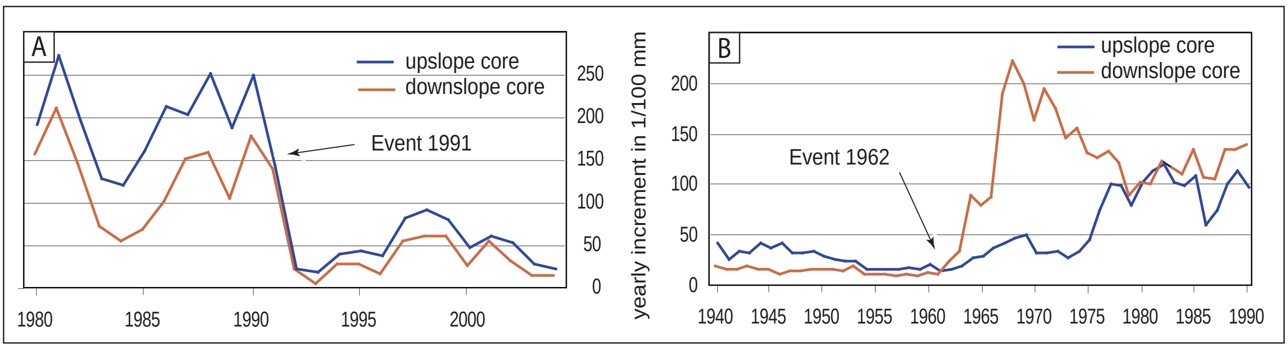

Fig. C4.3 *Examples of growth disturbances in tree-ring series as a result of debris-flow activity: (a) This L. decidua shows abrupt growth suppression following an event in 1991. (b) The growth curves of this P. abies exhibit eccentric growth following an event in 1962. In addition, compression wood can be identified on the downslope core of this tree.*

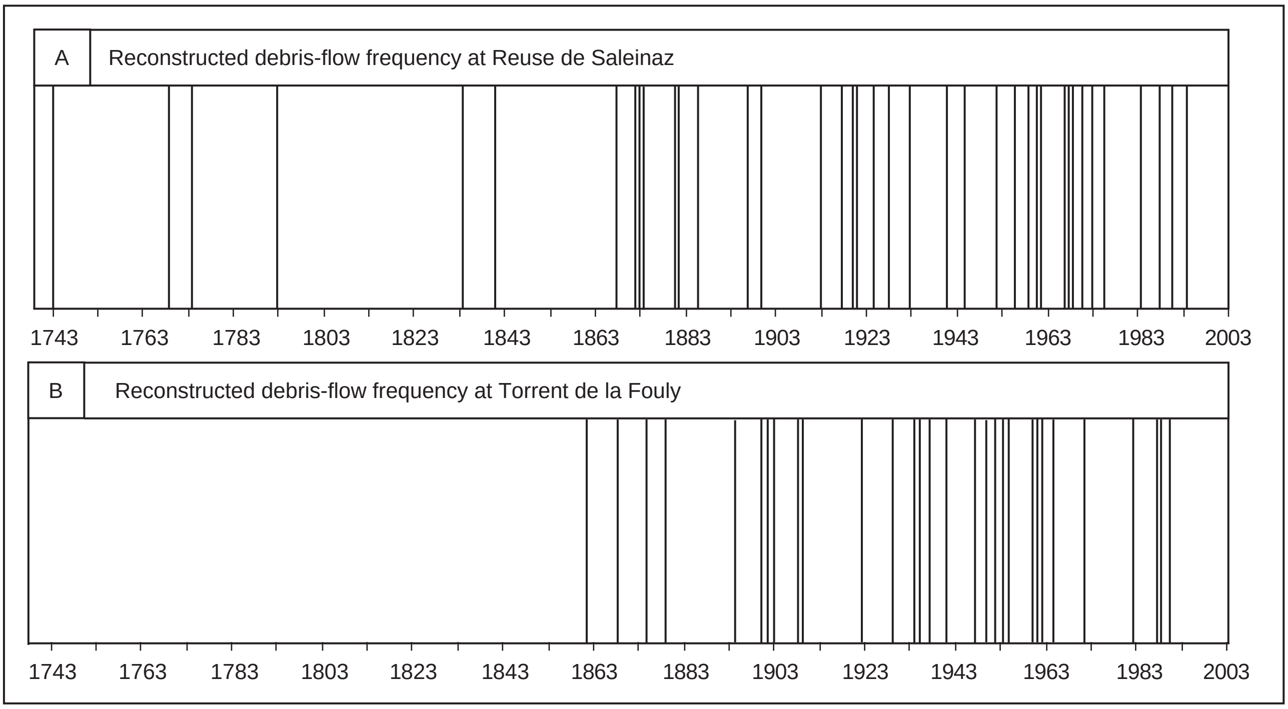

Fig. C4.4 *(a) Reconstructed debris-flow frequency for the Reuse de Saleinaz with 39 events between AD 1743 and 2003. (b) At Torrent de la Fouly, 30 events could be identified between AD 1862 and 2003.*

At **Torrent de la Fouly**, the identification of 80 GD allowed reconstruction of 30 events for the period 1862–2003 (Fig. C4.4b). According to our results, debris flows recurred at more or less regular intervals, and we could identify periods characterized by notable or negligible activity. A clustering of events can be observed between 1945 and 1955, and again in the early 1960s. In contrast, none of the debris-flow events known in the local archives could be recognized by analyzing the tree-ring series.

4.4 Spatial distribution of trees affected by debris-flow events

The spatial distribution of trees affected by the same event is of considerable help in determining the minimum spatial extent of past debris flows. We present results for the **Reuse de Saleinaz** only, as the number of trees sampled at Torrent de la Fouly was too small for this kind of interpretation. The examples provided in Figure C4.5 clearly indicate that individual events normally did not affect the entire cone but that they were limited to certain parts of the study area. In 1952 (Fig. C4.5a), a debris-flow event affected trees growing on the uppermost part of the cone. The spatial distribution of trees disturbed by a debris-flow event in 1962 (Fig. C4.5b) is quite similar. In contrast to the event in 1952, GD are restricted to trees growing close to the channel or on the outermost part of the cone, but not on its central part. Figure C4.5c provides an example from an event that influenced trees on the central part of the cone, where trees are old enough to record the event of 1834. Finally, Figure C4.5d represents an event where material left the currently active channel in the lowermost part of the cone and affected trees south of the channel.

4.5 Comparison of reconstructed events with data on flooding in neighboring torrents in Val Ferret

The debris-flow events reconstructed by means of dendrogeomorphological methods in this study were compared to debris-flow and flooding events recorded in local archives (Rey & Saameli, 1997). For each event, all torrents producing a debris-flow or flooding event were noted on a map of the entire valley in order to represent the spatial extent of the event. Based on this representation, it appears that

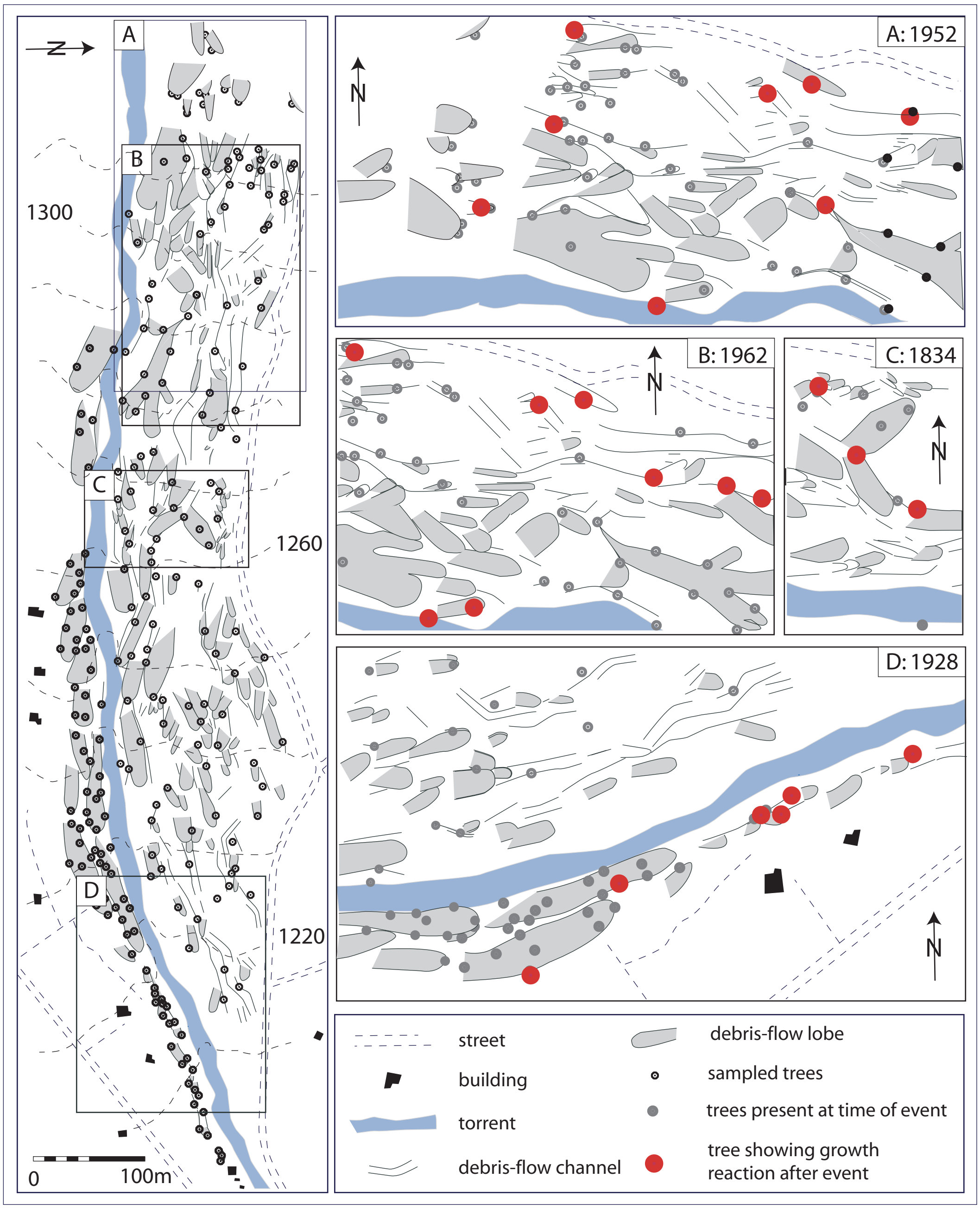

Fig. C4.5 *Spatial distribution of trees at the Reuse de Saleinaz cone showing growth disturbances in (a) 1952, (b) 1962, (c) 1834 and (d) 1928.*

there are at least two different types of events (Fig. C4.6). During some events, activity was restricted to only one or a few torrents (Fig. C4.6a). On the other hand, there is also evidence for simultaneous debris-flow activity in a majority of torrents. For instance and as illustrated in Figure C4.6b, nearly all torrents descending the eastern slopes of Val Ferret (with the exception of Torrent de Ferret and Combe à Paron) produced debris flows in August 1991.

5. Discussion

In this study, increment cores extracted from 278 living European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) trees allowed recognition of 333 growth disturbances (GD) caused by 69 debris-flow events. While, at Reuse de Saleinaz, 39 separate events could be identified since AD 1743, the reconstruction at Torrent de la Fouly covers 142 years and yields data on 30 events.

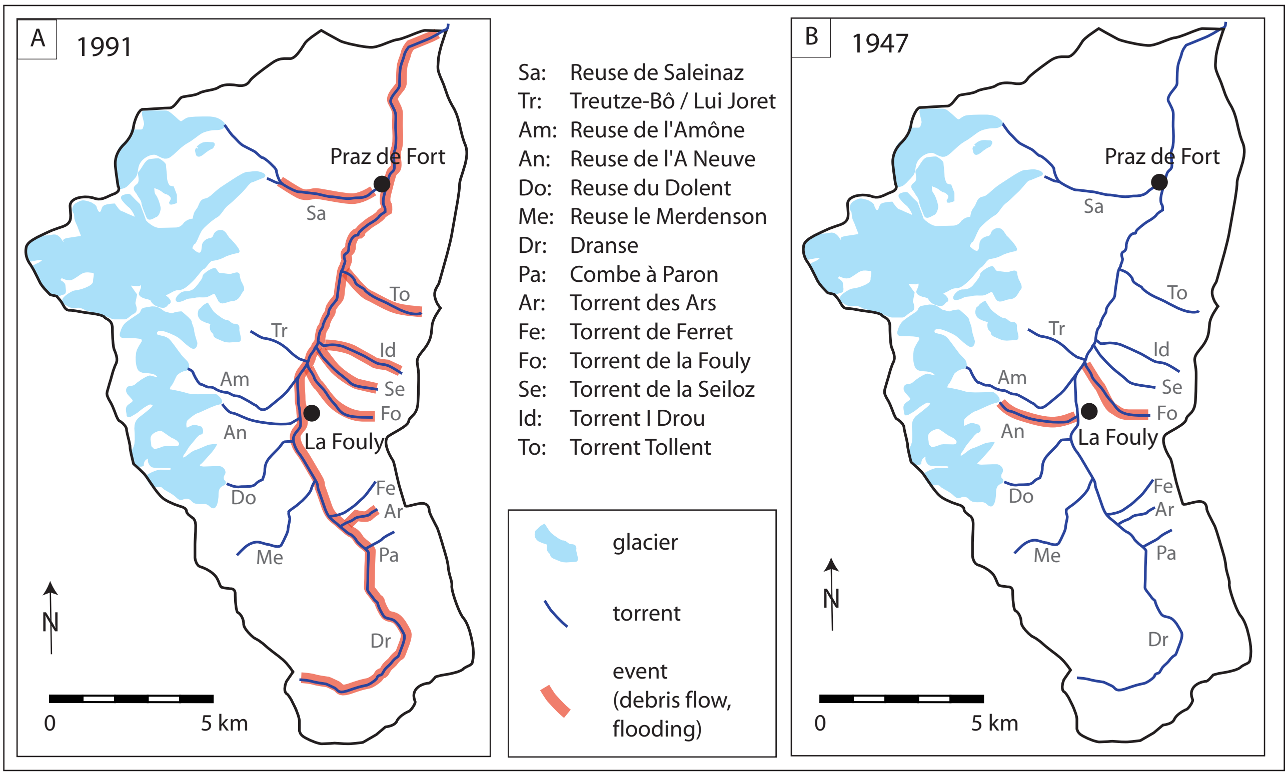

***Fig.C4.6** (a) Spatial distribution of debris flows and flooding triggered in large parts of the Val Ferret by persistent rainfall in 1991. (b) In contrast, only the Reuse de l'A Neuve and the Torrent de la Fouly produced debris flows during a local summer thunderstorm in 1947 (archival data: Rey & Saameli, 1997).*

For both study sites, the number of reconstructed debris-flow events must be seen as a minimum frequency, as the reconstruction of past events was limited by the age of the trees. In this sense, all events that occurred prior to AD 1680 do not appear in the reconstruction due to the absence of trees showing more than 325 tree rings at sampling height. The limited number of trees available prior to the 1850s may influence the quality of the reconstructed frequencies as well. Finally, debris flows remaining in the channel do not necessarily affect trees and may therefore not be identified by means of tree-ring analysis either. This fact is supported by archival data on the events of 1992 and 1993 in the Reuse de Saleinaz. The events could not be identified with dendrogeomorphological methods since surges apparently did not leave the current channel but, rather, caused erosion in the channel bed (Rey & Saameli, 1997).

The age structure of the forest stand at **Reuse de Saleinaz** clearly shows that the oldest trees can be found in the central part of the cone, whereas trees in the upper and lower parts are much younger. Trees growing in the uppermost part of the cone would be regularly eliminated by debris flows or rare snow avalanche activity; therefore, this sector has not been taken into account in the present study. In contrast, trees growing in the central part of the cone seem to be somehow more protected from geomorphic influence and anthropogenic activity. Geomorphic forms as well as the vegetation indicate that snow avalanches did not reach this part of the cone. Anthropogenic interventions would influence the age and succession rates of trees in the lowermost part of the cone (i.e. farming activities, extraction of fire- and construction wood). Given that tree age is the main limiting factor for the reconstruction of debris-flow events using dendrogeomorphological methods, the approach works best at study sites where anthropogenic influence is small and timber harvesting has been infrequent in the past few centuries.

The age structure also indicates two periods with considerable colonization between 1850 and 1880 as well as between 1930 and 1950. A previous forest growing at this location might have been eliminated by exceptionally large or destructive debris-flow events. Dendrogeomorphological data allowed reconstruction of a major event in 1841. Given that tree age was determined at sampling height and therefore does not give information on germination dates, it is feasible that the tree succession in the 1850s–1880s reflects a re-colonization of the cone following the event in 1841 (see Fig. C4.4a). This assumption is further supported by analyses of the spatial distribution of survivor trees showing GD in 1841 as well as by the position of trees germinating in the years following this event. The second period with considerable tree succession on the cone during the 1940s is limited to the uppermost part of the cone. On the basis of our reconstructions, we assume that a previous forest stand would have been destroyed by the substantial debris-flow activity in the 1920s, resulting in increased re-colonization starting in the 1930s.

In contrast, the trees bordering the currently active channel at **Torrent de la Fouly** do not show abrupt steps in their age structure. It is possible that the limited number of trees chosen for analysis is the reason for this absence of colonization periods here. Another explanation might be the smaller rock sizes present in the catchment area. Individual surges and presumably smaller events may have caused GD to trees but did not eliminate entire sectors in the past.

Jakob *et al.* (2005) highlighted the importance of channel recharge rates in the triggering of debris-flow events. At **Torrent de la Fouly**, small rocks are readily available and debris supply cannot be considered a limiting factor here. In contrast, rock sizes at **Reuse de Saleinaz** are dominated by boulders and small fractions are less readily available. Nonetheless, the reconstructed frequencies at Torrent de la Fouly and Reuse de Saleinaz appear to be very similar, with an average of one event identified every eight years for the period of reconstruction. This similarity in the frequency of events should, however, be interpreted with caution, as the reconstruction at Torrent de la Fouly was considerably limited by the small number of trees suitable for dendrogeomorphological analysis. In addition, the currently used channel has probably been active for at least several decades. It is deeply incised, and may, thus, have prevented a certain number of high-frequency small-magnitude events from leaving the channel and from affecting trees located on the banks or on the cone. Finally, debris-flow activity at Torrent de la Fouly appears to be only influenced by meteorological events, whereas glacier-lake outburst flooding (GLOF) triggered debris flows at Reuse de Saleinaz in 1920 and 1928 (Rey & Saameli, 1997).

The spatial distribution of trees affected during particular events indicates that debris flows are normally restricted to only some parts of the cone. Although different patterns of debris-flow activity have been identified on a forested cone in the Valais Alps (Bollschweiler *et al.,* 2007) such patterns could not be identified at **Reuse de Saleinaz**. It therefore seems that each event had its own characteristics and – except for the events remaining in the main channel – its own flow path. The limited number of channels and levees identified on the cone as well as the considerable number of lobate structures identified on the cone support this assumption. We therefore believe that as soon as previous debris flows left the main channel at Reuse the Saleinaz, the rough and porous surface of the cone caused surges to stop within a short distance. Based on the analysis of the deposits identified in the field, we also believe that only surges containing smaller rock sizes traveled to the northern and to the lowermost part of the cone.

A comparison of reconstructed events at Reuse de Saleinaz and Torrent de la Fouly with archival data on debris-flow and flooding activity in neighboring torrents reveals the existence of different spatial patterns of events. On the one hand, we identify debris flows and floods in a large number of torrents in Val Ferret that must have been triggered by persistent rainfall events affecting the entire valley. On the other hand, there is also evidence for more locally limited summer thunderstorms with debris flows and flooding in a very limited number of torrents. These observations need, however, to be interpreted very cautiously, as earlier events were only noted in archives if they caused major damage to infrastructure or even loss of lives. In a similar way, we observe an increase in debris-flow events noted in archives over the last century. Due to the changes in the awareness of the threats posed by debris flows and the enlargement of villages in Val Ferret, there is much high-quality information available on debris-flow events for the last two decades, whereas archival data remain comparably scarce for the early 20th century.

6. Conclusion

Tree-ring analysis in two Alpine catchments located in Val Ferret (south-western Switzerland) allowed reconstruction of 39 events at Reuse de Saleinaz and 30 events at Torrent de la Fouly. The reconstruction for the Reuse de Saleinaz covers 260 years. In contrast, tree age at Torrent de la Fouly limited the reconstruction to 141 years. Although the two investigated torrents possess different predisposition characteristics to debris flows, their debris-flow frequency is very similar, with one event every eight years on average. Therefore, we suppose that the recurrence of events for both torrents depends on precipitation events and thus has to be considered rather transport-limited than weathering-limited. The spatial distribution of trees that have been disturbed during earlier events indicates that events normally affected only a part of the cone. In addition, no characteristic patterns of spatial behavior could be identified. Therefore, we believe that surges leaving the currently active channel stopped after a short travel distance. Even though the age of trees growing on the cone limited the reconstruction, dendrogeomorphological methods proved to be a valuable tool to gain information on former debris-flow events at the study sites.

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CHAPTER D

RECONSTRUCTION OF SPATIAL PATTERNS OF PAST DEBRIS-FLOW EVENTS

Reconstruction of spatial patterns of past debris-flow events

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"Reconstructing spatio-temporal patterns of debris-flow activity using dendrogeomorphological methods"

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Abstract

Debris flows are a major threat in many parts of the Alps, where they repeatedly cause severe damage to infrastructure and transportation corridors or even loss of life. Nonetheless, the spatial behavior of past debris-flow activity and the analysis of areas affected during particular events have been widely neglected in reconstructions so far. It was therefore the purpose of this study to reconstruct spatio-temporal patterns of past debris flows on a forested cone in the Swiss Alps (Bruchji torrent, Blatten, Valais). The analysis of past events was based on a detailed geomorphic map (1:1000) of all forms related to debris flows as well as on tree-ring series from 401 heavily affected trees (*Larix decidua* Mill. and *Picea abies* (L.) Karst.) growing in or next to deposits. The samples were analyzed and growth disturbances related to debris-flow activity assessed, such as tangential rows of traumatic resin ducts, the onset of reaction wood or abrupt growth suppression or release.

In total, 960 growth disturbances were identified in the samples, belonging to 40 different event years between A.D. 1867 and 2005. In addition, the coupling of tree-ring data with the geomorphic map allowed reconstruction of eleven formerly active channels and spatial representation of individual events. Based on our results we believe that before 1935, debris flows preferentially used those channels located in the western part of the cone, whereas the eastern part of the cone remained widely unaffected. The spatial representation of the 40 events also allowed identification of five different spatial patterns for debris flows at the study site.

Keywords

debris flows, dendrogeomorphology, tree ring, geomorphic mapping, spatial patterns, abandoned channels

1. Introduction

Debris flows are a common mass-movement process in mountainous regions where they frequently leave traces in the landscape. At the mouth of gullies or torrent valleys, active debris-flow torrents build cone-shaped debris accumulations and characteristic depositional forms such as lobes and levees. The processes and forms related to debris-flow activity have extensively been described in the literature (Jakob & Hungr, 2005). Previous investigations repeatedly focused on e.g., the flow behavior and rheology (Costa, 1984, 1988; Johnson & Rodine, 1984; Rickenmann, 1999; Bollschweiler *et al.*, 2005) or on the assessment of threshold values for the triggering of events (Caine, 1980; Wilson & Wieczorek, 1995; Blijenberg, 1998; Bovis & Jakob, 1999; Huggel *et al.*, 2002; Cannon *et al.*, 2003). In a similar way, the magnitude and frequency of debris flows have repeatedly been reconstructed or the moment of past activity assessed by means of aerial photographs, and/or field investigations (Hungr *et al.*, 1984; Van Steijn, 1996; Zimmermann *et al.*, 1997, Corominas & Moya, 1999) as well as with lichenometry (Innes, 1983, 1985; Jonasson *et al.*, 1991; Winchester & Harrison, 1994; Helsen *et al.*, 2002).

Previous debris-flow studies using dendro-geomorpho-logical methods primarily focused on the dating of individual events or deposits (Stefanini & Ribolini, 2003), on the reconstruction of magnitude and/or frequencies (Strunk, 1997; Baumann & Kaiser, 1999, May & Gresswell, 2004; Stoffel *et al.*, 2005b, 2006a) or on a comparison of debris-flow data with flooding in neighboring rivers (Stoffel *et al.*, 2003).

While these tree-ring studies furnished valuable data on recurrence intervals of debris flows, they widely neglected the behavior of past debris-flow activity and the analysis of areas affected during particular events.

It is therefore the purpose of this study to date growth disturbances in heavily disturbed *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees on a debris-flow cone in the Swiss Alps so as (i) to reconstruct periods with debris-flow activity in currently abandoned channels and (ii) to assess the spatial extent of individual events. We report results obtained from detailed geomorphic mapping (1:1000) and dendrogeomorphological analysis of 401 trees growing on the Bruchji cone near Blatten b. Naters (Valais, Switzerland). Data allowed spatio-temporal reconstruction of 40 debris flow events between A.D. 1867 and 2005 as well as the determination of past debris-flow activity in eleven channels being currently abandoned.

2. Study site

The study was conducted on the cone of the Bruchji torrent, located north-northeast of the village of Blatten b. Naters (Valais, Swiss Alps, 46° 22'N / 7° 59'E; Fig. D2.1). The cone extends from 1380 to 1520 m a.s.l. and is covered with an open forest built of Norway spruce (Picea abies (L.) Karst.) and European larch (Larix decidua Mill.). Slope gradients on the cone average 13° and anthropogenic activity is most obvious in its lowermost part, where the cone surface has been strongly reshaped through the construction of holiday homes.

Debris flows are commonly triggered from an unstable zone located between 1600 and 2000 m a.s.l. (Fig. D2.1). Here, the retreat of the Aletsch Glacier following the last glaciation (i.e. Würm; Hantke, 1980) caused major slope instabilities, disintegrating huge amounts of gneissic bedrock. This material belongs to the crystalline Aar massif (Labhart, 2004) and is easily mobilized during heavy rainfall (Jossen, 2000). Once released, debris flows pass through a short (length: 100 m) and deeply incised gorge before they reach a well-developed cone (13 ha).

Archival data on past events in the Bruchji torrent are scarce. Debris-flow activity is noted for the period 1905–1907 (Jossen, 2000) and for four events after 1987. In between, there is a large gap and information does not exist.

In order to prevent future damage to infra-structure caused by debris flows, protection measures were undertaken in the late 1970s (debris retention basin, deflection dam; see Fig. D2.1) and the banks of the main channel were reinforced in order to

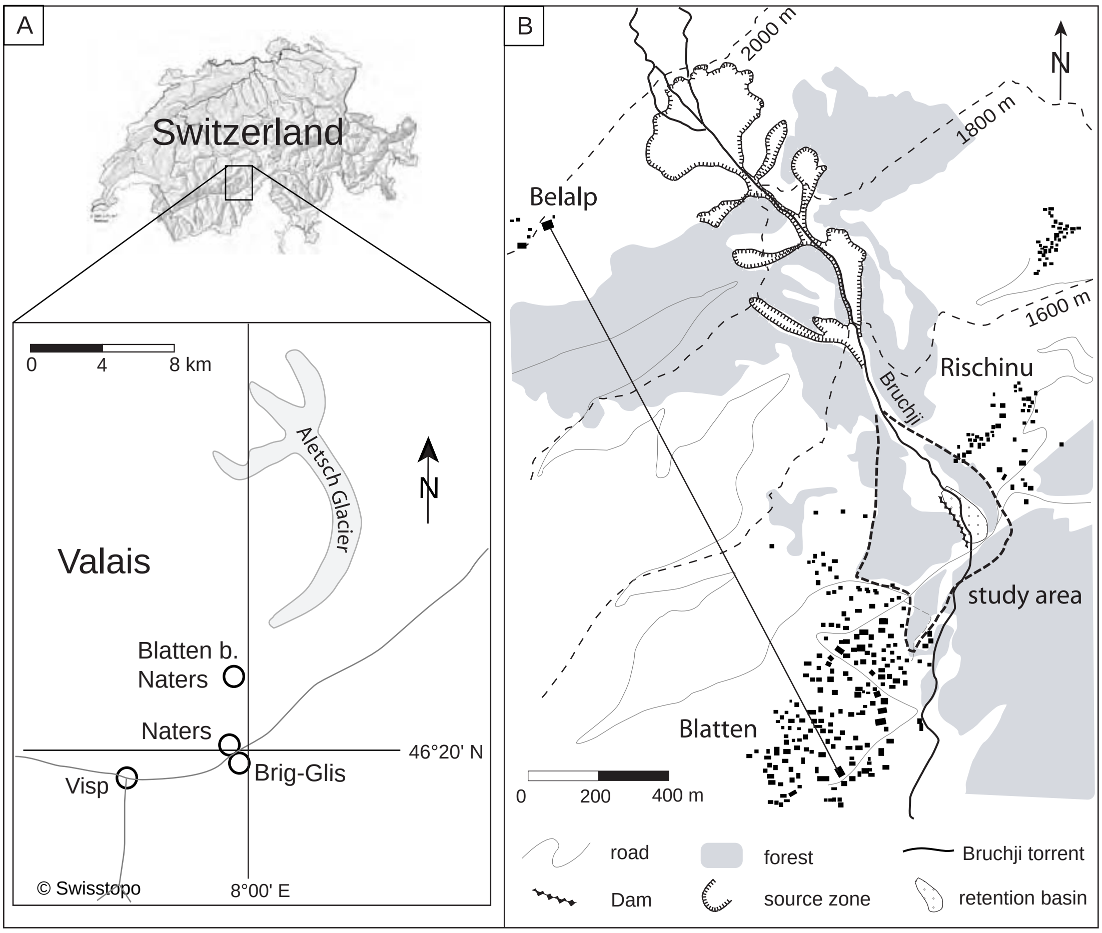

Fig. D2.1 (a) The Bruchji torrent is located in the Swiss Alps near the village of Blatten b. Naters (Canton of Valais). (b) Sketch map of the Bruchji torrent with its departure zone, the study site and the protection measures built in the late 1970s.

prevent debris flows from reaching the village of Blatten (Imhof, pers. comm.). Nonetheless, several debris-flow surges caused significant overbank sedimentation on 4 July 2001, which is the reason why the existing retention basin and the deflection dam were enlarged. Downstream of the retention basin, the channel was incised by approximately 1 m (Bollschweiler, 2003; Ehmisch, 2005).

3. Methods and material

3.1 Geomorphic mapping

In a first analytical step, all forms and deposits related to former debris-flow activity (i.e. lobes, levees or abandoned channels) were mapped in a scale of 1:1000. Due to the presence of forest on the cone, GPS devices could not be used. Thus the map was based on detailed field measurements using compass, tape measure and inclinometer.

3.2 Sampling strategy and dating of past events

Geomorphic processes may influence trees in various ways (see Alestalo, 1971; Shroder, 1978, 1980; Schweingruber, 2001). The impact of rocks and boulders or abrasion processes may cause scars to the stem surface or even decapitate trees. Unilateral pressure of flowing material can result in a tilting of the stem. Finally, material may bury the stem base when deposited. Affected conifer trees react to these impacts with callus tissue, tangential rows of traumatic resin ducts (Stoffel *et al.*, 2005a, c; Perret *et al.*, 2006), the formation of reaction wood (Giardino *et al.*, 1984; Braam *et al.*, 1987;

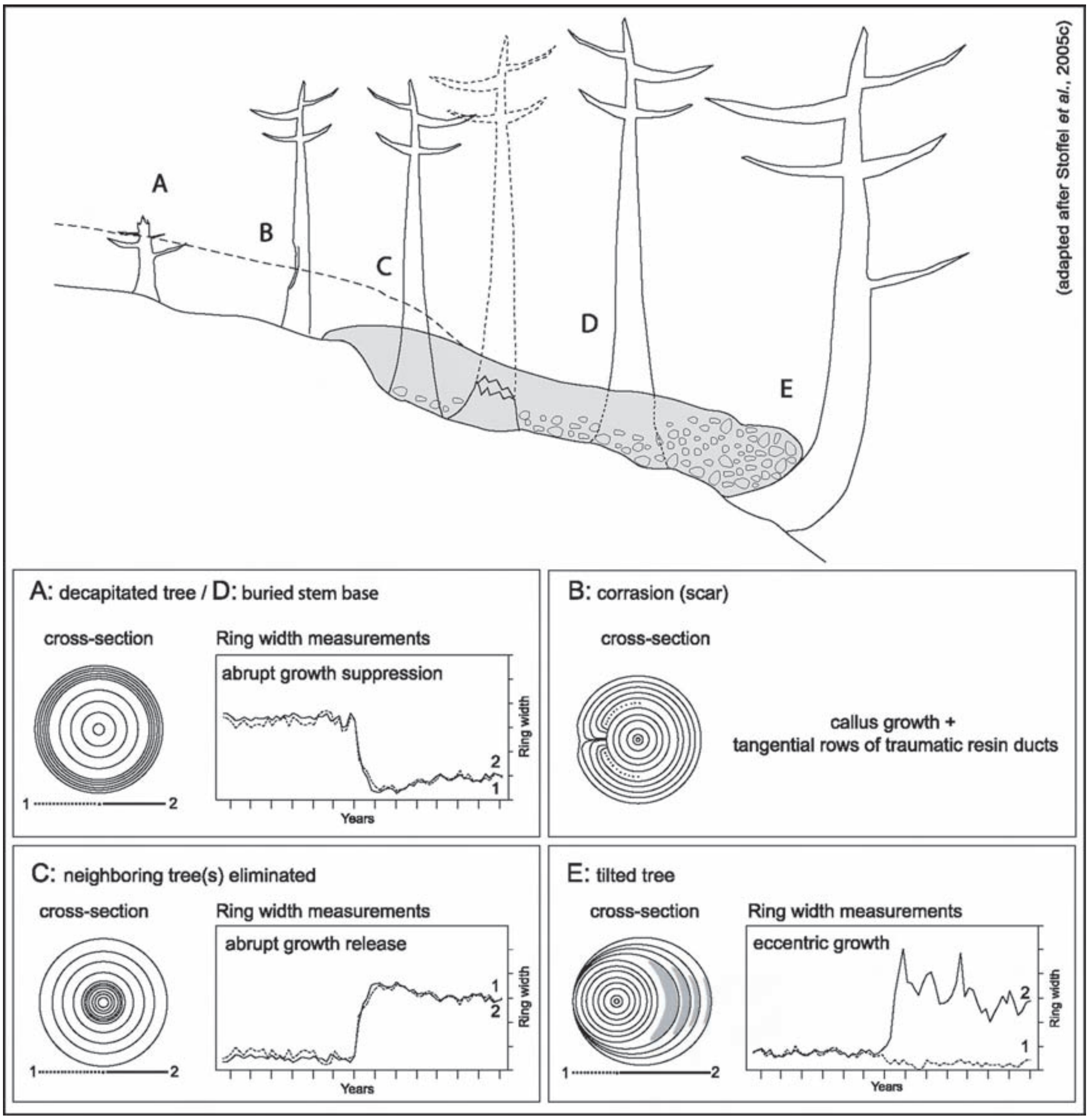

***Fig. D3.1** Growth reactions of trees affected by debris flows.*

Fantucci & Sorriso-Valvo, 1999; Stefanini, 2004; Stoffel *et al.*, 2005b) or with an abrupt growth suppression or release (Strunk, 1997). Figure D3.1 gives an overview of the different impacts of debris flows on trees and their reactions to the disturbances.

Within this study, 802 increment cores from 401 *Picea abies* and *Larix decidua* trees growing on the debris-flow cone were sampled. These species were chosen because they are excellent recorders of past events and because they have comparably low numbers of missing or false tree rings (see Schweingruber, 1978, 1996; Schweingruber *et al.*, 2006). Only trees obviously influenced by former events (i.e. tilted, injured or decapitated trees, buried stem base) were cored. Two cores were normally extracted per tree with increment borers, one on the side of the impact, another one on the opposite side of the trunk. Sampling height was chosen according to the morphology of the stem: Injured or tilted trees were sampled at the height of the disturbance; cores from trees with buried stem base or from decapitated trees were, in contrast, extracted next to the stem base so as to preserve as much tree-ring information as possible. For each tree sampled, additional data were gathered including (i) description of the disturbance and morphology, (ii) determination of its position within the deposits, (iii) tree diameter at breast height, (iv) position of the cores sampled (i.e. upslope, downslope, other), (v) information on neighboring trees. The position of each tree sampled was precisely marked on the geomorphic map.

In addition to the disturbed trees sampled on the cone, we selected undisturbed Larix decidua and Picea abies trees from a nearby forest stand showing no signs of debris-flow activity or any other geomorphic process. Reference chronologies were built with 30 trees per species so as to obtain information on "normal" growth conditions at the location (i.e. climate, insect outbreaks; Cook & Kairiukstis, 1990).

Samples were analyzed using the standard methods described by Bräker (2002). Individual working steps included surface preparation, counting of tree rings as well as measuring of ring widths using a digital LINTAB positioning table and TSAP 3.0 software (Time Series Analysis and Presentation; Rinntech, 2007). Increment curves of the disturbed trees were then crossdated with the reference chronology in order to correct faulty tree-ring series derived from disturbed samples (e.g., false or missing rings; Schweingruber, 1996). Thereafter, samples were analyzed visually and tree rings showing tangential rows of traumatic resin ducts (TRD), the onset of compression wood or callus tissue were noted on skeleton plots (Schweingruber *et al.*, 1990), before the growth curves of the disturbed trees were compared with the reference chronology of the corresponding tree species in order to determine initiation of abrupt growth suppression or release.

Based on the age of the selected trees (i.e. number of tree rings available on the increment core at breast height), we assessed the approximate age structure of the forest stand on the Bruchji cone.

3.3 Reconstruction of past channel activity and spatial patterns of former events

The position of all trees with growth reactions in the same event year was marked on the geomorphic map. This representation of trees affected during individual events allowed (i) reconstruction of the extent of events on the cone, (ii) identification and interpretation of spatial patterns of past events as well as (iii) an assessment of activity in currently abandoned channels.

4. Results

4.1 Geomorphic map

Mapping of the entire debris-flow cone (13 ha) in a scale of 1:1000 allowed identification of 164 debris-flow lobes and 53 segments of debris-flow levees. However, none of the channels identified on the cone is deeply incised and the lobate deposits are normally only poorly developed with smooth surfaces. Figure D4.1 shows all forms mapped and the position of the trees sampled.

Most deposits are present west of the currently active channel. On its upper part, the cone is relatively narrow and only a small number of geomorphic forms can be identified here, primarily levees interspersed with a few lobes. The biggest deposits are located in the central part of the cone, where a large number of lobes is present. It is also in this area where a large quantity of trees has been sampled. The lower part of the cone has, in contrast, been heavily reshaped by human activity. As a consequence, only a limited number of forms can be identified here and the number of trees sampled was comparably low.

4.2 Age structure of the stand

Data on the pith age at breast height indicate that the 401 Larix decidua and Picea abies trees on the Bruchji cone are, on average, 91 years old (STDEV: 32 years). While the oldest tree sampled for analysis attained sampling height in A.D. 1791, the youngest sample only reached breast height in 1987. As can be seen from Figure D4.2, the sectors to the east of the current channel contain the youngest trees. Above the debris-retention basin, trees reach an average of 51 years, whereas 63 tree rings were counted in those trees located below the basin. In contrast, the oldest trees can be found in the western part of the cone, where they locally reach an average of 150 years. Data also indicate that the area east of the active channel was apparently not colonized until the 1930s.

4.3 Growth disturbances and minimum frequency of past debris-flow events

In total, 960 growth disturbances (GD) were assessed in the 802 samples. Table D4.1 gives an overview on the different GD identified. Six different categories of GD have been defined. In the samples, we either identified single reactions in the form of tangential rows of traumatic resin ducts (TRD), abrupt growth changes (suppression or release), the onset of reaction wood or injuries. In addition, multiple reactions occurring simultaneously in a tree after disturbance (i.e. resin ducts and growth changes or resin ducts and reaction wood) were noted separately. Most frequently, GD were identified via the presence of TRD, occurring in 36% of all cases. The onset of reaction wood

Fig. D4.1 *Detailed geomorphic map (1:000) of the Bruchji cone representing all forms related to past debris-flow activity (levees, lobes, channels) and the position of all trees sampled.*

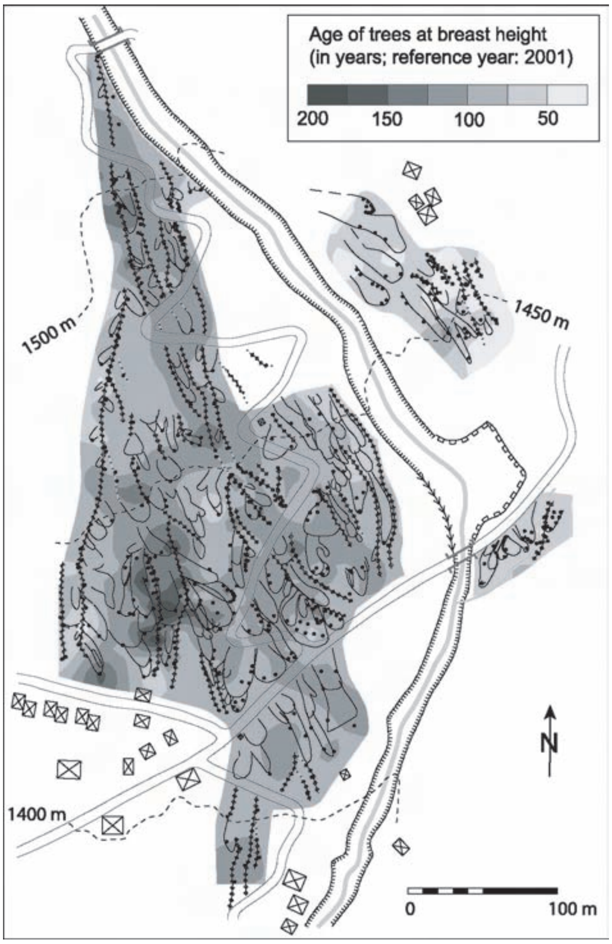

Fig. D4.2 Age structure of the forest stand on the Bruchji cone. The oldest trees are located in the western part of the cone whereas the trees in the eastern sectors are rarely older than 60 years. The oldest tree reached breast height in A.D. 1791.

Type of reaction	Number	%
Tangential rows of traumatic resin ducts	346	36
Tangential rows of traumatic resin ducts+onset of reaction wood	172	18
Onset of reaction wood	165	17
Abrupt growth change (suppression or release)	122	13
Tangential rows of traumatic resin ducts+abrupt growth change	117	12
Injury	38	4
Total	960	100

***Table D4.1** Different growth disturbances (GD) assessed in the 802* Larix decidua *Mill. and* Picea abies *(L.) Karst. samples.*

totaled 17% of all GD, whereas the combination of TRD and abrupt growth changes occurred in 12%. Abrupt growth changes without TRD were recognizable in 13%. In contrast, injuries could only rarely be assessed (4%). Figure D4.3 gives two examples of GD leading to the reconstruction of event years. While Figure D4.3a illustrates a distinctive growth suppression in 1960 following an event in 1959, Figure D4.3b shows the growth curves of a tree with eccentric growth and reaction wood as a result of tilting of the stem in 1927.

Overall, the identification of the 960 GD allowed reconstruction of 40 event years between 1867 and 2005. Figure D4.4a indicates the seven events known from archival data (i.e. 1907, 1987, 1990, 1994, 1995, 1996 and 2001), whereas Figure D4.4b shows the 40 event years reconstructed in this study with dendrogeomorphological methods. Three of the seven documented event years (1996,

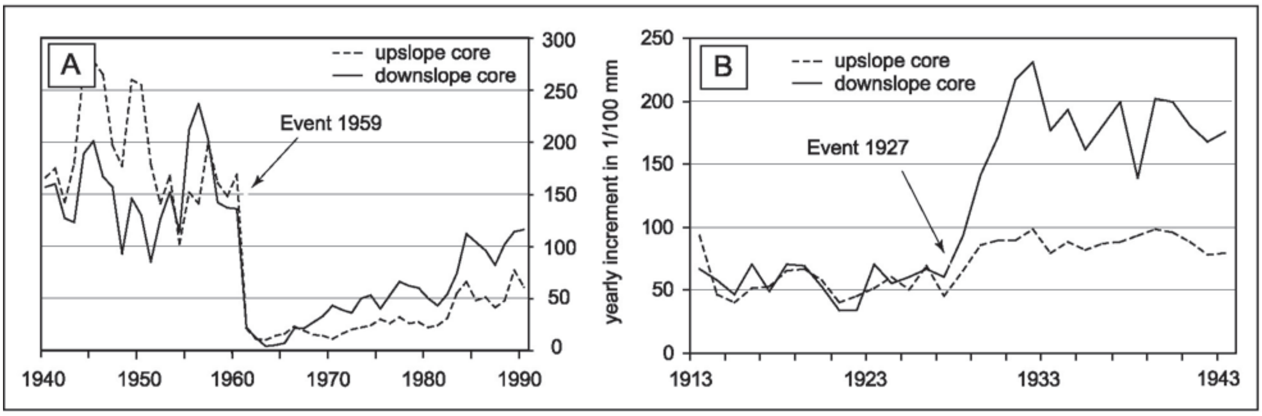

***Fig. D4.3** Growth curves of trees affected during past events. (a) The increment curves of this tree show an abrupt growth suppression as a reaction to burying by debris-flow material in 1959. (b) As a reaction to the tilting by an event in 1927, this tree started to form reaction wood in the downslope core in the year following the disturbance.*

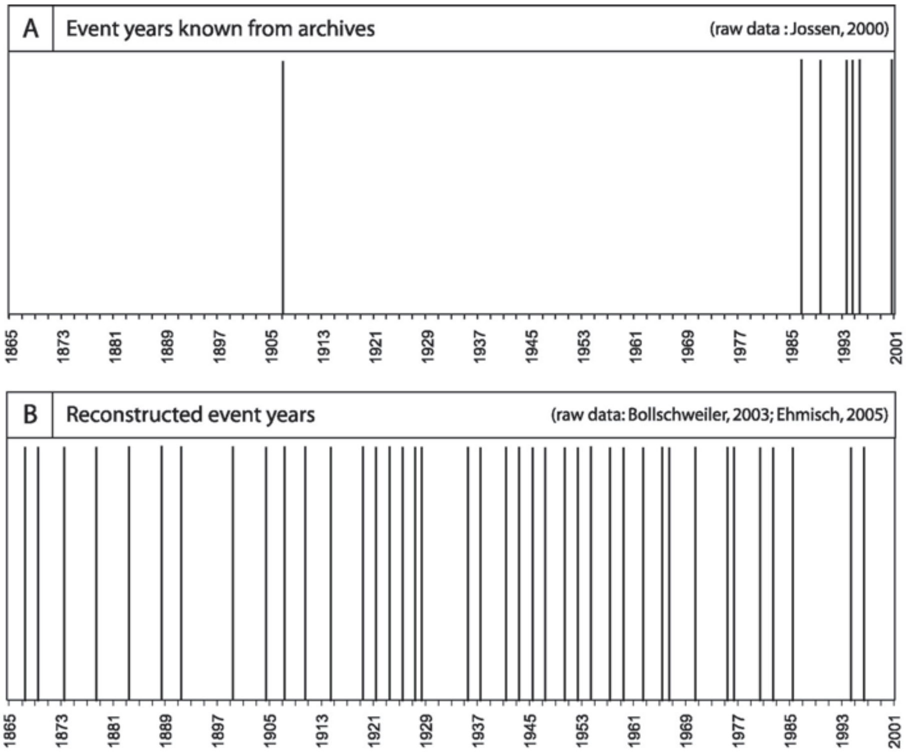

Fig. D4.4 *Reconstructed frequency of debris flows in the Bruchji torrent. (a) Archival data report seven events for the 20th century, with six events concentrated to the last 20 years. (b) Tree-ring data, in contrast, produced data on 40 events between A.D. 1867 and 2005.*

1994 and 1907) could be identified in the tree-ring series as well. In contrast, the event years 1987, 1990 and 1995 could not be reconstructed with dendrogeomorphological methods. Since the event of 2001 occurred during the fieldwork for this study, no GD could be assessed in the tree rings. In addition to the events known from archives, 37 new event years were identified.

4.4 Reconstruction of formerly active channels

The localization of the trees with GD in a particular year on the geomorphic map allowed assessment of spatial patterns and activity in currently abandoned channels. The visualization of the event years on the map yielded data on eleven formerly active channels and their activity during the past decades. Figure D4.5 shows the location of the different channels on the map. For some of the channels, only short fragments of their lateral levees can be identified, e.g. for channels 4 or 10. Here, only some 30 m of the levees are still recognizable in the field, whereas signs of other channels can be followed over a considerable distance (up to 300 m) on the cone. Table D4.2 provides data on past debris flows in the eleven channels and clearly indicates that mainly channels 1, 2, 3 and 5 have been repeatedly active during past events. The most recent events in channels 1 and 5 were dated to 1978, whereas activity in channels 2 and 3 only ceased in 1982. In contrast, only very limited activity could be reconstructed for the other channels, with only one event (1957) dated for channel 9. As a result of the protection measures (retention basin, channel reinforcement) initiated in the 1970s, channel activity in the western part of the cone was interrupted. Nevertheless, the event in 1982 reached channel 3 and affected trees in the western part of the cone.

Channel	First event	Last event	Number of events
1	1867	1978	18
2	1867	1982	25
3	1869	1982	10
4	1952	1962	3
5	1869	1978	20
6	1907	1947	5
7	1891	1954	3
8	1904	1962	6
9	1957	1957	1
10	1952	1985	8
11	1952	1980	3

Table D4.2. *Debris-flow channels and periods of activity: the first and the last event reconstructed for individual channels are noted as well as the total number of events reconstructed between A.D. 1867 and 2005. For the location of the individual channels see Fig. D4.5.*

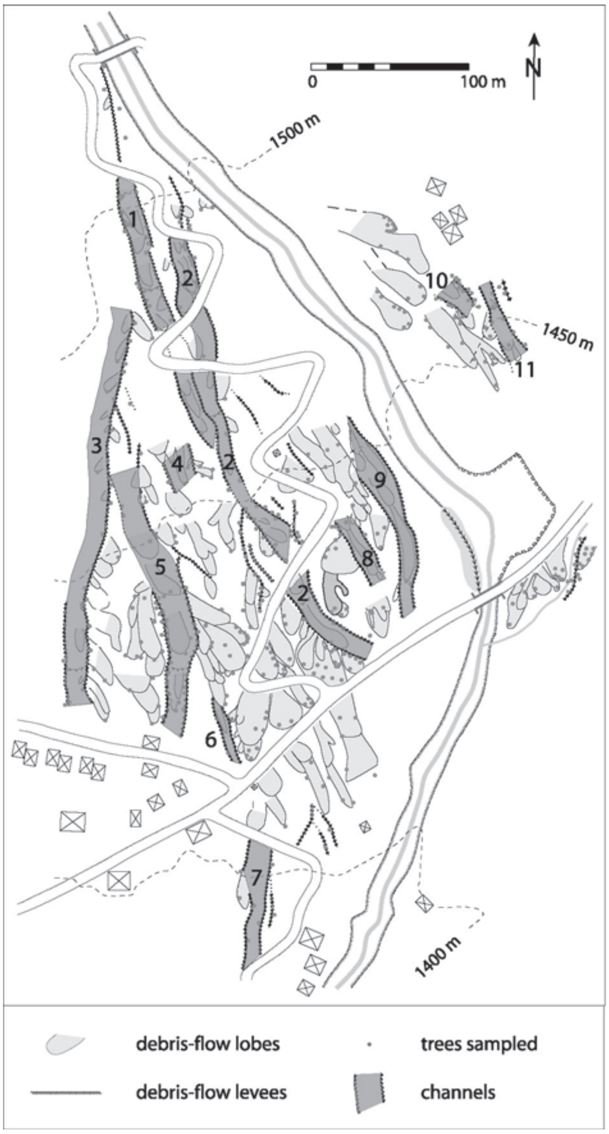

Fig. D4.5 Localization of the eleven channels identified on the cone.

4.5 Spatial patterns of former events

The position of all trees showing growth disturbances (GD) in a specific event year was then used to assess spatial patterns of the 40 events reconstructed on the cone for the period A.D. 1867–2005. Based on the spatial distribution of trees disturbed during particular events, five different patterns of spatial activity were distinguished. The five patterns are described below and illustrated with one characteristic example each:

Pattern A: Debris flows affecting the western part of the cone

Events affecting the western part of the cone are mainly characterized by activity in channel 3 with debris-flow material leaving the currently active channel directly at the apex of the cone. On its way down the cone, breakouts of surges from channel 3 can occasionally be observed at about 1470 m a.s.l. with a subsequent activation of channel 5. The spatial distribution of trees affected during particular events also indicates that debris flows even continued from channel 5 to the lowermost part of the cone using channels 6 and 7. Figure D4.6a illustrates the spatial behavior of debris-flow activity on the cone during an event in 1907. In this example no trees were influenced in the lowermost part of channel 3.

Events affecting the western part of the cone (pattern A) were most frequently reconstructed on the cone with a total of 18 events. Two of them (i.e. 1881, 1937) apparently left channel 3 near the apex of the cone and five others (i.e. 1869, 1891, 1921, 1925, and 1976) passed through channel 5 but not through channel 1. There is also evidence from the tree-ring records and geomorphic mapping that the remaining eleven events (i.e. 1873, 1878, 1883, 1899, 1907, 1910, 1914, 1928, 1947, 1970 and 1978) did apparently not use channels 1 and 5. From the data, we assume that past debris flows preferably followed channels 1 and 5 over the entire period of reconstructed debris-flow activity, with events dated for the first time in 1869 and in 1978 for the last time.

Pattern B: Debris flows affecting the central part of the cone

Debris flows affecting the central part of the cone are mainly characterized by activity in channels 1 and 2. Here, debris-flow material left the currently used channel at the apex of the cone as well. The spatial distribution of trees affected during particular events also indicates that debris flows even continued from channel 2 to the lowermost part of the cone. In contrast, the early events in the central part of the cone could only be reconstructed in the uppermost segments of channels 1 and 2. Figure D4.6b illustrates the spatial behavior of debris-flow activity on the cone during an event in 1919 with

Fig. D4.6 *Spatial patterns of past debris-flow events: (a) Debris flows affecting the western part of the cone and channel 3 as exemplified with an event in 1907 (pattern A). In some cases, surges even reached the lowermost parts of the cone following channels 5, 6 and 7. (b) Debris flows restricted to the central part of cone occurred e.g., in 1919 using channels 1 and 2 (pattern B).*

GD also identified in the lowermost part of the cone. In total, pattern B could be reconstructed for four events (1867, 1919, 1923 and 1927).

Pattern C: Debris flows affecting the eastern part of the cone

Debris flows affecting the eastern part of the cone are mainly characterized by activity in the currently used channel and breakouts of surges at different locations. Most commonly, material left the channel at about 1470 m a.s.l. and affected trees east of the channel. In addition, trees below the debris-retention basin were influenced by debris-flow activity of this pattern. Spatial distribution of trees affected during certain events also indicates that debris flows left the currently active channel between 1450 and 1500 m a.s.l. towards the west, causing growth disturbances to trees near channels 8 and 9. Figure D4.6c illustrates the spatial extent of debris-flow activity during an event in 1980. In this example, no trees were influenced west of the currently active channel. Pattern C could be reconstructed for eight events, with three events only affecting trees east of the channel (i.e. 1980, 1985 and 1996) and five events affecting trees on both sides (i.e. 1945, 1950, 1957, 1965 and 1994). While no events could be reconstructed for the eastern part of the cone before 1945, all events after 1982 apparently caused GD to trees growing in this part of the cone.

Pattern D: Debris flows affecting the eastern and the western part of the cone

Debris flows affecting the eastern and western parts of the cone are mainly characterized by activity in channel 3 and in the currently active channel. In the western part, breakouts from channel 3 apparently occurred at about 1470 m a.s.l. following channel 5 and sometimes even continuing to the lowermost part of the cone using channels 6 and 7. In addition, material leaving the currently used channel at the apex of the cone affected channels 1 and 2. The spatial distribution of trees disturbed during particular events also indicates that debris flows continued to the lowermost part of channels 1 and 2 during some events. In the eastern part of the cone, the currently active channel has seen breakouts to the east at about 1470 m a.s.l. and below the debris-retention basin. Trees standing west of the currently active channel were also injured during some events as a result of breakouts between 1450 and 1500 m a.s.l. Figure D4.6d illustrates the spatial extent of debris-flow activity on the cone during an event in 1954. In this example, affected trees indicate activity in channels 3 and 5 down to the lowermost part of the cone. Surges also left the currently active channel at about 1480 m a.s.l., thus disturbing trees in the eastern part of the cone. In

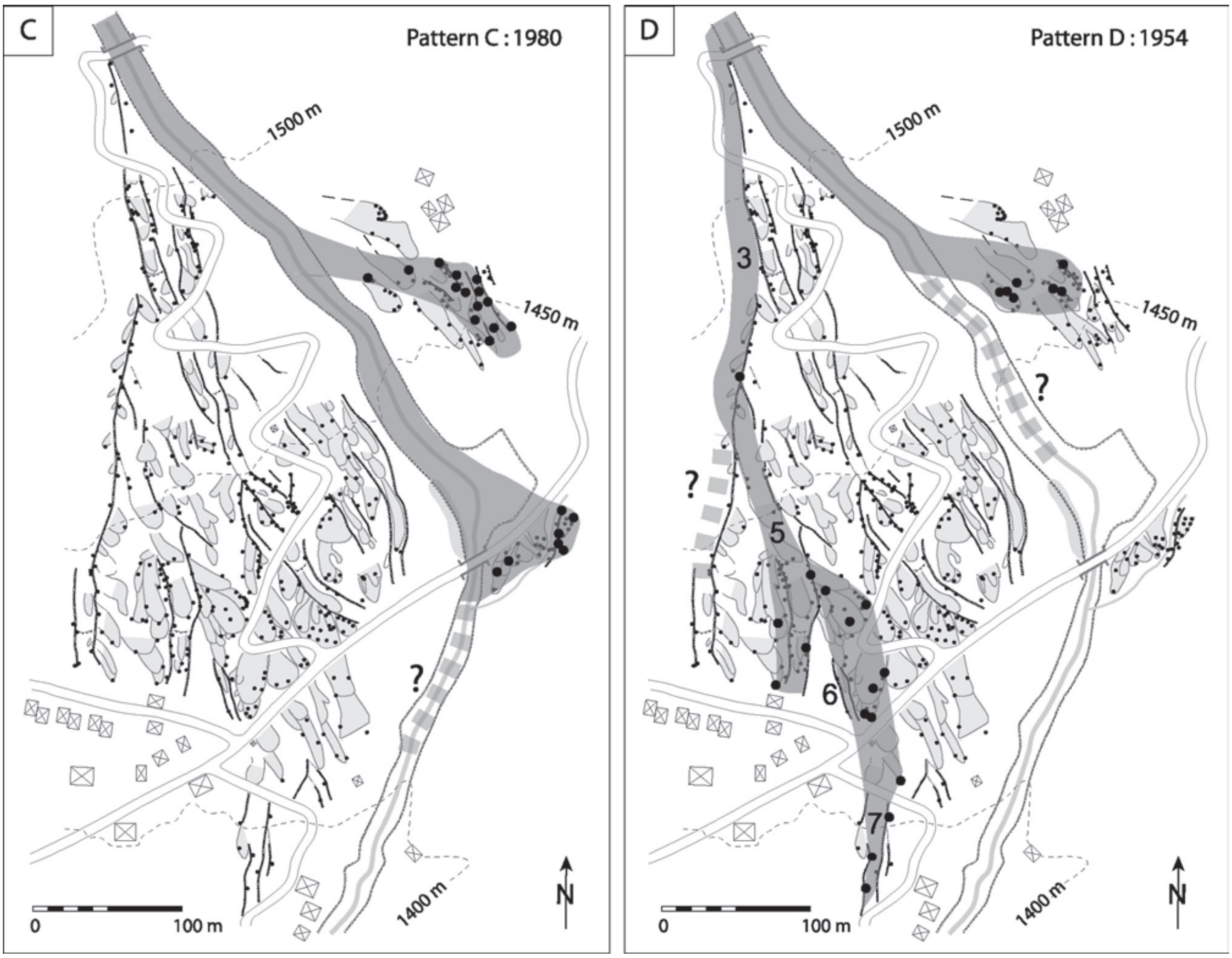

Fig. D4.6 (continued) (c) Debris flows only influencing the eastern part of the cone illustrated with the event of 1980 (pattern C). (d) In pattern D, surges used different channels at the apex of the cone and, thus, affected both the western (channel 3) and the eastern part of the cone. The debris flow of 1954 is a typical event showing this behavior.

total, five events (1952, 1954, 1966, 1975 and 1982) could be assessed for pattern D.

Pattern E: Debris flows affecting the entire cone

During debris-flow events of pattern E, disturbed trees can be identified in (almost) all parts of the cone and signs are not limited to individual channels. Figure D4.6e illustrates the spatial behavior of debris-flow activity on the cone during an event in 1962. In this example, no trees were influenced in the lowermost part of the cone. Pattern E could be reconstructed for five events (1935, 1941, 1943, 1959 and 1962).

Fig. D4.6 (continued) (e) During some events, trees located over large areas of the cone showed growth disturbances caused by debris-flow activity (pattern E). As can be seen from the distribution of trees disturbed by the 1962 event, almost the entire cone was affected by the surges.

5. Discussion

In this study, a coupling of detailed geomorphic mapping and dendrogeomorphological analysis has been used to assess the frequency and spatial extent of debris-flow events on the Bruchji torrent (Blatten b. Naters, Valais, Swiss Alps) for the last 140 years. The analysis produced data on 40 events between A.D. 1867 and 2005 and allowed reconstruction of past activity in eleven channels that are currently abandoned. In addition, the large amount of tree-ring data and the results from the geomorphic mapping enabled distinction of five different patterns of spatial activity of former debris-flow events.

The dendrogeomorphological reconstruction of debris-flow events at the Bruchji torrent was, however, mainly limited by the relatively young age of the trees. Even though we identified some trees with more than 200 tree rings in the western part of the cone, the average age of the trees sampled was only 91 years. In the eastern part of the cone, most trees were even younger and germinated only about 60 years ago. Furthermore, small debris-flow surges may have remained in the incised channels and did not necessarily cause growth disturbances (GD) to any of the investigated trees. For example, the events of 1987, 1990 and 1995, known from archives could not be identified in the tree-ring series. Since these events left the currently active channel only in non-forested sectors, it was not possible to reconstruct them with means of tree-ring analysis. As a result, the number of reconstructed events for the Bruchji cone has to be seen as a minimum frequency of past debris-flow activity in this torrent. However, the reliability of the reconstruction can be considered high because of the large number of trees showing GD for individual event years. Similarly the spatial extent of the events on the debris-flow cone appears to be very reliable for at least the 20th century. In contrast, we were not always able to delimit the extent of events in the lowermost parts of the cone as human activity considerably reshaped the cone surface here. On a regional level, the frequency of debris-flow events at Bruchji torrent is comparable to that reconstructed for the Ritigraben torrent (Stoffel & Beniston, 2006). Other geomorphic events, such as snow avalanches or rockfall activity have never been witnessed at the study site and have therefore no influence on tree growth.

The age structure of the stand has been approximated by counting the number of tree rings present on the increment cores sampled at breast height. However, we are aware that tree age at breast height does neither provide germination nor inception dates (Gutsell & Johnson, 2002). In addition, the pith as well as the innermost rings of some trees were rotten, making it impossible to assess the real age of the tree. Nonetheless, we are convinced that the approach furnishes valuable data on the age structure of the stand with reasonable precision.

In total, 960 GD were assessed in the 802 *Larix decidua* Mill. and *Picea abies* (L.) Karst. samples. Tangential rows of traumatic resin ducts (TRD) represent 36% of all GD, while injuries only account for 4% of the reconstructed GD. This scarcity of injuries as compared to other signs of past activity may be explained through the sampling strategy. We used increment cores for the sampling instead of cross-sections since the forest stand at the study site has a protective function against debris flows. The thick bark of L. decidua and P. abies trees efficiently blurs evidence of past events, as it grows abundantly and sporadically scales off its outermost layers (peeling; Stoffel & Perret, 2006). Therefore, injuries are easily overgrown and no longer visible on the stem surface. Nonetheless, we are confident that these overgrown signs of past events were accurately dated via the presence of TRD formed next to the injuries.

The spatio-temporal representation of tree-ring data on the geomorphic map allowed assessment of activity in eleven abandoned channels as well as on the extent of past events on the cone. While reconstructions suggest very frequent debris-flow activity in channels 1, 2, 3 and 5, events did apparently not or only exceptionally affect other channels during the last 140 years. We believe that the scarcity of events in the channels on the eastern part of the cone is rather the result of the limited age of trees than of an absence of events in this sector in the late 19th or early 20th century. As suggested by the age distribution of trees (see Fig. D4.2) and confirmed by an aerial photograph dated to 1936 (Fig. D5.1), the eastern part of the cone served as grazing land during the first decades of the 20th century. This explains why the forest could only develop over the last 60 years. It also seems that the demolition of two buildings by a debris-flow

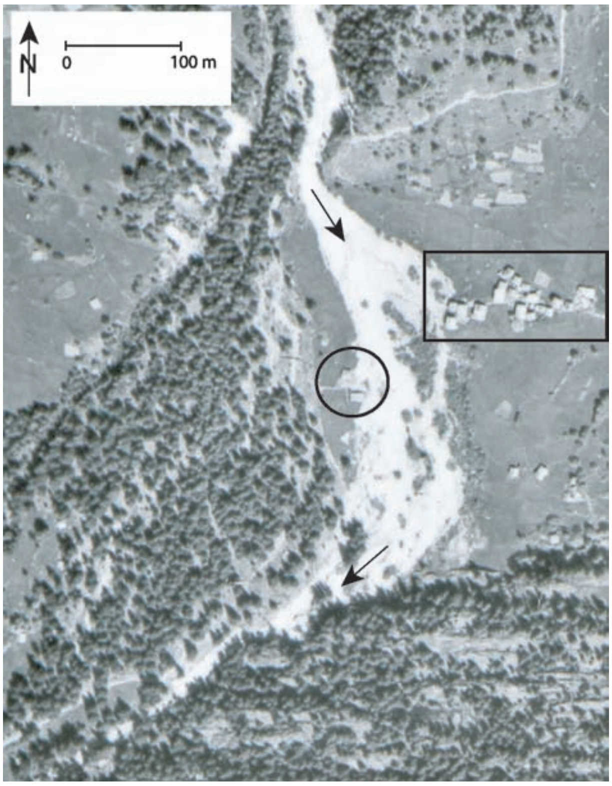

Fig. D5.1 *Aerial photograph of the Bruchji cone taken in May 1936. Two buildings (circle) are located within the deposits and appear to have been severely affected by the debris-flow event reconstructed for 1935. Towards the northeast of the damaged building, houses of a small hamlet (rectangle) are found very close to the deposition zone of the 1935 event as well. Arrows indicate the flow direction of water in the torrent (aerial photograph reproduced with courtesy of swisstopo (BA068080)).*

event in 1935 and the covering of the grazing lands with considerable amounts of material favored the abandonment of the cultivated lands and, hence, the establishment of the present forest stand.

Based on our data, we were also able to distinguish five spatial patterns for past debris-flow events. As a result of the age of trees sampled, events occurring before 1935 were limited to the western (pattern A) or the central part (pattern B) of the cone and GD cannot be identified in trees located elsewhere at the study site. Nonetheless, we believe that events affecting the eastern part of the cone must have been very unusual before 1935. Even though tree-ring data cannot be used here to underpin this assumption, we are confident that neither the small hamlet nor the two buildings located within the deposits of the 1935 event would have been constructed or the grazing land used (see Fig. D5.1) had there been frequent debris-flow activity in this part of the cone. Another aerial photograph taken in August 1940 confirms our assumption, as one of the houses had been removed. In contrast, events reconstructed for the period 1935–2005 did apparently more often affect the eastern (pattern C) or both the eastern and the western parts (pattern D) of the cone.

In the late 1970s, different protection measures have been undertaken so as to prevent debris-flow material from reaching the western part of the cone as well as the village of Blatten b. Naters. Therefore, the banks of the active debris-flow channel have been reinforced at the apex of the cone so as to prevent debris flows from leaving the currently active channel. In addition, a small retention basin has been constructed. Even though these protective measures aimed at eliminating debris-flow activity in the western part of the cone, we can see from reconstructed GD in the trees that at least the event of 1982 still reached channels 3 and 5.

Based on our data, the areas affected during particular events, the scarcity of lobate deposits, the smooth cone surface and based on personal observation made during a series of debris-flow surges on July 4, 2001, we believe that a majority of the reconstructed events must have had a rather high water content and should be considered hyperconcentrated rather than "classical" debris flows. This is especially true for the events covering the entire cone (pattern E; e.g., 1962, 1941) but also for some of the other events that affected a large number of trees over a large area of the cone (e.g. 1982, 1966, 1952). The distribution of trees affected during particular events also corroborate our assumption on the repeated presence of hyperconcentrated flows on the cone. Due to the high water content and the limited amount of abrasive material and boulders, trees standing in the direction of the flow did not always show GD during a particular event year, even though we are confident that they must have been located within the area affected by the event. As a result, we assume that only those trees directly hit by rocks and boulders or suffering from abrasion by the finer fractions transported during the event were sufficiently affected to show GD, whereas those trees "only" influenced by the action of water or mud did not react upon the disturbance.

Finally, the geomorphic map shows that a large number of channels but only a limited number of lobes can be observed on the cone. Therefore, we suppose that only comparably little material was deposited on the cone during past events. This is in contrast to findings of Haeberli et al. (1991) suggesting that up to 80-90% of debris-flow material is generally deposited on cones. Due to the high amount of water present in many of the past events, it is also conceivable that material has been left on the cone but reworked or removed by subsequent surges. As a result, it was not possible within this study to date deposits on the cone with tree-ring analysis. In a similar way, the levees identified on the cone were normally not very well formed, as can be seen e.g., in the upper part of channel 5. For different events reconstructed in this channel, trees located outside the channel seem to have been affected by the event as well and show distinct growth reaction.

6. Conclusion

The combination of detailed geomorphic mapping and tree-ring analysis allowed reconstruction of eleven formerly active channels and the spatial occurrence of past debris flows. Based on the data, five different patterns of spatio-temporal activity of past debris flows could be identified on the forested cone of the Bruchji torrent. While older events normally affected trees in the western part of the cone, the flow regime apparently changed in the mid-1930s towards the eastern part of the cone. As a result of different protection measures realized in the late 1970s, channels in the western part of the cone are no longer active today. In addition, tree-ring based reconstructions also allowed identification of several events that affected the entire cone and caused growth disturbances to a large number of trees. Due to the limited number of deposits left on the cone, the spatial patterns of past events and the large number of trees affected during individual event, we believe that many of the reconstructed events would have been hyperconcentrated rather than debris flows.

The methods developed in this study can be readily transferred to any other alpine catchments and should therefore be used in similar environments for a better understanding of past and potential future debris-flow processes.

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CHAPTER E

COUPLING OF EVENT RECONSTRUCTION WITH MINIMUM AGE DATING

Coupling of event reconstruction with minimum age dating

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"Dynamics in debris-flow activity on a forested cone - a case study using different dendroecological approaches"

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Abstract

Dendrogeomorphological analyses of trees affected by debris flows have regularly been used to date past events. However, this method has always been limited to forested cones where trees registered the impact of previous events. The minimum age dating of trees growing in the debris deposits can, in contrast, provide information on the latest possible moment of past activity. In this paper, we report on results obtained from a combination of these two approaches on a forested cone in the Valais Alps (Switzerland). A detailed geomorphic map in a scale of 1:1000 served as a basis for the sampling strategy. Disturbed *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees growing in the deposits allowed reconstruction of 49 events between AD 1782 and 2005 as well as the determination of the spatial extent of events. In the debris-flow channels where survivor trees are missing, we selected the oldest post-event trees and assessed their age by counting their growth rings. Missing rings due to lack of center as well as to sampling height were added so as to determine real tree age. The combination of the dendrogeomorphological event reconstruction with the assessment of germination dates of successor trees allowed realistic approximation of the minimum time elapsed since the last debris-flow activity in 23 of the 29 channels present on the current-day cone surface. In general, channels in the northern part of the cone and those close to the currently active channel generally show signs of (sub-) recent activity with one last overbank sedimentation event in the 1980s, whereas signs of debris-flow activity are absent from the channels in the outermost part since the late 19th century. As a consequence of the deeply incised channel and the stabilization measures undertaken along the banks, signs of debris flows are missing in the tree-ring record for the past two decades.

Keywords

debris flow, tree-ring analysis, dendrogeomorphology, dendrochronology, landform surface dating, Swiss Alps

1. Introduction

Geomorphic processes are widespread phenomena in mountain regions, where their repeated occurrence may result in characteristic landforms such as debris-flow cones. In inhabited areas, these mass movements may cause damage to transportation corridors and buildings or even lead to the loss of lives. As a consequence, the understanding of the debris-flow process as well as the behavior of events in space and time is crucial for the mitigation of hazards and risks (Carrara *et al.* 1999; Cardinali *et al.* 2002; Pasuto & Soldati, 2004). For many torrents in Alpine regions, however, systematic acquisition of data on past debris flows only started after a series of catastrophic events in 1987 and 1993 (Haeberli *et al.* 1991; Rickenmann & Zimmermann, 1993; Zimmermann *et al.* 1997); there is still a considerable lack of knowledge on earlier events for many regions. Thus the reconstruction of past activity is essential for the understanding of current debris-flow dynamics in mountain torrents and possible future developments due to potential climatic change (Goudie, 2006).

The most accurate method for dating events over several centuries in the past is dendrogeomorphology. This technique is based on the fact that trees growing in temperate climates form annual growth rings and that they record external disturbances such as climatic fluctuations or geomorphic events in their tree-ring series (Schweingruber, 1996, 2001). Given that a tree is directly impacted by a geomorphic event, tree-ring dating can pinpoint the year or even the season in which the disturbance occurred. Research on the reactions of trees to geomorphic events has commonly been based on Alestalo's (1971) pioneering results, as he was the first to provide detailed results on the influence of slope movements on tree-ring formation. More recently, dendrogeomorphological techniques have been widely used to reconstruct the frequency, magnitude or spatial patterns of rockfall activity (Stoffel *et al.* 2005c; Perret *et al.*, 2006) or for the calibration of rockfall models (Stoffel *et al.*, 2006b). In a similar way, past snow avalanches (Butler *et al.*, 1992; Rayback, 1998; Hebertson & Jenkins, 2003) or landslides (Fantucci & Sorriso-Valvo, 1999; Stefanini, 2004) have been assessed with tree rings.

Previous debris-flow studies using dendrogeomorphological methods primarily focused on the dating of individual events or deposits (Stefanini & Ribolini, 2003), on the reconstruction of magnitudes and/or frequencies (Strunk, 1997; Wilkerson & Schmid, 2003; May & Gresswell, 2004; Bollschweiler & Stoffel, 2007) or on a comparison of reconstructed debris-flow data with flooding events in neighboring rivers (Stoffel et al., 2005b). Further, the spatial patterns of past debris flows on forested cones have been studied by Bollschweiler *et al.* (2007). Based on tree-ring evidence, Stoffel & Beniston (2006) were able to identify changes in the seasonality of debris-flow activity since the Little Ice Age.

Particularly large or devastating debris flows may eliminate entire forest stands, rendering the reconstruction of previous events impossible with dendrogeomorphological methods. Since cleared surfaces are normally recolonized by seedlings in the years following the devastating event, germination ages of trees growing on landform surfaces have also been used in a number of studies to estimate the time of creation of new landforms or the time of surface-clearing disturbances to existing landforms (Sigafoos & Hendricks, 1969; Shroder, 1980; McCarthy & Luckman, 1993; Winter *et al.*, 2002). Similarly, this method can be used to date surfaces cleared by debris-flow activity.

The aim of this study was to combine dendrogeomorphological analyses with an assessment of germination dates of successor trees in order to understand the dynamics of past debris-flow events on a forested cone in the Valais Alps, Switzerland. In a first step, all forms related to debris-flow activity such as lobes, levees and abandoned debris-flow channels were mapped in a scale of 1:1000. Disturbed trees growing in these deposits were analyzed to reconstruct the debris-flow frequency and the spatial extent of previous events. For the sectors of the cone where no disturbed trees are present, undisturbed trees growing in previously active debris-flow channels were sampled and their age assessed so as to approximate the minimum time elapsed since the last event in these channels. The coupling of data on events in channels with the minimum age dating allowed reconstruction of the spatial dynamics of debris-flow activity on the cone.

2. Study site

The study of past debris-flow dynamics was conducted on the cone of the Grosse Grabe torrent, located on the west-facing slope of the Matter Valley (Valais, Swiss Alps; 46°10’ N, 7°47’ E; Fig. E2.1). The catchment area (Fig. E2.2a) of the torrent totals 1.5 km^2 and extends from the Breithorn summit (3,178 m a.s.l.) to the Mattervispa River (1,200 m a.s.l.). The considerable gradient between the source and the cone results in steep torrent topography (on average 25°; Fig. E2.2b). The upper part of the catchment is dominated

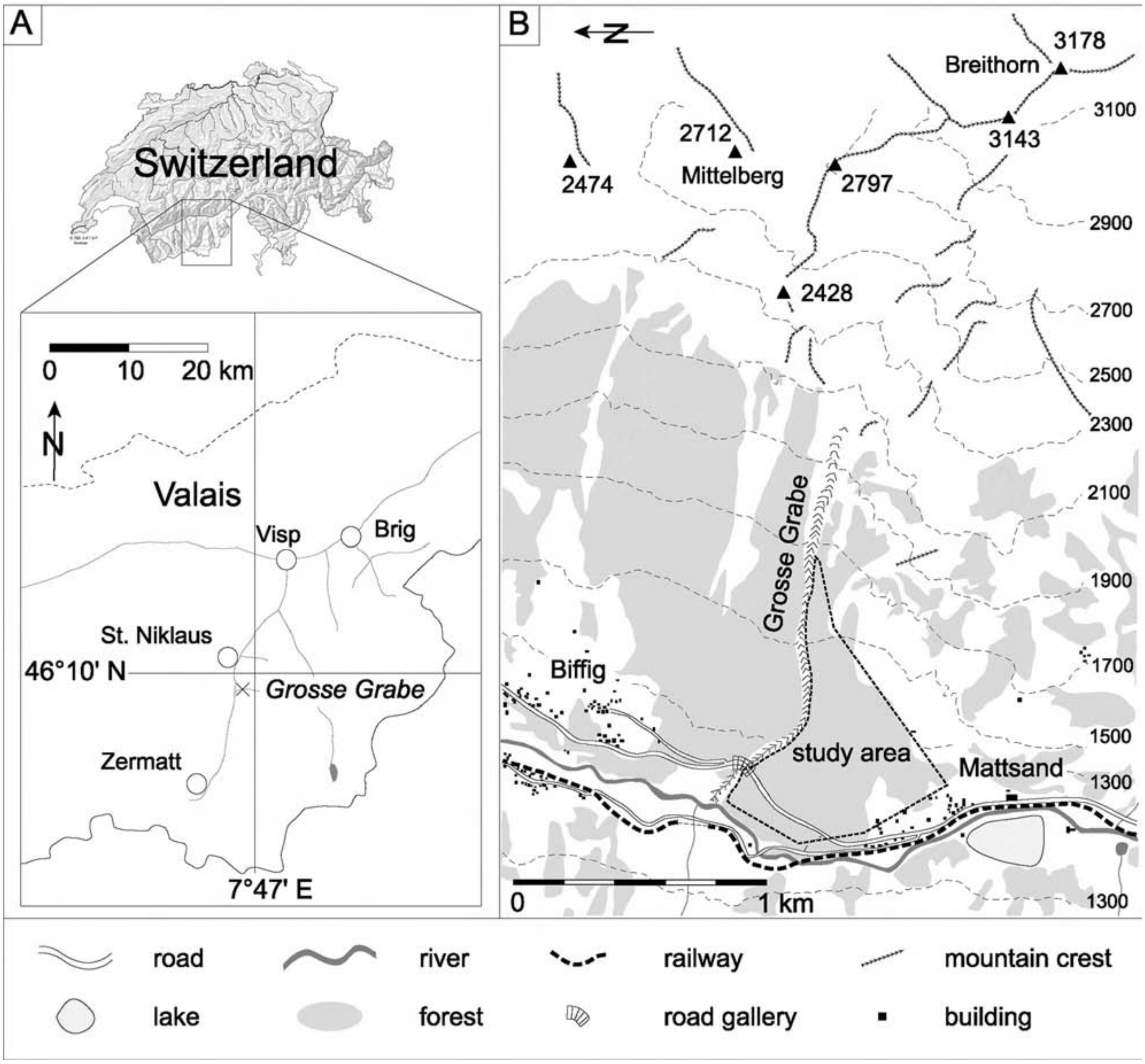

Fig. E2.1 (a) The study site is located in the Matter Valley close to St. Niklaus. (b) Sketch map of the study site with the Grosse Grabe torrent and the large debris-flow cone (= study area).

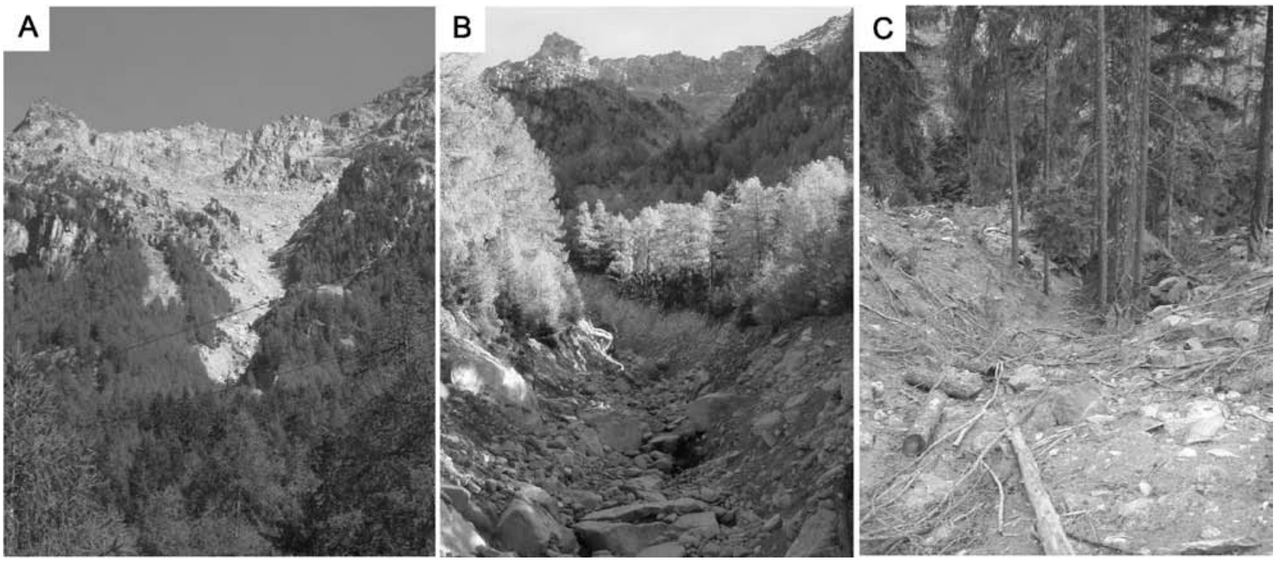

Fig. E2.2 *(a) View of the upper catchment area. (b) The currently active debris-flow channel passes a forest of Larix decidua Mill. und Picea abies (L.) Karst. trees. (c) On the debris-flow cone, a large number of previously active channels can be identified.*

by gneissic rocks belonging to the crystalline Mischabel unit, while in the lower part, debris originating from various gravitational processes (i.e. rockslides, rockfall) cover the bedrock (Labhart, 2004). A considerable part of the upper catchment is located above tree line and characterized by steep scree slopes without any vegetation or dominated by scarce patches of alpine grass. The debris-flow cone extends from 1,200 m a.s.l. to 1,600 m a.s.l. and is vegetated by a forest primarily composed of European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.; Fig. E2.2c). On the cone, slope gradients average 14° and deposits of past debris flows can exclusively be found south of the currently active channel. In the lowermost part of the cone, a gallery was built in 1970 to protect the main road connecting Zermatt to Visp from debris flows. Anthropogenic influence on the cone is most pronounced in its southernmost part, where deposits have been removed for the construction of houses of the hamlet of Mattsand. The area below the main road is not covered in this study, since deposits in this part of the cone have been considerably reshaped and logging activity has become important in the past few decades. Similarly, we did not analyze trees growing on the uppermost part of the cone, as trees may have been influenced by rockfall or snow avalanche activity as well. Archival data on past events only cover the last 13 years, with debris-flow activity noted for 1993, 1994, 1999 and 2000. Data also suggest that debris flows at Grosse Grabe were most frequently triggered during prolonged rainfall events (Seiler & Zimmermann, 1999).

3. Methods

3.1 Geomorphic mapping

In a first analytical step, all forms and deposits related to previous debris-flow activity (i.e. lobes, levees or abandoned channels) were mapped in a scale of 1:1000. Due to the presence of the forest on the cone as well as the shielding effect of the high summits except from the north, GPS devices could not be used. Therefore, the map was based on detailed measurements using compass, tape measure and inclinometer.

3.2 Sampling strategy

Larix decidua and *Picea abies* trees that had obviously been disturbed by previous debris-flow events were cored using a Suunto increment borer (max. length 40 cm, Ø 6 mm). Within this study, we preferably selected trees that showed scars, candelabra growth, exposed root systems as well as buried or tilted stem bases resulting from the impact of past events. Two cores per tree were normally extracted, one in the flow direction, the other on the opposite side of the trunk. Sampling height was chosen according to the morphology of the stem. Tilted or injured trees were sampled at the height of the disturbance, whereas decapitated trees or trees with a buried stem base were cored as close to the ground as possible so as to gather as much information as possible. In total, 71 strongly affected Larix decidua and Picea abies trees were sampled with 150 cores for this study.

In the channels located in the southern sectors of the cone, disturbed trees were very scarce and sometimes even totally absent. Therefore, we sampled 72 undisturbed trees for minimum age dating in these sectors. One core per tree was extracted as close to the ground as possible to minimize the loss of increment rings due to the sampling height. The position of all trees cored – disturbed and minimum age dating – was accurately marked on the geomorphic map.

In addition to the disturbed trees and the trees sampled for minimum age dating, we cored 17 *Larix decidua* (34 increment cores) and 18 *Picea abies* (36 increment cores) trees outside the debris-flow cone that had not been affected by past geomorphic activity. These samples were then used to build a reference chronology representing normal growth conditions at the study site, i.e. those influenced by climate or insect outbreaks (Douglass, 1929; Cook & Kairiukstis, 1990; Vaganov *et al.*, 2006).

3.3 Dating of debris-flow events and reconstruction of their spatial extent

The samples from the disturbed trees were analyzed using standard dendrochronological methods (see Bräker, 2002). Individual steps included surface preparation, counting of tree rings, measuring of tree-ring widths using a LINTAB measuring table and TSAP 3.0 software (Time Series Analysis and Presentation; Rinntech, 2007). Growth curves of trees were then crossdated with the reference chronology. Afterwards, tree-ring series were analyzed visually so as to identify growth disturbances caused by past debris-flow events. The presence of tangential rows of traumatic resin ducts as well as callus tissue bordering injuries (Stoffel et al., 2005a; Perret et al., 2006) were noted on skeleton plots (Schweingruber et al., 1990). The study of the ring-width series as well as the visual inspection of samples further allowed determination of abrupt growth decrease after stem burial or root exposure (Schweingruber, 1996, 2001), the onset of compression wood after stem tilting (Giardino et al., 1984; Braam et al., 1987; Fantucci & Sorriso-Valvo, 1999) or abrupt growth increase in survivor trees after the elimination of neighbors (Schweingruber, 1996). The identification of events was based on the number of samples simultaneously showing a growth disturbance as well as on the distribution of affected trees on the cone. Thereafter, we grouped GD occurring simultaneously in different trees and defined criteria for the determination of event years: For reasons of limited sample depth (i.e. limited age of trees), strong and abrupt GD were considered an event year for the period 1780–1910 as soon as signs were present in at least two trees. However, if only one individual tree showed GD in a year, the event was regarded as probable and illustrated with a dashed line in the debris-flow frequency. In contrast, (i) weak GD identified in several cores or (ii) abrupt GD identified in one individual tree were disregarded for events occurring after AD 1910, and only the years with at least two abrupt GD identified in the samples were kept for further analysis. In addition, we identified the position of all trees with growth reactions during the same event on the geomorphic map. This representation of trees affected during individual events allowed reconstruction of the spatial extent of events on the cone as well as an assessment of the activity in currently abandoned channels.

3.4 Minimum age dating

Tree germination rates are best determined by counting the annual growth rings in a cross section taken from the root crown (i.e. germination) level (McCarthy *et al.*, 1991). However, destructive sampling is not always possible in protection forests. On the other hand, branches, obstacles and rot may require sampling positions higher up on the stem. In these cases, an age correction factor needs to be added to compensate for the time a tree takes to grow to sampling height (McCarthy *et al.*, 1991). A basic assumption of several height-age models is that apical growth is equally proportioned within a sampled section (e.g.

Carmean, 1972; Lenhart, 1972; Schweingruber, 1996). Accordingly, averaged data should provide an accurate estimate of apical growth (McCarthy *et al.*, 1991). Therefore, we divided tree height by the number of tree rings to get an average rate for the yearly apical increment for each tree. The sampling height was then divided by the yearly increment so as to obtain the number of missing rings. In addition, the number of missing rings was estimated whenever the pith was not present on the core. This correction was undertaken using a transparent sheet with concentric rings (Bosch & Gutiérrez, 1999). In contrast, we did not perform an age correction for the colonization time gap (Pierson, 2007) in this study, i.e. an estimate of time elapsed between the last debris-flow event in a channel and the germination of pioneer trees. As the tallest trees growing in a channel are not necessarily the oldest ones, we sampled – as far as possible – several trees per channel so as to minimize the risk of disregarding the oldest post-event tree.

3.5 Determination of last moment of activity

For the determination of the last moment of debris-flow activity in the currently abandoned channels, we dated the last event by means of dendrogeomorphological methods and the sampling of disturbed trees. In a second step, the germination date of the oldest tree was determined for channels where none of the trees of the present-day forest stand showed disturbances caused by past debris-flow activity. The coupling of data on debris-flow events with data on minimum ages of undisturbed trees growing in previously active channels allowed determination of the minimum time elapsed since the last event. This procedure allowed assessment of the spatio-temporal dynamics of past debris flows on the entire cone.

4. Results

4.1 Geomorphic mapping

On the debris-flow cone of the Grosse Grabe torrent, an area of 30 ha was mapped in a scale of 1:1000 and 29 abandoned channels were identified on its present-day surface. In addition, 61 segments of levees were mapped. These levees were comparably short and/or isolated and could therefore not be associated with a channel. Lobate deposits are relatively scarce with only 14 forms identified on the cone. Figure E4.1 shows all forms mapped on the cone as well as the position of all trees sampled within this study. It can also be seen from Figure E4.1 that the channels and their lateral levees are best developed in the upper part of the cone. In contrast, channels are less deeply incised and the debris-flow forms much smoother in the lower segments of the cone between the power line and the main road. It is also in this sector that most of the lobate deposits can be found. Below the main road, no deposits were mapped because of the strong anthropogenic influence.

4.2 Age structure of the stand

The average age of all trees sampled on the cone is 140 years (STDEV: 66 years). The oldest tree cored shows 356 tree rings at sampling height (1649 AD), while the youngest tree reached breast height only in AD 1963. As can be seen from Figure E4.2, the age structure of the trees selected for analysis is quite heterogeneous. The oldest trees can be identified in the central part of the cone but a single old tree is located on the uppermost part of the cone. In addition, trees growing on the uppermost part close to the currently active debris-flow channel show comparably high ages with an average of 165 years. In contrast, young trees are located on the lower part of the cone close to the active channel and in channel 22, where most trees reached sampling height in the early 20th century.

4.3 Growth disturbances and debris-flow frequency

The 71 *Larix decidua* and *Picea abies* trees sampled on the cone allowed identification of 242 growth disturbances (GD; Table E4.1). Injuries or the adjacent callus tissue were only occasionally identified on the increment cores (3%), whereas tangential rows of traumatic resin ducts (TRD) were commonly found in the samples (50%). Abrupt growth changes such as sudden increase or decrease in the yearly ring widths were found in 17% and 11% of the samples, respectively. The onset of reaction wood after tilting was found in 19%.

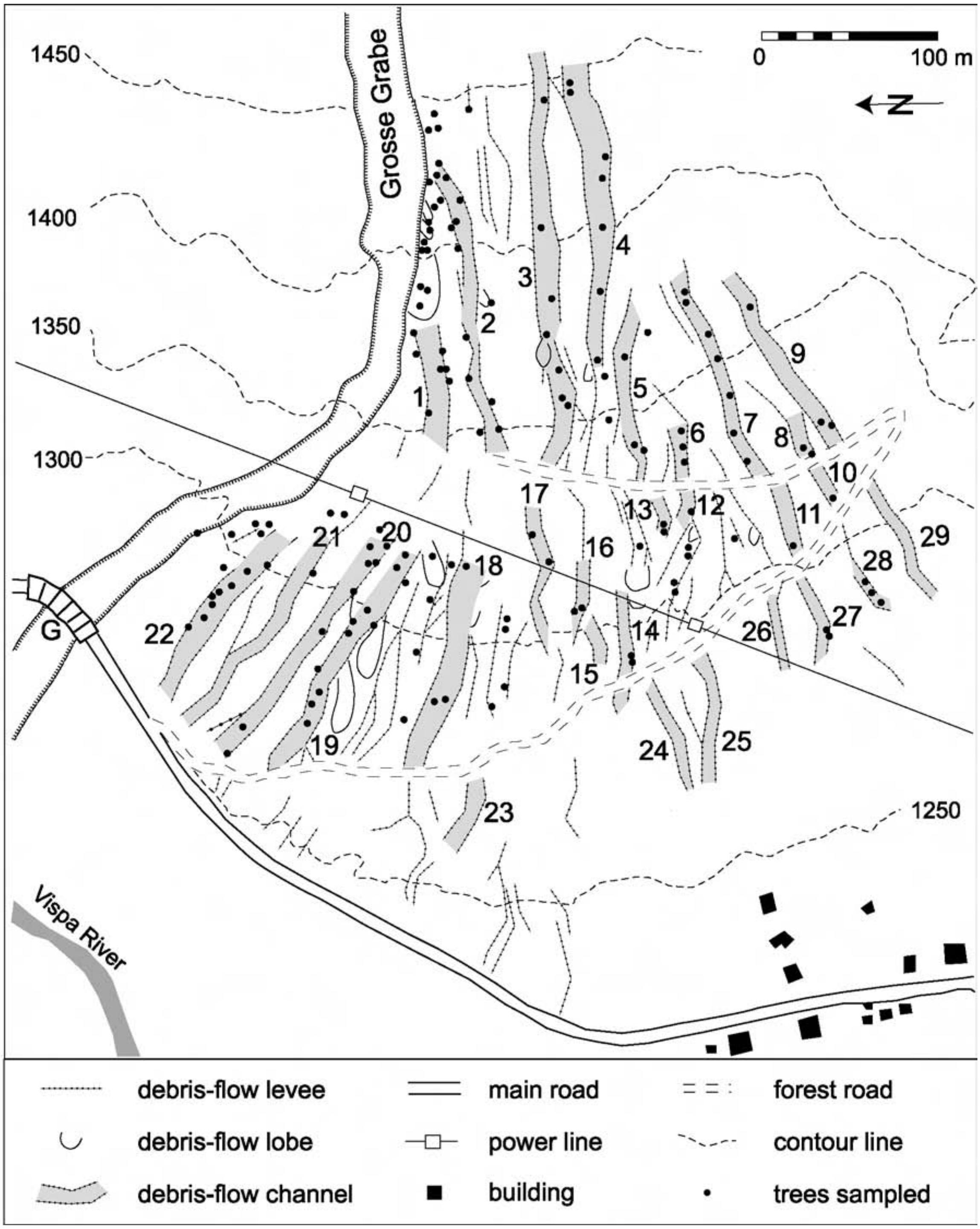

Fig. E4.1 *Detailed geomorphic map (original scale: 1:1000) of all debris-flow forms and deposits identified on the cone. The main road is protected by a road gallery (G). In total, 29 channels, 61 additional segments of levees as well as 14 lobate deposits could be identified.*

In total, the analysis of GD occurring simultaneously in different trees allowed the reconstruction of 49 event years between AD 1782 and 2005. Figure E4.3 gives the reconstructed debris-flow frequency for the Grosse Grabe torrent. As can be seen from the illustration, the reconstruction yielded data for only a limited number of events in the 19th century. In contrast, the tree-ring records suggest several periods with increased activity during the 20th century. Such clustering of events can primarily be identified for the periods 1905–1907 or 1917–1928 as well as

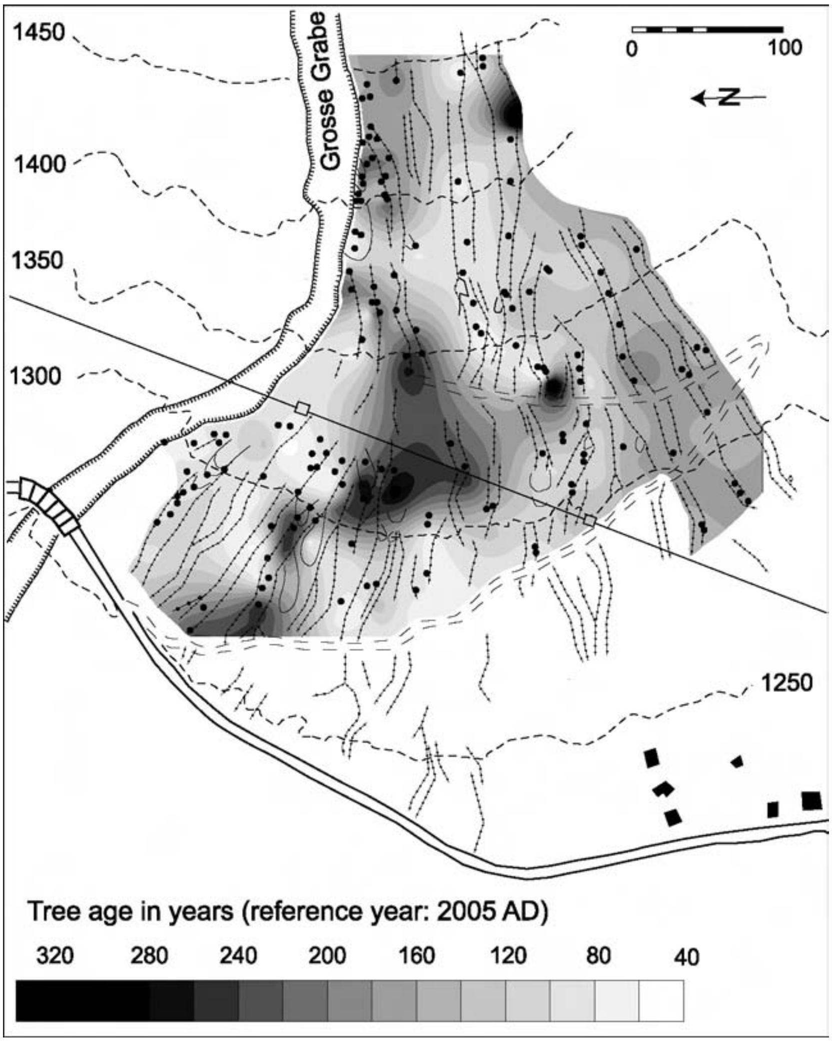

Fig. E4.2 *Age structure of the forest stand on the cone. The oldest trees are located on the central as well as in the uppermost part of the cone. The oldest tree reached sampling height in AD 1649, whereas the youngest tree is only 42 years old. Trees in the lowermost part of the cone close to the torrent are much younger than the average, which is 140 years.*

between 1970 and 1982. In addition, Table E4.2 gives details on the number of trees showing GD as a result to an event year.

4.4 Spatial extent of past events

The spatial extent of past events was assessed by investigating the position of all trees showing GD in a specific year. In general, events could only be reconstructed for the northern part of the cone. In the southern part, there were no disturbed trees, which did not allow the reconstruction of previous events by means of dendrogeomorphological methods. Figure E4.4 illustrates the spatial patterns of four different debris-flow events and the position of all trees with GD during the years in question: In 1917 (Fig. E4.4a), debris-flow surges apparently passed south of the current channel at ~1320 m a.s.l. and caused damage to trees in channel 22 (for channel numbers see Fig. E4.1). In contrast, a debris-flow event in 1918 (Fig. E4.4b) caused damage primarily

	Amount	%
Tangential rows of traumatic resin ducts	121	50
Compression wood	45	19
Growth increase	42	17
Growth decrease	26	11
Injuries	8	3
Total	242	100

Table E4.1 *Growth disturbances (GD) assessed in the 150 samples of strongly affected Larix decidua Mill. and Picea abies (L.) Karst. trees.*

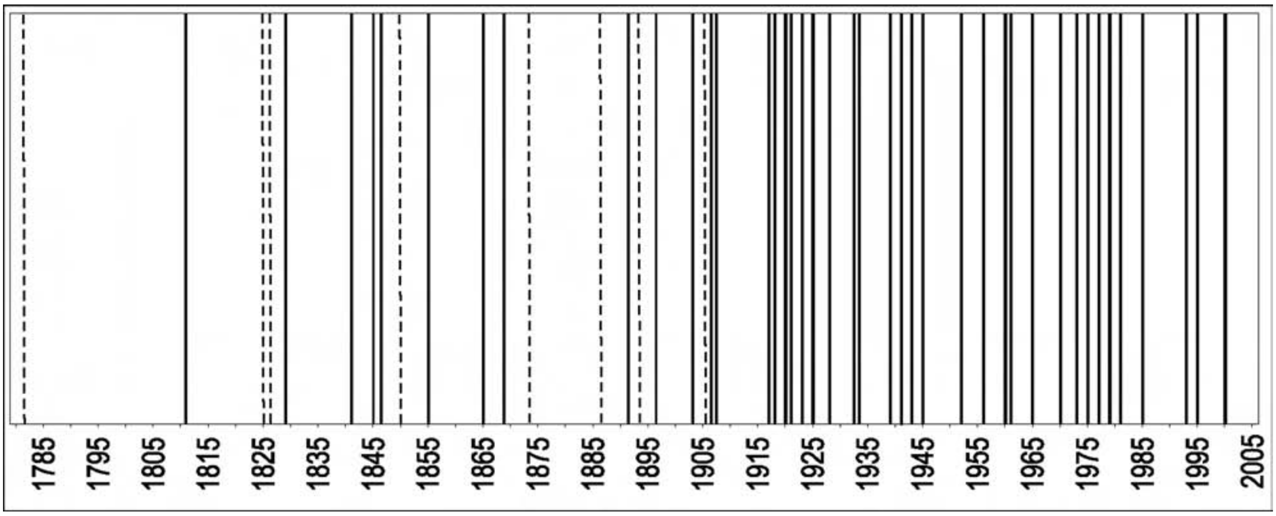

Fig. E4.3 *Minimum debris-flow frequency for the Grosse Grabe torrent. In total, 49 events between AD 1782 and 2005 were reconstructed. Only a limited number of events could be reconstructed for the 19th century. Dashed lines indicate those events that were dated via the presence of GD occurring in one tree only.*

Year A.D.	2000	1995	1993	1985	1981	1979	1977	1975	1973	1970	1965	1961	1960	1956	1952	1945	1943
No. of trees with GD	2	4	2	5	6	5	10	9	6	5	4	3	2	5	5	10	8
Year A.D.	1941	1939	1934	1933	1928	1925	1923	1921	1920	1918	1917	1908	1907	1906	1903	1897	
No. of trees with GD	6	5	8	4	9	5	8	7	6	10	10	4	3	1	2	2	
Year A.D.	1894	1892	1887	1874	1869	1865	1855	1850	1847	1845	1841	1829	1826	1825	1811	1782	
No. of trees with GD	1	3	1	1	2	3	2	1	3	2	2	1	1	2	2	1	

Table E4.2 *Number of trees showing GD after the incidence of a debris flow in particular years.*

to seven trees sampled on the uppermost part of the cone. Debris-flow material seems to have left the current channel at ~1430 m a.s.l., passing through channel 2 on its way further down the cone. In addition, the event even disturbed trees in channel 19 on the lower part of the cone. A series of debris-flow surges dated to 1928 (Fig. E4.4c) must have left the current channel at the cone apex, thus activating channels 2, 4 and 7 located in the southern part of the study area. In addition, some of the material caused GD to trees growing in channels 21 and 22. Figure E4.4d provides the spatial distribution of a limited number of trees that were damaged by debris-flow activity in 1952. Here, debris-flow surges apparently passed through channels 1 and 2 and even reached the lower parts of the cone.

From our data, it also appears that – throughout the period of reconstruction – debris-flow activity was greatest in channels 2 and 22. In channel 2, there is evidence for 28 previous events and at least 16 events caused damage to trees growing in or next to channel 22 (see Table E4.3). In contrast, signs of past activity are normally lower for the other channels, with only one to nine events identified. Overall, debris-flow events could be reconstructed in 13 of the 29 channels. In contrast, trees did not show any signs of past activity in the 16 other channels identified on the cone.

4.5 Approximation of last moment of past activity

Since past debris-flow events and their spatial extent could only be reconstructed on the northern part of the cone, we determined the age of the oldest post-event trees to approximate the minimum time elapsed since the last moment of debris-flow activity on the southern part of the cone. For the unaffected trees considered for the minimum age dating, two steps of age correction were carried out so as to determine the real age as precisely as possible. First, missing rings due to the sampling height had to be added. The yearly

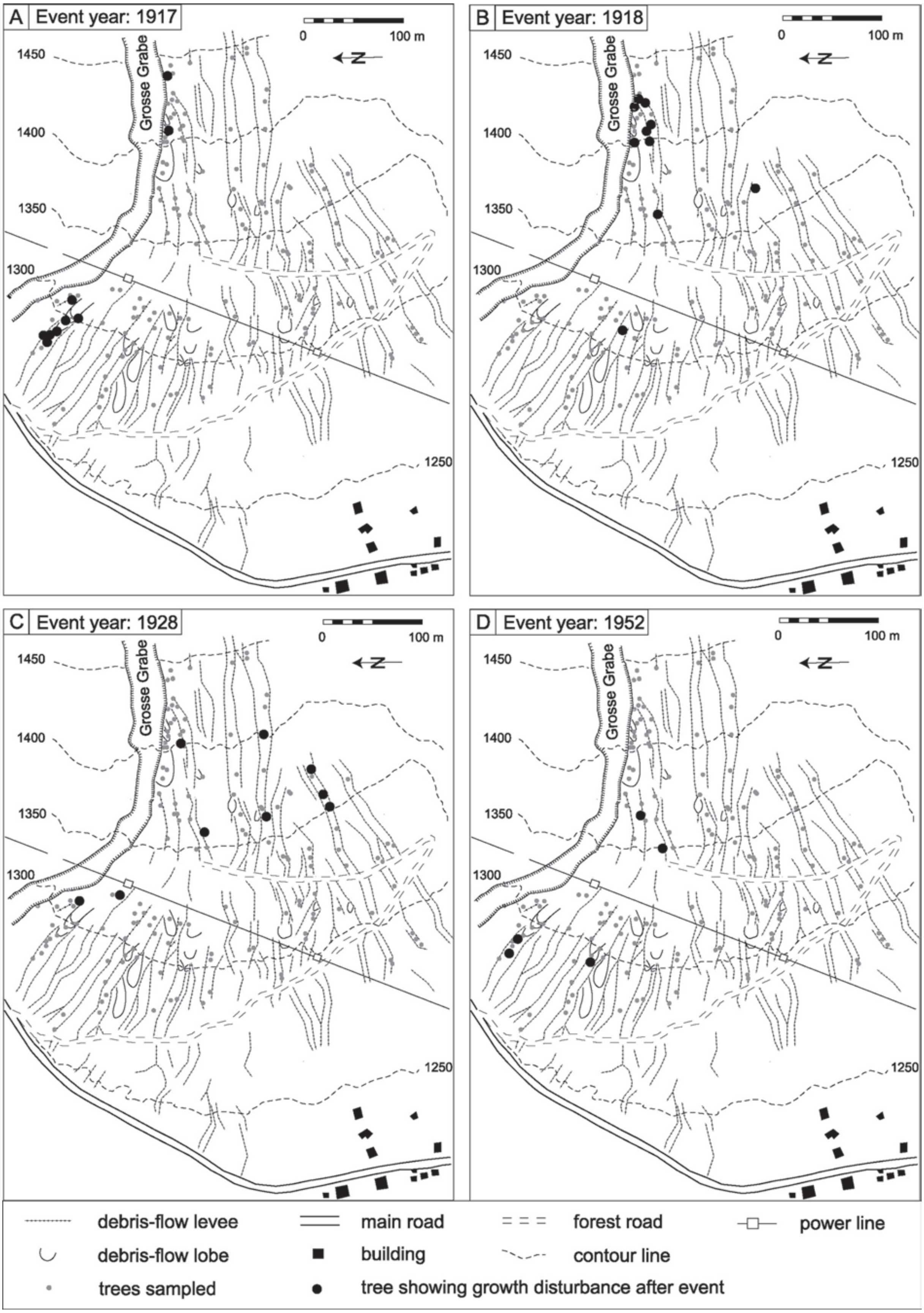

Fig. E4.4. *Spatial distribution of trees showing growth disturbances following the events of 1917 (a), 1918 (b), 1928 (c) and 1952 (d).*

Channel no.	No. of disturbed trees	No. of undisturbed trees	No. of events	Last event	Age of oldest tree	No event since
1	7	0	8	1979	1786	1979
2	15	0	28	1985	1735	1985
3	0	7	0	–	1912	1912
4	1	7	7	1956	1670	1956
5	1	2	2	1908	1649	1908
6	0	3	0	–	1898	1898
7	0	7	4	1939	1834	1939
8	0	2	0	–	1819	1819
9	0	3	2	1855	1841	1871
10	0	1	0	–	1866	1866
11	0	1	0	–	1834	1883
12	0	1	0	–	1894	1894
13	0	2	0	–	1879	1879
14	0	2	0	–	1909	1909
15	0	0	0	–	–	–
16	1	1	3	1975	1873	1925
17	1	1	1	1925	1752	1925
18	1	2	3	1973	1867	1973
19	8	3	9	1975	1740	1975
20	3	6	5	1945	1763	1945
21	3	0	4	1965	1875	1970
22	8	2	16	1977	1870	1977
23	0	0	0	–	–	–
24	0	0	0	–	–	–
25	0	0	0	–	–	–
26	0	0	0	–	–	–
27	0	2	0	–	1855	1855
28	0	3	0	–	1817	1817
29	0	0	0	–	–	–

Table E4.3 *A combination of data on the moment of the last event with the age of the oldest post-event trees growing in channels was used to determine the minimum time elapsed since the last event in previously active debris-flow channels. For the location of the individual channels see Fig. 3.*

vertical increment ranged from 0.1 to 0.5 m with an average of 0.21 m (STDEV: 0.09 m). Therefore, the missing rings due to sampling height averaged 3.3 years (min. 1; max. 9; STDEV: 2.0 years). Similarly, additional year rings added to correct errors due to the absence of the pith on the sample varied between 1 and 20 years with an average of 5.9 years per core (STDEV: 5.2 years).

In a subsequent step and in order to obtain a more complete image of debris-flow dynamics at the study site, reconstructed data on past debris-flow events were coupled with data on the age of the oldest trees growing in the abandoned debris-flow channels. Table E4.3 gives an overview of the channels, the number of trees sampled per channel, the number of events reconstructed as well as the age of the oldest tree. A combination of all these data was then used to assess the minimum time that had elapsed since the last event.

Figure E4.5a illustrates the channels where past debris-flow activity could be dated by means of dendrogeomorphological methods. Here, years shown indicate the last moment of last activity in these channels. By way of example, it can be seen that trees in channels 16 and 17 recorded a last event in 1925. In contrast, no event could be identified in channel 5 after 1908. The last events in the channels located next to the currently active one were registered in AD 1979 and 1985, respectively.

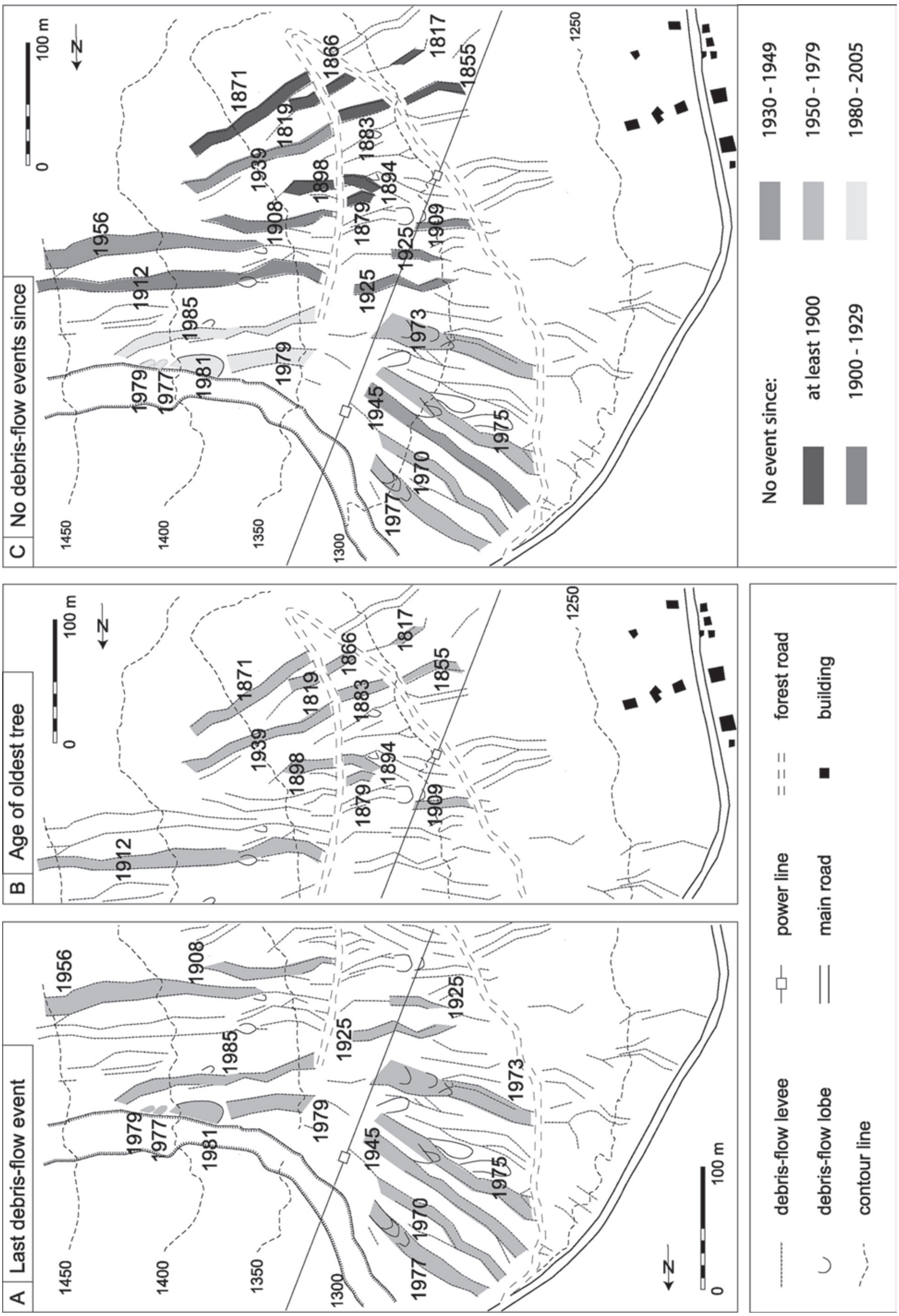
A Last debris-flow event
B Age of oldest tree
C No debris-flow events since
debris-flow levee
debris-flow lobe
contour line
power line
main road
forest road
building
No event since:
at least 1900
1900 - 1929
1930 - 1949
1950 - 1979
1980 - 2005
0
100 m
N

Fig. E4.5. *A. The last debris-flow event in channels with disturbed trees took place between 1908 and 1985. B. The oldest undisturbed trees in channels reached sampling height between 1817 and 1939. C. A combination of data on past events including minimum ages of undisturbed trees growing in channels provides information on the latest possible moment for debris-flow activity in particular channels.*

Figure E4.5b provides the age of the oldest living trees growing in channels where signs of past debris-flow activity are absent. The calendar years are meant to provide an idea of the minimum time elapsed since the last event. Germination dates of the oldest living trees vary between AD 1817 and 1939.

The results of the two preceding approaches are coupled in Fig. E4.5c, with calendar years indicating the latest possible moment of debris-flow activity in the channel. From our data, we can see that the time elapsed since the last debris-flow activity clearly increases with the distance from the currently used channel, with the last activity identified in the early 1980s close to the current channel, whereas GD in trees are missing in the southern and central sectors of the cone since the late 19th century.

5. Discussion

In this study, we report on a reconstruction of debris-flow events on a forested cone in the Valais Alps (Switzerland) based on detailed geomorphic mapping and tree-ring analyses. Dendrogeomorphological investigations of 71 heavily affected *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees allowed reconstruction of the frequency and the spatial extent of past debris-flow activity. In total, 49 events could be identified for the period AD 1782–2005. In addition, we determined the germination ages of the oldest trees in those channels where trees were missing obvious signs of past debris-flow activity. These dates served as an approximation of the minimum time elapsed since the last possible event in channels.

The debris-flow frequency represents the minimum number of events that occurred in this torrent in the recent past. The study of past events was mainly limited by the age of the trees, which averaged only 140 years. Even though the oldest tree reached sampling height in AD 1649, only a limited number of trees used in this study were older than 200 years. Therefore, the age of the trees appears to be much lower than those at other sites in the valley and is basically due to considerable logging activity on the cone. As a result, the increasing number of events in the 20th century is at least partially due to an increase in the number of sampled trees.

In addition, it is feasible that changing climatic conditions and the abundance of summer precipitation events at the end of the Little Ice Age and in the early 20th century (Pfister, 1999; Stoffel & Beniston, 2006) may have had an effect on the release of debris flows and therefore on the frequency as well. At the same time, the apparent decrease in event frequency that starts to emerge from the tree-ring reconstruction in the 1980s was primarily due to considerable channel incision (about 6–8 m) and to bank stabilization measures, which prevented present-day debris-flow surges from leaving the channel. As a result, and on the basis of observations recorded on century-old topographic sheets of the study region, we should not overlook the fact that channel incision events may have occurred in the past as well, and that our tree-ring based reconstruction may have failed to detect small debris-flow surges that did not leave the channel and cause growth disturbances (GD) to trees growing on the cone.

The age structure of the stand was determined by counting the number of tree rings present on the increment cores. An interpolation allowed representation of the spatial distribution of tree ages on the cone. The map clearly indicates that a large number of trees growing close to the present-day channel in the lower part of the cone reached sampling height in the early 20th century. As human interventions cannot be considered the main reason for this concentration of germination and as other geomorphic processes are absent here, it is feasible that a very large debris-flow event at the end of the 19th or in the earliest days of the 20th century could have eliminated a previously existing stand and have left open space for the germination of new trees.

Tree-ring analyses in combination with detailed geomorphic mapping further allowed determination of the spatial extent of events. Nonetheless, the amount of data on the distribution of past events on the cone is mainly limited by the number and the age of trees showing signs of past events. Hardly any information on past events exists for the southernmost part of the cone, as geomorphic forms might be older than the ages attained locally by *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees. Another reason for the absence of trees might be their elimination either by exceptionally large and devastating debris flows in the past or through logging activity on the cone. Nonetheless, we are confident that the spatial extent of past events could be realistically determined for at least the sectors close to the torrent.

Due to the absence of disturbed trees in the channels of the southern part of the cone, we selected 71 undisturbed trees for a minimum age dating of inactivity in these forms. The age of trees was determined through the counting of tree rings present on the increment cores. Thereafter, the number of rings missing to the pith was approximated with a transparent sheet with concentric rings. This approach – initially developed by Bosch & Gutiérrez (1999) – furnishes a realistic idea of the number of missing rings in cases where there are not too many rings missing before the pith. However, given that the center is distant from the location where the sample was taken and given that tree rings are narrow, the accuracy of the method remains limited. Furthermore, the approach used in this study is based on the assumption that growth of the innermost tree rings is constant and sudden changes in tree-ring width do not occur. As a result, it was not possible to account for such growth changes in this study. We are aware of these methodological limitations, and have to admit that there is probably no other way of assessing the real germination dates of disturbed trees. Nevertheless, we are convinced that the results presented on the minimum age of the tree are reasonably accurate. Similarly, we have to stress that the presence of growth reductions will more probably result in an underestimation rather than an overestimated of missing rings, which supports the idea of providing "minimum ages" of forms and deposits.

The same restrictions apply for the age correction due to the sampling height. Again, we assumed that the growth of the young seedling is constant. Sudden growth changes occurring in the rings that are only present below sampling height could not be identified and the age of the undisturbed trees might again have been underestimated. As a consequence, the approaches chosen for the minimum age dating of inactivity in debris-flow channels represent a valuable approximation for the estimation of the time elapsed since the last activity, but they tend – at the same time – to underestimate the real age of trees and, hence, the age of geomorphic forms in the present case.

Another factor that may influence the results is the time that passes between the moment of channel clearing by debris flows and the moment when seedlings start to recolonize the area. Pierson (2006) refers to this interval as germination lag time (GLT), while previous studies preferred the term "ecesis interval" (e.g. Desloges & Ryder, 1990; McCarthy & Luckman, 1993). According to Pierson (in press), this GLT for surfaces newly formed through lahars varies between 1 and 14 years. In glacial forefields, the GLT is generally higher with 5 to 60 years (McCarthy & Luckman, 1993). At our site, we believe that GLT are relatively short since climatic conditions are favorable for tree growth and seed sources are abundant. This assumption is further supported by personal observations made on a cone formed by a rockslide at Grossgufer (see Schindler *et al.*, 1993) in the same valley in 1991. Here, colonization of the cone had already started in the year following the event. As a result, we deliberately did not account for GLT in our study, as it can be considered very low at the study site.

Even though the methods used have their limitations, this study allowed for the first time reconstruction of the spatial and temporal dynamics of debris-flow activity on a forested cone, where deposits are in some places older than the oldest trees.

6. Conclusion

The combination of different dendroecological methods allowed reconstruction of 49 event years between AD 1782 and 2005 as well as the determination of the minimum time elapsed since the last debris-flow event for previously active channels. For cones or sectors where trees are obviously influenced by debris flows, dendrogeomorphological methods analyzing distinct growth disturbances in the tree-ring series are suitable for the determination of event years. In combination with geomorphic mapping, the spatial extent of previous events can be determined. In contrast, for cones or sectors of cones where deposits of the current-day surface are older than trees growing in the deposits, this method is not applicable. However, tree ages of the oldest post-event trees growing in the previously active channels allow determination of the latest possible moment of debris-flow activity in these channels. Therefore, the approach presented here is appropriate especially for debris-flow cones with comparably young trees, either because of repeated and devastating debris-flow events that cleared entire surfaces or because of logging activity. The combination of both techniques – dating of growth disturbances and assessing tree age of post-event trees - allows determination of the spatio-temporal dynamics of past debris-flow activity over the past few centuries on forested cones.

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CHAPTER F

OVERALL CONCLUSIONS

1. Overall Discussion and conclusions

1.1 Main results

In this PhD thesis, past debris-flow activity was reconstructed using tree-ring analyses and a detailed database elaborated for four catchments. The main part of this thesis was developed in four papers presented in Chapters B, C, D and E.

The first paper focused on the onset, formation and extension of tangential rows of traumatic resin ducts (TRD) after injury. This was the first time that fundamental research has concentrated on the vertical and tangential extension of TRD in trees that have been impacted by debris-flow activity under natural conditions. The results showed that TRD extend, on average, for 74 cm in the vertical dimension, and that they are present in 18% of the ring's circumference remaining vital after the impact. The values identified in this pioneering study are much larger than those identified after artificial treatment or injury infliction to seedlings and juvenile trees (e.g., Lev-Yadun, 2002; Franceschi et al., 2002; Luchi et al., 2005).

In the second paper, frequencies from two torrents in the Val Ferret were reconstructed, and differences in the incidence of events were assessed. Although the two study sites evince considerably different characteristics in the geology, debris-flow material and catchment morphology, the frequencies are very similar with, on average, an event identified every eight years for the period covered by the reconstructions. Consequently, it seems that the release of debris flows would be rather transport- than weathering-limited in both catchments, and that events are triggered by similar meteorological phenomena. It also appears that two types of triggering events predominate in the Val Ferret: On the one hand, debris flows seem to be triggered by synoptic weather systems and associated persistent rainfall in the Val Ferret during late summer and fall. On the other hand, there is also evidence for thunderstorms in summer, which are often quite limited in area and only affect individual catchments in the valley.

The third paper addressed the debris-flow activity in eleven abandoned channels that are still visible on the present-day cone surface of the Bruchji torrent. By the identification of 40 events and the distribution of trees affected, five different patterns of spatial behavior of debris flows were reconstructed for the last 140 years. The study showed that individual surges regularly left the current channel at the cone apex, and that individual events repeatedly affected large portions of the forest, without necessarily leaving large amounts of material on the cone.

In the fourth paper, two dendroecological approaches were combined to assess past debris-flow activity on the cone of the Grosse Grabe torrent. Besides the use of "classical" dendrogeomorphological methods, the age of the oldest post-event tree was assessed for each channel in the sectors where disturbed trees were absent. Using this minimum age dating of geomorphic forms, the study also aimed at identifying the last possible moment of debris-flow activity in the channels present on the cone. Based on the data, it becomes evident that the time elapsed since the last event increases with distance from the currently active channel.

In the four papers summarized above, the possibilities of dendroecological methods in general, and dendrogeomorphological approaches in particular, were illustrated. It was also shown that a combination of different techniques can help to improve the quality and quantity of the results obtained. In addition, the pioneering results gathered on the occurrence and extension of tangential rows of traumatic resin ducts (TRD) around injuries opens new and challenging perspectives for the identification and dating of past debris-flow activity. However, as a slight delay of TRD formation was observed in those segments located at some distance from the injury, increment cores need to be taken close to it.

Where no trees were affected by debris flows, dendrogeomorphological methods fail to provide data on past activity. Thus, the age of the oldest post-event trees growing on individual deposits can be assessed. This approach allows an approximation of the minimum age of the forms.

1.2 Comparison of debris-flow frequencies

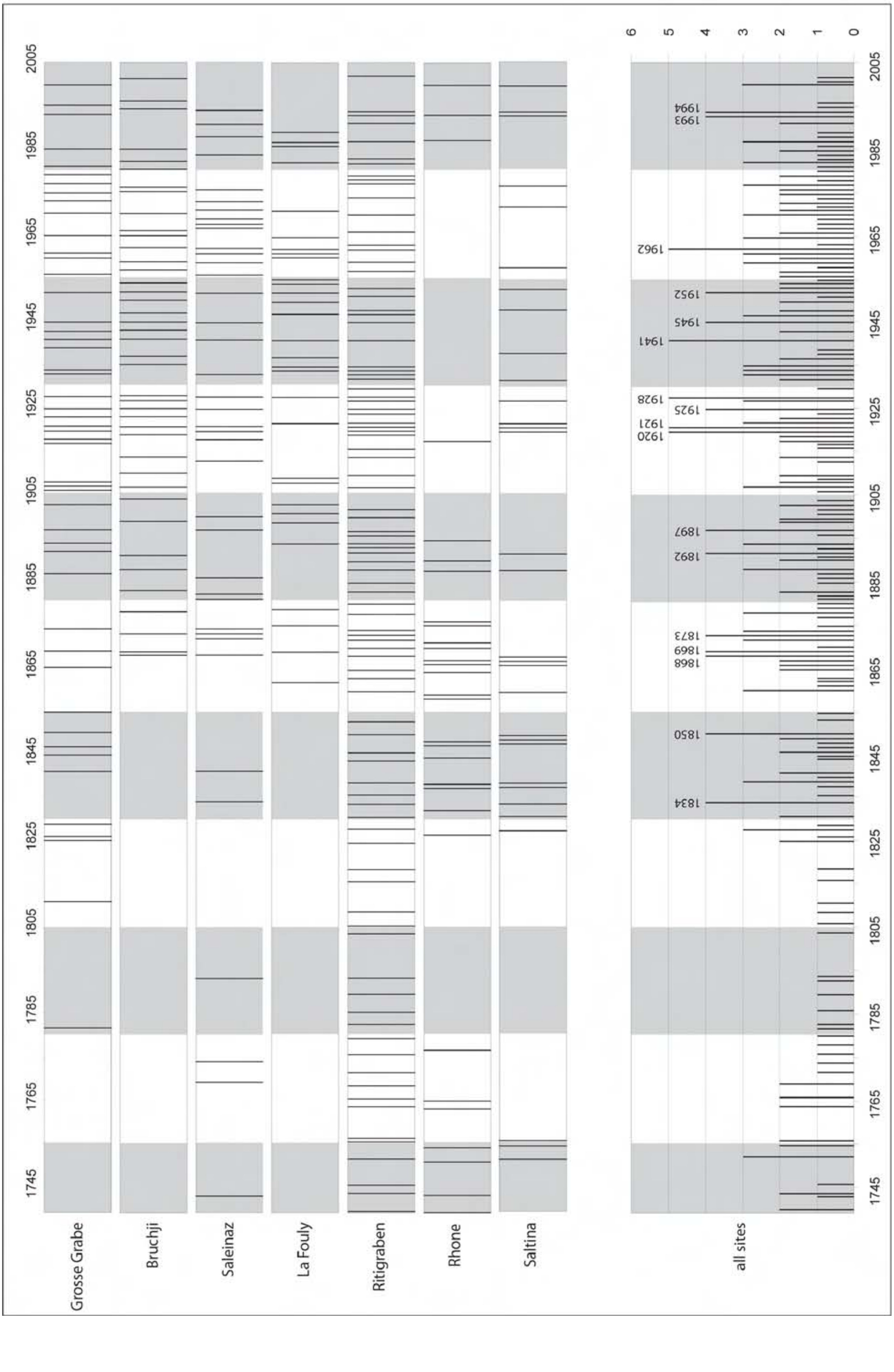
Within this PhD thesis, debris-flow frequencies were reconstructed for four catchments of the Valais Alps (Switzerland). Figure F1.1 provides an overview of the frequencies for all torrents investigated in this study (Grosse Grabe, Bruchji, Reuse de Saleinaz, Torrent de la Fouly) between 1745 and 2005. For the sake of comparison the tree-ring based frequency of the Ritigraben torrent (Stoffel & Beniston, 2006) is illustrated as well, as it is located in the Valais Alps and close to the Grosse Grabe. Archival data on flooding activity in the Rhone stream (Lütschg-Lötscher, 1926; Pfister, 1999; Jossen, 2000; BWG, 2002) and the Saltina river (Lütschg-Lötscher, 1926; Imboden, 1996) complement the data presented in Figure F1.1. It is worthwhile to note that the data presented for the four torrents investigated in this thesis exclusively contain events reconstructed with dendrogeomorphological methods. Recent debris-flow activity recorded in the archives, but not identified in the tree-ring series, is disregarded so as to prevent an "artificial" increase in the frequency for the period covered by archival data.

At the bottom of Figure F1.1, an overall frequency ("all sites") is provided, and the number of torrents that have produced a debris-flow or flooding event in the same year, are illustrated. Years with events in all seven, or in six, of the catchments cannot be identified from the overview. In contrast, we observe signs of debris-flow and flooding activity in five of the catchments in 1920, 1921, 1928, 1941 and 1962. The incidence of events in four catchments in the same year is more frequent, and can be identified on twelve occasions in the 19th and 20th centuries (1834, 1850, 1868, 1869, 1873, 1892, 1897, 1952, 1993 and 1994).

However, the identification of events in the same year does not necessarily mean that the different torrents have been active and reacting to the same meteorological event at the same time within the year. Consequently, an event year does not always refer to a single event. Events can be triggered, either by persistent rainfall affecting large parts of the Valais Alps, or by locally limited summer thunderstorms. When synoptic weather systems are active in the late summer or fall, torrents located in different regions of the Valais Alps may react with debris-flow or flooding activity. Local thunderstorms and heavy rainfall in summer will, in contrast, only influence torrents within comparably small and well-confined regions. As a result, a series of locally active thunderstorms at different times in the summer are able to trigger a large number of independent events and cause a spatial distribution of damage resembling one large persistent rainfall event during this period.

In the illustration, it also appears that the frequency and the number of events considerably decreased before the 19th century. This reduction is, at least, partly due to the length of the reconstruction, as, for example, the age of the trees sampled at Bruchji and Torrent de la Fouly is rather limited and analyses do not yield any signs of debris-flow activity prior to 1850. Therefore, the cumulative frequency given for the seven catchments needs to be read with caution. In addition, one needs to be aware that none of the frequencies presented is complete, and that they are derived from different sources with a consequent varying resolution and quality (archival data vs. reconstructions; for limitations also see Chapter F1.4).

Fig. F1.1 *Frequency of debris-flow and flooding events for several catchments in the Valais Alps (see text for details and data sources).*


Grosse Grabe
Bruchji
Saleinaz
La Fouly
Ritigraben
Rhone
Saltina
all sites
1745
1765
1785
1805
1825
1845
1865
1885
1905
1925
1945
1965
1985
2005
0
1
2
3
4
5
6
1834
1850
1868
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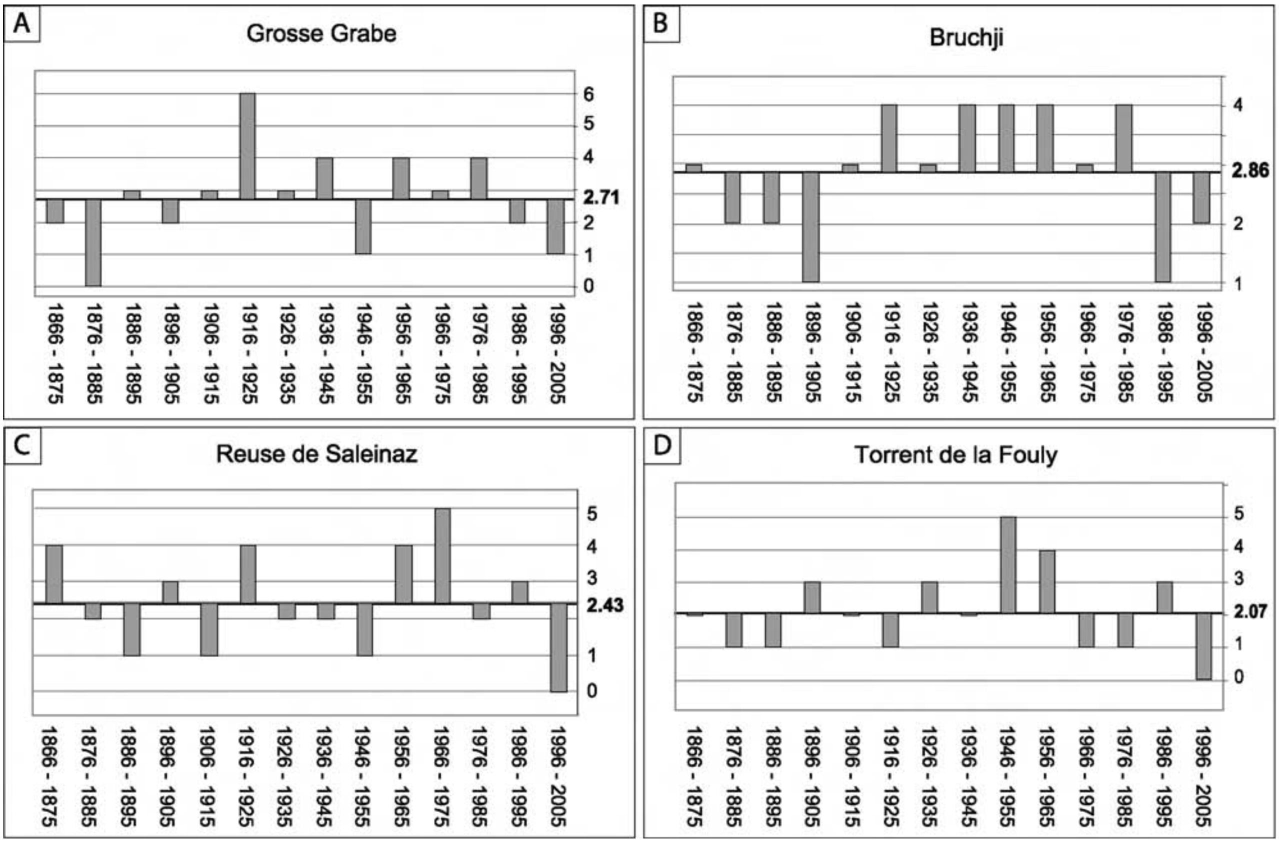

***Fig. F1.2** Reconstructed 10-year frequencies of debris-flow events between 1866 and 2005 for the different study sites. Data are presented as variations from the mean 10-year frequency as reconstructed for each study site.*

In order to facilitate a comparison of debris-flow frequencies in the torrents investigated in this thesis, decadal frequencies are given in Figure F1.2. The number of events reconstructed per decade proves to be very similar for all torrents during the period 1866–2005, with decadal averages ranging from 2.07 (Torrent de la Fouly) to 2.86 events 10 years^{-1} (Bruchji).

Although this similarity in the frequencies again needs to be interpreted with caution, one can assume that the initiation of debris flows at the four study sites would be rather transport- than weathering-limited. At all sites, there are sufficient amounts of easily erodible material available in the departure zones and along the channels, and the triggering of events primarily depends on precipitation events with a sufficient influx of water.

On the cone of the **Grosse Grabe** torrent (Fig. F1.2a), 2.71 events 10 years^{-1} could be reconstructed, on average, with considerable differences existing between individual decades. While no events could be derived from the tree-ring series for the period 1876–1885, six events were dated between 1916 and 1925. During the last two 10-year segments (1986 – 2005), the reconstruction suggests a decrease in the decadal number of events.

The **Bruchji** torrent (Fig. F1.2b) shows comparably low 10-year frequencies for most of the 19th century, and an increase can only be observed after 1906. Towards the end of the 20th and the beginning of the 21st century, a decrease is again suggested by the tree-ring based reconstruction. The overall average for the Bruchji amounts to 2.86 events 10 years^{-1} for the period represented.

The 10-year frequencies reconstructed for the **Reuse de Saleinaz** (Fig. F1.2c) and the **Torrent de la Fouly** (Fig. F1.2d) differ from those identified for the other two torrents. For both torrents, there are no obvious long-term trends observable, but considerable differences exist in the activity between the 10-year segments. Again, both torrents show a distinct decrease in the frequency between 1996 and 2005.

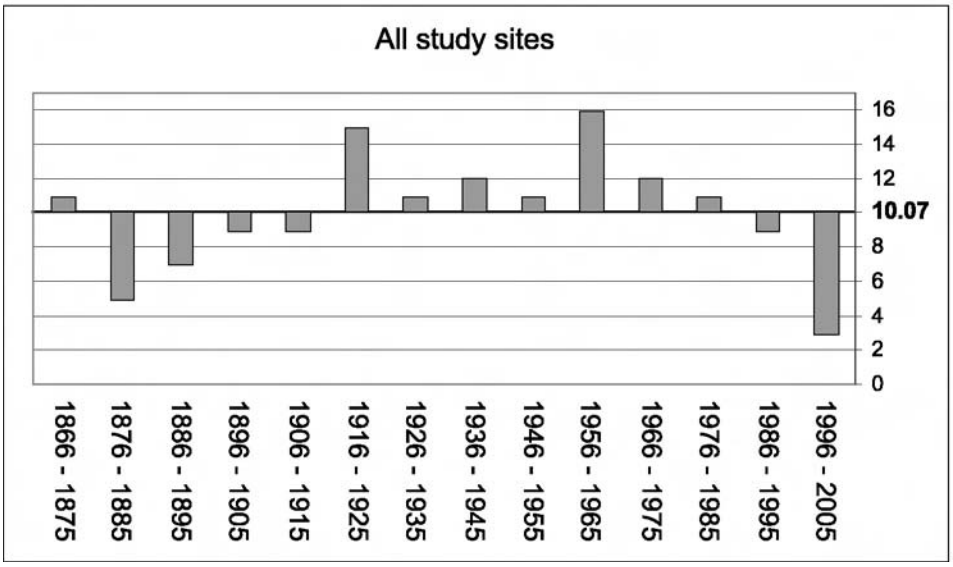

Fig. F1.3 *Reconstructed 10-year frequencies of debris-flow events for all study sites between 1866 and 2005. Data are presented as variations from the mean 10-year frequency (10.07 events).*

In Figure F1.3, the reconstructed 10-year frequencies are totaled for the four study sites (Grosse Grabe, Bruchji, Reuse de Saleinaz, Torrent de la Fouly), resulting in 10.07 events reconstructed per 10-year period, on average. From the data, two 10-year segments emerge with considerably higher frequencies, namely between 1916–1925 and 1956–1965. As observed in the 10-year frequencies of the individual torrents, the number of recon-structed events decreases again before 1915. Nonetheless, it also becomes obvious from Figure F1.3 that the last 10-year segment (1996 – 2005) is that with the smallest number of events identified for the last 140 years.

A similar decrease in debris-flow activity during the last ten years (1996–2005) was also observed in the Ritigraben torrent (Figure F1.4; Stoffel & Beniston, 2006). Here, a mean number of 4.21 events 10 years^{-1} were reconstructed and the torrent was most active between 1916 and 1935, when 14 events occurred in 20 years.

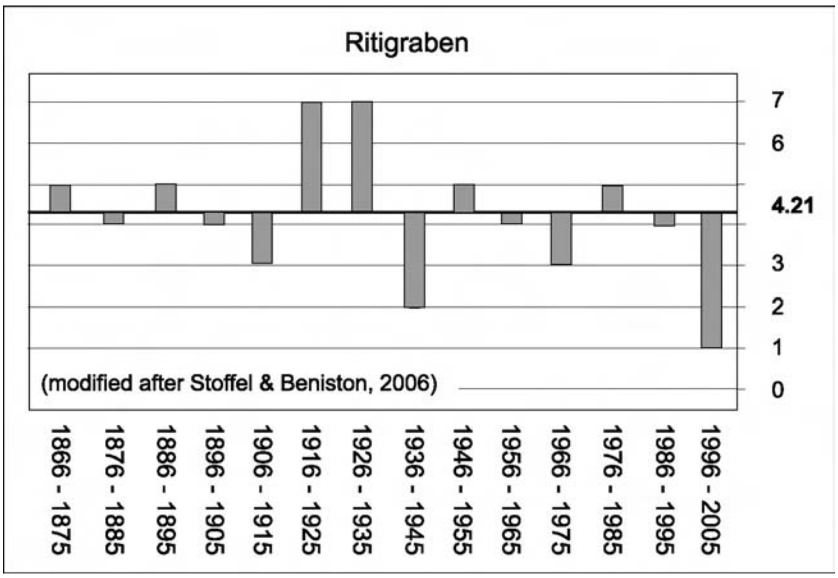

Fig. F1.4 *Reconstructed 10-year frequencies of debris-flow events at Ritigraben between 1866 and 2005 (Stoffel & Beniston, 2006).*

However, a decrease in the reconstructed frequency does not necessarily imply that there have been fewer debris-flow events. Smaller events remaining in the channel will not necessarily have affected trees on the cone, and cannot therefore be reconstructed with dendrogeomorphological methods. On the other hand, it is also possible that large and erosive surges lead to a deepening of the channel, thus preventing succeeding debris flows from leaving the channel. Anthropogenic interventions in the form of bank reinforcements can also influence the reconstructions. On the cone of the Bruchji torrent, banks have been stabilized and small dams have been built between 1976 and 1978. Consequently, the numbers of events that are still leaving the channel have considerably decreased following such interventions. Similarly, the channel of the Grosse Grabe torrent is deeply incised, and parts of its banks have been reinforced after two events in 1993 and 1994. Again, most debris flows currently remain in the incised channel and do not affect trees growing on the banks or on the cone.

1.3 Influence of climatic changes on Debris-flow activity

In the previous sections, it has been stated that the release of debris flows depends primarily on the presence of triggering precipitation events, and not on the availability of sediments. It is also obvious that debris flows and floods are released by individual meteorological events. Consequently, an analysis of changes in climatic conditions can also help to understand the presence or absence of past events.

Thus, the high frequencies reconstructed at the four study sites for the period 1916–1935 occurred at a time when warm, wet conditions prevailed in the Swiss Alps during the summers (Pfister, 1999). Although the low frequencies reconstructed over the last 10-year period are partly due to the construction of protective measures at the four study sites, they are also the result of a significant reduction in heavy precipitation events in the late summer and early autumn (see Schmidli & Frei, 2005).

Based on the A2 greenhouse-gas emissions scenario obtained from the previous IPCC report (Inter- governmental Panel on Climate Change; Nakićenović *et al.*, 2000), a number of Regional Climate Models suggest a shift in the occurrence of heavy precipitation events in the Swiss Alps from summer towards autumn (and spring) in such a greenhouse climate by 2100 (Beniston, 2006). As autumn temperatures are projected to remain 4–7° C below actual summer temperatures in a future greenhouse climate (Stoffel & Beniston, 2006), part of the precipitation could fall as snow at higher altitudes, and thus in the departure zones of debris flows. Consequently, the buffering effect of snow on rapid runoff could impede the release of debris flows and it is, thus, plausible that debris flows will not necessarily occur as frequently in future, as they did in the past in torrents with classical departure zones located at high elevations (Stoffel *et al.*, 2007).

These potential changes in precipitation regimes projected to occur in a greenhouse climate would probably have different consequences for the catchments investigated in this thesis. In the Grosse Grabe and Reuse de Saleinaz torrents, departure zones are located in periglacial environments and at elevations > 3,000 m a.s.l. As a result, it is possible that debris flows will not necessarily occur as frequently in the future as they did in the past, and that there will be a shift in the seasonality of heavy precipitation events from (early) summer towards late summer and early autumn, as proposed for the Ritigraben (Stoffel *et al.*, 2007).

At Torrent de la Fouly and Bruchji, the primary departure zones are located well below 2,800 m a.s.l., and permafrost does not influence debris-flow activity here. In the Bruchji torrent, the main area for sediment supply is located < 2,000 m a.s.l., where debris flows are normally released during heavy rainfall or hailstorm events from the heavily fractured material. The consequences of changes in the seasonality of heavy precipitation events on the incidence of debris flows will probably be less important in these two torrents.

1.4 Limitations of the methods

In the previous paragraphs, the possibilities of dendrogeomorphological methods for the analysis and reconstruction of past debris-flow activity have been described and discussed. At the same time, some limitations of the method will be presented as well.

The most important restriction of dendrogeomorphological methods resides in the fact that tree-ring based reconstructions of debris-flow activity are limited to channels and cones covered with forest. In addition, trees on the cone need to be affected by past debris-flow events and should react to the impact with growth disturbances (GD). The length and quality of the reconstruction is strongly influenced by the age of the trees showing GD. Therefore, the potential for dendrogeomorphological studies is generally quite limited on cones where logging activity was important in the past. Anthropogenic interventions may affect the geomorphology of the present-day cone surface. If geomorphic features (e.g. channels, deposits) are remodeled, the quality of the geomorphic map will be diminished and the assessment of the spatial extent of past events restricted.

On surfaces where disturbed trees are absent, the age of the oldest post-event trees can be determined so as to identify the minimum age of forms. However, this method does not produce data on past events, but only on the last possible occurrence of debris-flow activity. In addition, the time lapse between the occurrence of an event that would have cleared the surface and the recolonization of the bare surface by trees needs to be estimated as well. Consequently, this approach furnishes valuable data on the minimum age of forms but, nevertheless, remains only an approximation.

In a similar way, debris-flow frequencies reconstructed with dendrogeomorphological methods have to be seen as minimum frequencies. Debris flows remaining in the channel and not affecting trees cannot normally be identified in the tree-ring series. As a result, morphological changes of the channel, such as deepening by erosive surges or anthropogenic interventions, will inevitably influence the reconstructed frequency of past events.

The method also has its limitations when it is used for the assessment of magnitudes of individual events, as GD in trees cannot provide indications on the amount of material transported in the flow. It is true that tree-ring analyses allow dating of individual debris-flow deposits on the present-day cone surface (Stoffel *et al.*, 2007) and, therefore, estimations of the amount of material deposited on the cone during an event. At the same time, the approach neither takes into account the material transported in the debris-flow mass without deposition on the cone, nor overriding and erosion of (older) deposits by more recent debris-flow activity. As a result, it is (almost) impossible to determine the magnitude of events with tree-ring analyses alone.

1.5 Implications of tree-ring studies for hazard assessment

While this PhD thesis primarily aimed at identifying past debris-flow activity and at understanding the dynamics of the process, it also yielded valuable information for the assessment of hazards and risks for the torrents investigated. Tree-ring based reconstructions of past and contemporary frequencies provide a realistic image of the debris-flow activity in the torrents; but they have, at the same time, their limitations as to the estimation of magnitudes of past (and potential future) events. Consequently, the approach cannot apparently provide sufficiently detailed information for the dimensioning of protective countermeasures as long as it is based exclusively on the identification of GD in tree-ring series. But the methods used in this thesis can assist the assessment and identification of hazards and risks in other ways. For instance, the coupling of tree-ring data with the results of geomorphic mapping allows indication and dating of activity in previously active flow paths, as well as the identification of segments along the currently used channel where overbank sedimentation or breakouts occurred during previous events. Consequently, the approach can be employed to designate sectors where breakouts and the re-activation of abandoned channels could potentially occur during future events. In the following illustration, two examples are given to illustrate the potential of dendrogeomorphological studies in hazard assessment.

On the forested cone of the **Bruchji** torrent (Fig. F1.5), dendrogeomorphological analyses indicate five segments along the present channel where potential breakouts could occur during future events. At the cone apex, the torrent's direction changes from north-south to northwest-southeast. Several older channels oriented north-south exist in this part of the cone and could be re-activated following breakouts, as observed e.g., during the July 2001 debris-flow surges. Similar zones exist further down in the channel, as well as at the lower end of the debris-retention basin where material has left the insufficiently large construction in July 2001. As a consequence, future events could again fill the retention basin and material could be diverted onto the road leading to the village of Blatten.

On the forested cone of the **Grosse Grabe torrent** (Figure F1.6), tree-ring analysis and geomorphic mapping indicate the presence of three potential breakout zones, with the uppermost one located at 1420–1440 m a.s.l. Surges leaving the currently active channel at this sector would probably re-activate a channel that has regularly been used by past events (for details see Chapter E). At 1320–1360 m a.s.l., where the active channel changes its direction from east-west to southeast-northwest, breakouts could be reconstructed for several events in the past, and are still evident today as witnessed by the presence of several deposits found on the cone surface. Consequently, currently abandoned channels could be re-activated at this location as well. The third potential breakout zone is located on the road gallery and material could cause sedimentation on the main road leading to Zermatt.

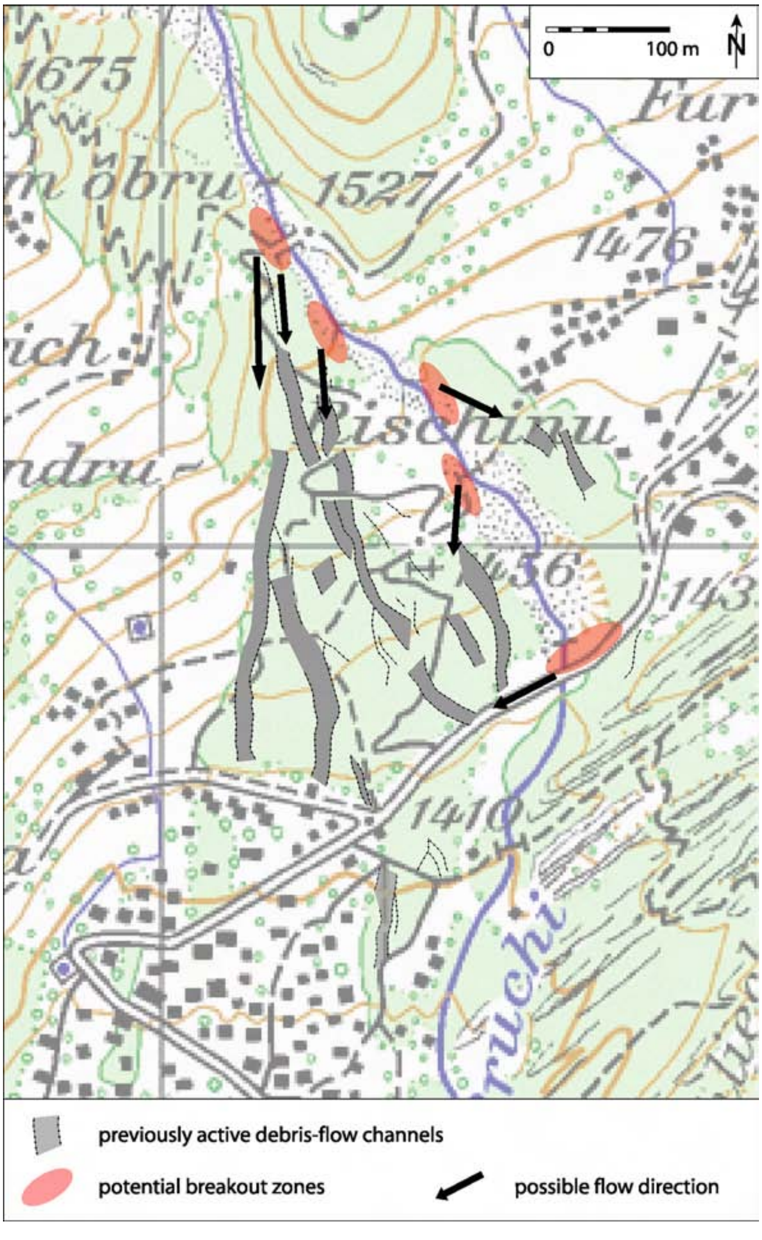

Fig. F1.5 Map indicating channel segments where potential breakouts could occur and re-activate abandoned channels on the forested cone of the Bruchji torrent (map reproduced by permission of swisstopo (BA071655)).

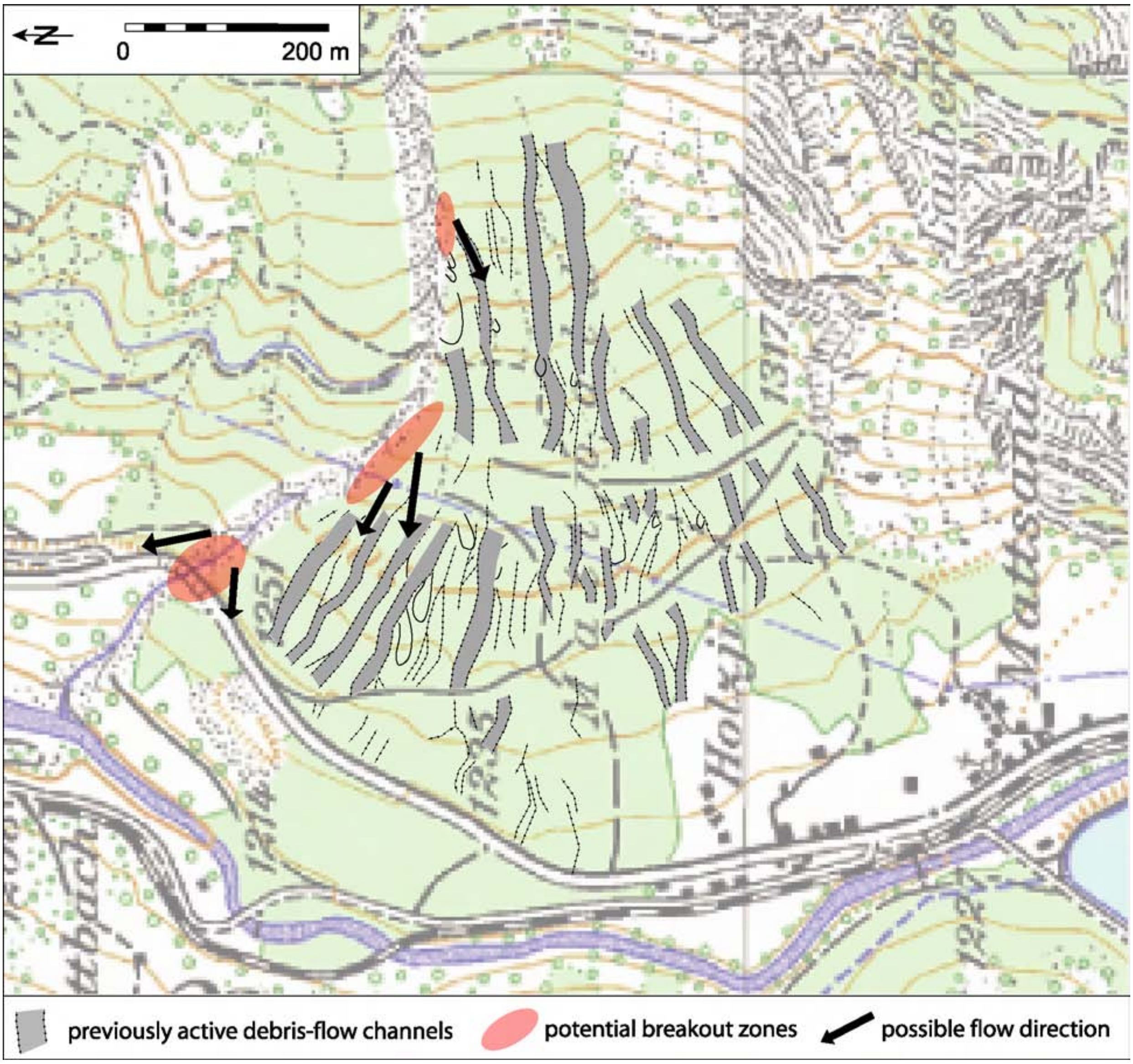

Fig. F1.6 *Map indicating channel segments where potential breakouts could occur and thus re-activate abandoned channels on the forested cone of the Grosse Grabe torrent (map reproduced by permission of swisstopo (BA071655)).*

While dendrogeomorphological methods cannot provide all of the answers to the questions asked by hazard and risk specialists, it has been shown by these two examples that tree-ring analysis on forested cones is able to contribute largely to a better understanding of the process at basin-scale, the frequency of events, spatial patterns of past activity and the moment of last activity in currently abandoned channels. Having said this, it becomes evident that the contribution of dendrogeomorphology is essential for a realistic assessment of hazards and the production of hazard maps.

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2. Further research suggested

While this PhD thesis produced answers to several aspects of tree-ring analysis and debris-flow activity, it also raised a large number of new questions and suggestions for future research.

2.1 Methodology

In the first paper presented in this PhD thesis, new insights were gained on the vertical and tangential extensions of tangential rows of resin ducts (TRD) in trees affected by debris flows. Based on the results, suggestions were made regarding how to better sample injured trees in future studies so as to find TRD on the increment cores. While new questions emerged from the study of tree reactions to geomorphic impacts, others remain still open.

It has been shown that trees impacted at the very end of, or even outside, the growing season in October or November produce a first series of TRD at the beginning of the new tree ring. But when do TRD start to occur when the injury is inflicted during the growing season? Would the reactions in the selected trees be even more pronounced if wounding occurred during the growing season, as argued by e.g., Bannan (1936) or Cruickshank *et al.* (2006)?

Similarly, the onset and degree of other reactions following debris-flow events need to be investigated in greater detail as well. When does reaction wood start to form in the developing xylem after stem tilting? Is the dating of events with seasonal precision possible when analyses focus on the onset of compression wood? Likewise, future studies should investigate the vertical and tangential extensions of compression wood in trees that have been tilted by debris flows.

Similarly, the vertical extent of growth suppression following decapitation, root erosion or stem burial needs to be assessed as well. Is growth suppression more pronounced close to the ground than further up in the stem? Does suppression initiate directly after the impact, or is some delay observable? In addition, it would be interesting to investigate if the height of stem burial or the decapitation position with subsequent loss of branches available for photosynthesis correlate with the degree of suppression observed in the tree-ring series in the years following the impact.

A large number of trees was in general sampled for the reconstruction of past debris-flow activity on forested cones. However, how many trees do we really need to sample in order to provide reliable results on frequencies or spatial patterns of events? Butler *et al.* (1987) described a number of studies using different amounts of trees for the assessment of previous events. According to this study, the number of trees used for the reconstruction of past events varies from one single tree (Burrows & Burrows, 1976) for the determination of past avalanches to more than 59 trees (Cook & Jacoby, 1983) for streamflow reconstruction in order to obtain replicable results. Conclusive data on the number of trees to be sampled for debris-flow reconstructions are not available and future studies should focus on this aspect as well.

Similar questions arise when large surfaces need to be investigated. In this study, we always tried to sample as many trees as possible from all deposits identified in the field so as to reconstruct the spatial extent of past debris-flow events. However, this renders reconstructions very time-consuming. In rockfall research, reconstruction of past activity was determined by the analysis of disturbed trees along horizontal and vertical transects (e.g., Stoffel *et al.*, 2005c; Schneuwly & Stoffel, in prep.). Is a similar sampling strategy also admissible for debris-flow research on forested cones? How important would the loss of data on the spatial and/or temporal occurrence of debris flows be if sampling was effected along transects?

In this thesis, the main tree species used for the analysis of past debris flows were European larch (*Larix decicua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.). On the Reuse de Saleinaz cone, some samples were taken from Scots pine (*Pinus sylvestris* L.). While growth disturbances could easily be assessed in L. decidua and P. abies trees, dating past debris-flow events proved to be more difficult with P. sylvestris, as trees from the Pinus species do not form (tangential rows of) traumatic resin ducts. As a result, the assessment of growth disturbances was limited to abrupt growth changes and to the onset of compression wood. For future studies, it would be worthwhile to investigate growth reactions in Pinus trees in more detail to elaborate new dating techniques for this species.

Similarly, the potential of deciduous trees for the reconstruction of past geomorphic processes would merit greater attention in future studies. So far, deciduous trees were mainly used for the dating of slow mass movements, such as landslides (e.g., Fantucci & McCord, 1995; Stefanini, 2004). What is the potential for using angiosperms in the reconstruction of fast-flowing movements?

Finally, it seems questionable if reference chronologies imperatively need to be built from undisturbed trees in dendrogeomorphological investigations. Provided that a sufficiently large number of samples is collected from disturbed trees growing in or on the debris-flow deposits, individual tree-ring series would only have a small influence on the overall chronology. How important would differences be between a "classical" reference chronology and the overall mean curve built from the disturbed trees? Would it therefore be conceivable to build reference chronologies in future studies from the growth curves of all disturbed trees?

2.2 Debris-flow research

In the papers presented in this thesis, the seasonality of debris-flow events has not been assessed. As a result, debris-flow activity occurring in the same year in different torrents has not necessarily been triggered by the same meteorological event, but rather by different local thunderstorms that have occurred at different periods of the year. In order to identify individual events, instead of event years, the seasonality of events needs to be determined with greater detail at the different study sites. Stoffel & Beniston (2006) determined the seasonality of events by the assessment of the intra-annual position of tangential rows of traumatic resin ducts within the tree ring, systematic evaluation of archival data and data from local meteorological stations. The same approach could be used at the study sites analyzed in this thesis so as to obtain more detailed information on the events and their intra-seasonal timing.

In a similar way, more debris-flow producing catchments need to be investigated in the Canton of Valais and in other regions of the European Alps in order to acquire more data on regional patterns of events, their occurrence and on the meteorological conditions that are causing them. In addition, it would be very interesting to see if there are any differences in the occurrence or the behavior of debris flows in torrents located in different valleys or regions.

Several studies have defined threshold values for the amount and intensity of the rainfall needed to trigger debris-flow events (e.g., Caine, 1980; Wilson & Wieczorek, 1995; Bacchini & Zannoni, 2003). As illustrated in the different papers, threshold values vary considerably between the study sites. Consequently, local rainfall data should be analyzed for the different catchments to obtain detailed insight on the thresholds existing at a local level.

For the assessment of hazards and risks, additional knowledge is needed concerning the magnitude of past events. As the dating of deposits on the present-day cone surface cannot produce detailed information on the amount of material transported during past events, further approaches are needed to approximate magnitudes of past and potential future events. These approaches include the analysis of geological and geomorphic processes present in the departure zone and along the channel. In the perspective of ongoing climatic changes, torrents with departure zones in glacial and periglacial domains will most probably be influenced by warmer temperatures and changes in the seasonality of precipitation events. Will the retreat of glaciers lead to more frequent and more important instability of moraines, and to more material being supplied to the channels? What will be the influence of permafrost degradation on the frequency and magnitude of events?

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CHAPTER G

APPENDICES

Appendix 1

Markus Stoffel, Michelle Bollschweiler and Gion-Reto Hassler

"Differentiating past events on a cone influenced by debris-flow and snow avalanche activity - a dendrogeomorphological approach"

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Abstract

Dendrogeomorphology was used to investigate past events on a cone affected by both debris flows and snow avalanches. We report on results of 520 cores from 251 injured *Larix decidua* Mill. and *Picea abies* (L.) Karst. trees sampled on the Birchbach cone (Swiss Alps). Detailed analysis of tree-ring sequences allowed dating of 561 growth disturbances in individual trees for a 252-yr period, extending from 1750 to 2002, which could be attributed to 30 different event years. We then localised the position of rows of traumatic resin ducts (TRD) within the tree ring so as to assess the intra-seasonal position of damage. In agreement with data on the local growth period, TRD located at the beginning of the new growth ring were considered the result of avalanche impacts that occurred during the dormant season or in earliest earlywood between late October and early May. In contrast, TRD found in late earlywood or within latewood were considered the result of periglacial debris-flow activity, as these layers of the tree ring are locally formed between July and early October.

For nine out of the 30 reconstructed event years, the intra-seasonal timing of TRD indicated that reactions must be the result of past snow avalanche activity. In 19 other event years, TRD showed that damage has been caused between July and early October and, thus, through debris flows in the Birchbach torrent. Finally, the spatial patterns of trees showing reactions as a result of particular events were assessed so as to approximate the extent of past debris flows and snow avalanches.

Keywords

debris flow; snow avalanche; dendrogeomorphology; frequency; Swiss Alps

1.1 Introduction

Debris-flow and snow avalanche activity can frequently be observed in mountain regions, where their repeated occurrence may result in characteristic landforms, such as cone-shaped debris accumulations at the mouth of gullies or torrent valleys. Typical morphologies of debris-flow or snow avalanche landforms have repeatedly been described in the literature. As for the processes and forms related to debris flows, past investigations primarily focused on, e.g., their flow behaviour and rheology (Costa, 1984, 1988; Johnson & Rodine, 1984; Takahashi, 1991; Rickenmann, 1999; Johnson, 2003; Bollschweiler *et al.*, 2005) or on triggering factors (Caine, 1980; Bovis & Jakob, 1999; Huggel *et al.*, 2002; Cannon *et al.*, 2003; Stoffel *et al.*, 2003). In a similar way, the magnitude and frequency of debris flows have repeatedly been reconstructed or the moment of past activity assessed by means of field investigations (e.g., Hungr *et al.*, 1984; Zimmermann *et al.*, 1997), lichenometry (e.g., Rapp & Nyberg, 1981; Innes, 1985; Jonasson *et al.*, 1991; Helsen *et al.*, 2002) or dendrogeomorphological analyses (e.g., Strunk, 1995, 1997; Baumann & Kaiser, 1999; May & Gresswell, 2004; Jakob *et al.*, 2005; Stoffel *et al.*, 2005b).

Research on characteristic forms, landscapes or the geomorphic activity of snow avalanches has commonly been based on the pioneering results obtained in Rapp's 'Kärkevagge' study (Rapp, 1960), which provided the first detailed descriptions and quantitative estimates of debris transport and erosion by snow avalanches. Since that study, the geomorphic work of snow avalanches, the morphology of runout zones or avalanche talus as well as debris transport by avalanches have been analysed and quantified in different mountainous regions all over the world (e.g., Gardner, 1970; Luckman, 1977, 1978; Huber, 1982; Ward, 1985; Ackroyd 1986; André, 1990; Bell *et al.*, 1990; Smith & McClung, 1997; Jomelli, 1999). Similarly to debris flows, deposits from former events have been dated by radiocarbon (Smith *et al.*, 1994), lichenometric (McCarroll, 1993; Matthews & McCarroll, 1994) and dendrogeomorphological analyses (Johnson *et al.*, 1985; Butler *et al.*, 1992; Patten & Knight, 1994; Rayback, 1998; Hebertson & Jenkins, 2003).

However – and even though Luckman (1992) pertinently emphasises that debris-flow and snow avalanche processes regularly occupy common starting and runout zones – analyses so far have only exceptionally focused on both processes simultaneously. Moreover, the few studies addressing avalanche landscapes in general and the occurrence of both processes in particular have most frequently been realised above tree line or on non-forested slopes. Similarly, tree-ring analyses have, up to now, only been used to reconstruct past events in forest stands influenced either by debris-flow or snow avalanche activity, but not by both processes at the same time.

It is therefore the purpose of this study to simultaneously investigate and date past debris-flow and snow avalanche activity on a forested cone in the Swiss Alps. We report on results obtained from dendrogeomorphological analysis covering the last 252 years. The present paper primarily provides an illustration of how growth disturbances caused by debris-flow events can be differentiated from signs associated with snow avalanche activity in heavily disturbed Larix decidua Mill. and Picea abies (L.) Karst. trees. Thereafter, we assess the approximate area affected as well as the origin of past debris-flow and snow avalanche events on the cone using tree-ring records in conjunction with the results from geomorphic mapping.

1.2 Study area

The area investigated within the present study is the Birchbach cone, located southeast of the village of Blatten (Lötschental valley, Swiss Alps, 46° 25'N / 7° 49'E; Fig. G1.1). The catchment area of the Birchbach torrent covers 2.54 km^2 and the length of the primary channel totals 2.65 km. The cone itself is illustrated in Figure G1.2 and extends from approximately 1500 to 1660 m a.s.l. It has a mean slope gradient of 17°, a cone area of 0.72 km^2 and is covered with an open forest composed of European larch (*Larix decidua* Mill.) and a few Norway spruce trees (*Picea abies* (L.) Karst.). While the apex of the cone remains largely free of vegetation, pioneer bushes such as green alder (*Alnus viridis* (Chaix) DC.) colonize those areas of the site repeatedly affected by snow avalanches. Meteorological data for Ried (see Fig. G1.1) indicate mean yearly precipitation totals of 1113 mm and

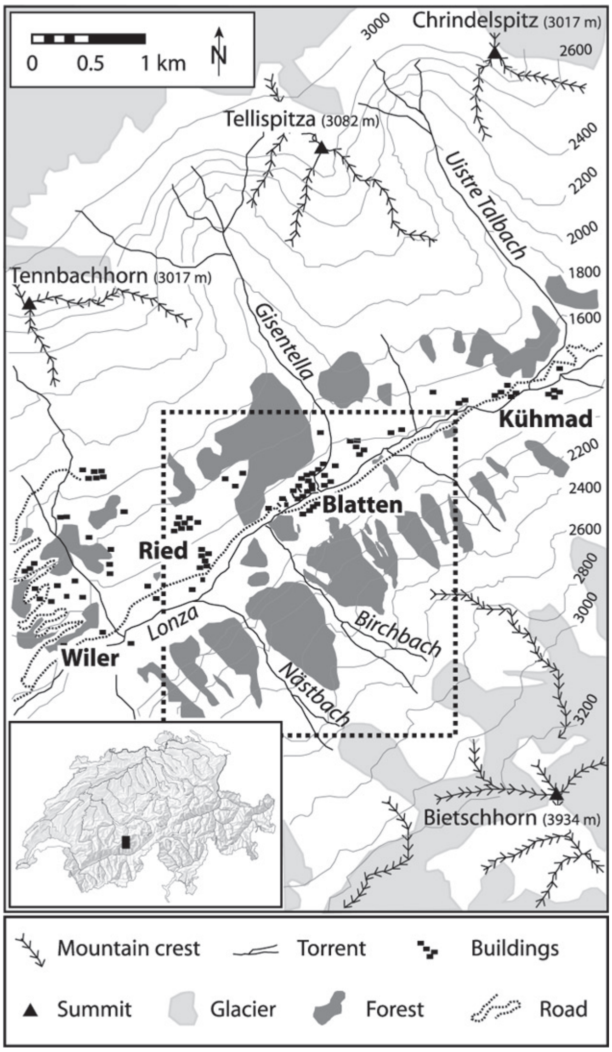

Fig. G1.1 Location of the study site Blatten as well as the meteorological station Ried within the central Lötschental valley (Valais, Switzerland). The dashed rectangle indicates the area illustrated in Figure G1.2.

a mean temperature of 4.8 °C. The growth period of *Larix decidua* and *Picea abies* lasts locally from early May to mid-October (Fischer, 1980).

Debris flow material commonly originates from the huge, unconsolidated morainic deposits located in the forefields of the hanging glacier northwest of the Bietschhorn summit (3934 m a.s.l., Fig. G1.1). The material consists of paragneissic and granite basement rocks of the Aar massif (Labhart, 2004). The high elevation of the departure zone and the presence of contemporary permafrost indicated by a regionally calibrated GIS model (Imhof, 1996) restrict the release of debris flows to a few months in summer and early autumn. Evidence for past debris flows is available from oral history for the 16th century (Guntern, 1978).

Snow avalanches reaching the cone primarily pass through the 'Birchchinn' avalanche gully shown in Figure G1.2. It is, however, possible that exceptionally large (powder) snow avalanches passing the 'Nästchinn' or 'Blötza' tracks may cause damage to trees growing on the Birchbach cone as well. A large database on 286 destructive snow avalanche events since 1680 exists for the Lötschental valley and is illustrated in Table 1. Records suggest that more than 70% of the snow avalanches occurred in December, January or February. The database also contains records for the 'Birchchinn', 'Nästchinn' and 'Blötza' tracks (Fig. G1.2; Table G1.1), indicating that avalanches would have been triggered exclusively between December and March (Bellwald, 2003). Wet-snow avalanches occurring within the growth period of Larix decidua and Picea abies have never been attested on the Birchbach cone. In contrast, destructive snow avalanche events in May or even early June are known to have repeatedly reached the valley floor southwest of the village of Wiler (Fig. G1.1).

As a reaction to the debris-flow and snow avalanche activity, a large protection dam (390 m in length, 12 m in height) was built on the slope in the early 1990s so as to protect the buildings located at the northeastern edge of the Birchbach cone. On the slope opposite the cone, a road gallery was constructed in 1993 in order to protect the main road connecting Blatten with Wiler from future 'Blötza' avalanches (Jossen, 1994; SLF, 2000; Fig. G1.2).

1.3 Material and methods

1.3.1 Geomorphic mapping and sampling of increment cores

In a first step, geomorphic mapping of forms and deposits associated with past debris-flow and snow avalanche activity was realized in a scale of 1:1000 and the position of disturbed trees growing on the cone assessed. Thereafter, 520 increment cores were sampled from 251 Larix decidua and Picea abies trees that had obviously been disturbed by past debris flows and/or snow avalanches. Within this study, we preferably selected trees with scars,

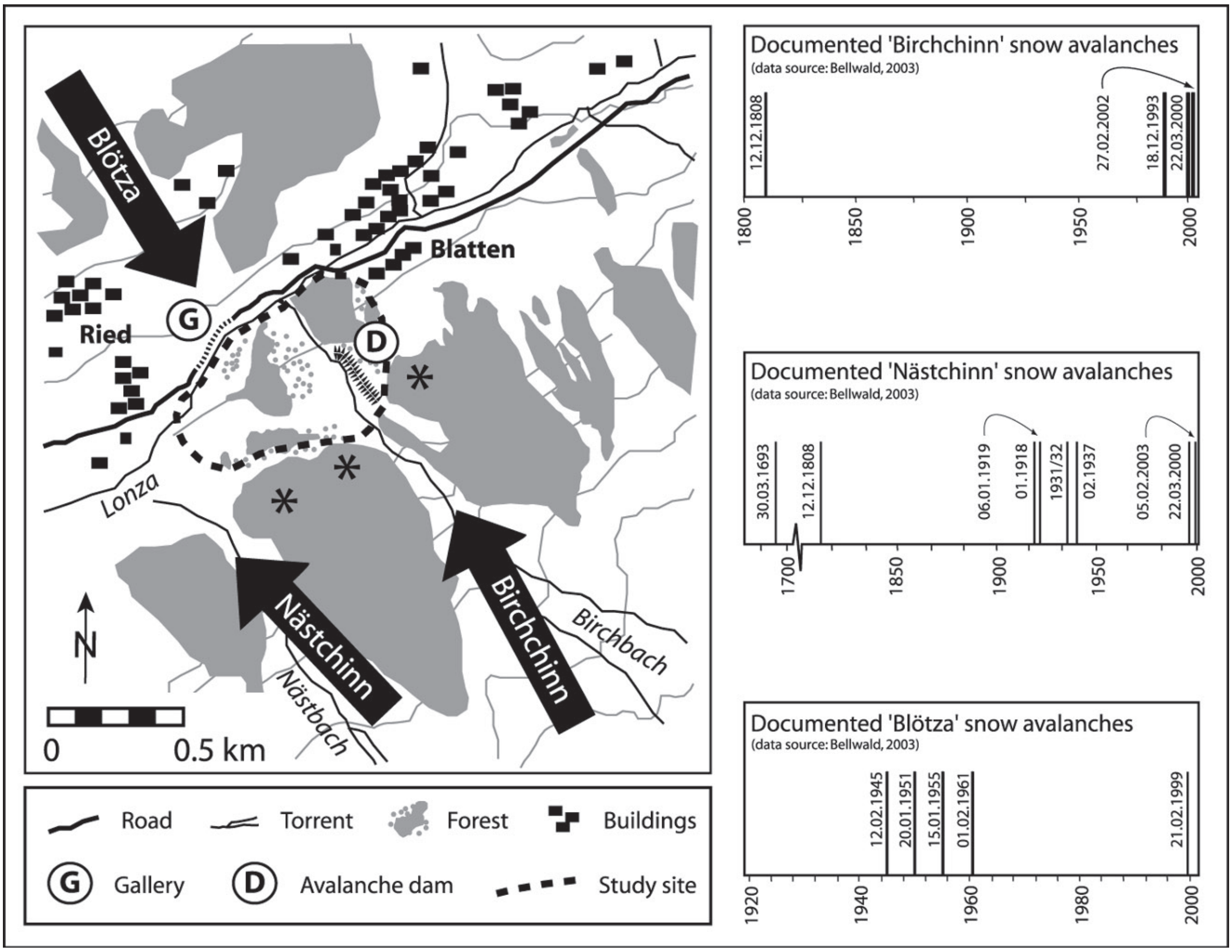

Fig. G1.2 *(left) Avalanche tracks and debris-flow torrents that might influence the Birchbach cone. Note the large earth-fill dam (D) and the road gallery (G) constructed in the early 1990s to protect the settlement of Blatten as well as the road connecting the village with Ried and the main valley. In the areas indicated with asterisks, undisturbed trees were sampled to build a local reference chronology. The dashed polygon gives the position of the area investigated. (right) Archive data on past snow avalanche events in the 'Birchchinn', 'Nästchinn' and 'Blötza' tracks.*

Timing of avalanches (archival data)	Lötschental (1680–2003)	Birchchinn (1808–2003)	Nästchinn (1693–2003)	Blötza (1945–2003)
Not specified ('*winter*')	21 (7·4%)	–	–	–
September	1 (0·3%)	–	–	–
October	4 (1·4%)	–	–	–
November	4 (1·4%)	–	–	–
December	47 (16·4%)	2	1	–
January	71 (24·8%)	–	1	2
February	88 (30·8%)	1	1	3
March	26 (9·1%)	1	2	–
April	14 (4·9%)	–	–	–
May	7 (2·4%)	–	–	–
June	3 (1·1%)	–	–	–
TOTAL	**286**	**4**	**5**	**5**

Table G1.1 *Archival data on the timing of past snow avalanche activity (adapted from* BELLWALD*, 2003).*

candelabra growth, loss of apex, as well as buried or tilted stems resulting from past events. Two cores per tree were then extracted with increment borers, one in the flow direction of past snow avalanches and debris flows and another on the opposite side of the trunk (max. length of cores: 40 cm, Ø 6 mm). To gather a maximum of information on the growth disturbances (GD) caused by past events, increment cores were preferably sampled at the height of the visible damage or within the segment of the stem tilted during past events.

Furthermore, additional data were gathered for each tree sampled. Information included (i) a determination of its 3D-position within the deposits; (ii) sketches and position of visible defects in the tree morphology, such as scars, broken crowns or branches, candelabra growth or tilted stems; (iii) the position of cores sampled (i.e. upslope, downslope, other); (iv) tree diameter at breast height (DBH) derived from circumference measurements and (v) data on neighbouring trees as well as micro-topography.

1.3.2 Tree-ring analyses

Samples were then prepared in the laboratory as described by Phipps (1985) and Krusic *et al.* (1987), before the cores were analysed visually and obvious growth anomalies noted on ‘skeleton plots’ (Schweingruber *et al.*, 1990). Ring-widths of disturbed increment cores were measured using a digital LINTAB positioning table connected to a Leica microscope and TSAP 3.0 software (Time Series Analysis and Presentation; Rinntech, 2007).

Thereafter, two reference chronologies were built with 34 increment cores each, sampled from Larix decidua and Picea abies trees growing in undisturbed stands located northeast of the cone. The sites selected for the sampling of reference trees are indicated by asterisks in Figure G1.2. This step primarily served to compare general growth patterns of undisturbed trees with the tree-ring records of disturbed trees so as to allow distinction of predominant growth conditions (climate, insect outbreaks) from GD induced by geomorphic processes. The comparison further allowed cross-dating of undisturbed with disturbed tree-ring records and, where applicable, correction of faulty tree-ring sequences derived from disturbed samples (e.g., density fluctuations or missing rings; Cook & Kairiukstis, 1990; Schweingruber, 1996).

1.3.3 Age structure of the stand

Based on the pith age of the selected trees at breast height, the approximate age structure of the forest stand on the Birchbach cone was assessed. We are aware that tree age at breast height provides neither germination nor inception dates. Nonetheless, it may furnish valuable data on major disturbance events at the cone with reasonable precision, as Larix decidua and Picea abies have been shown to recolonize the surfaces cleared by snow avalanches in the years following an event.

1.3.4 Growth disturbances in trees and their seasonal timing

Once all disturbed samples had been age-corrected, increment curves were investigated so as to assess GD such as the initiation of abrupt growth reductions, recovery or the onset of compression wood (Shroder, 1980; Braam *et al.*, 1987; Schweingruber, 1996; Fantucci & Sorriso-Valvo, 1999). Further attention was given to the visual analysis of tree rings showing callus tissue overgrowing scars, rows of traumatic resin ducts (TRD) or reaction wood in tilted conifer stems (Schweingruber, 2001; Stoffel *et al.*, 2005c; Perret *et al.*, 2006). Growth disturbances observed in individual trees were then compiled in a database (Hassler, 2004).

Thereafter, we grouped GD occurring simultaneously in different trees and defined criteria for the determination of event years. For reasons of limited sample depth (i.e. limited age of trees), strong and abrupt GD were considered an event year for the period 1750–1850, even if signs were present in only one single tree. In contrast, (i) weak GD identified in several cores or (ii) abrupt GD identified in one single tree were disregarded for events occurring after AD 1850, and only the years with several abrupt GD identified in the samples were kept for further analysis.

After the assessment of event years, we analysed the onset of abrupt changes in cell formation within individual tree rings. Following Stoffel et

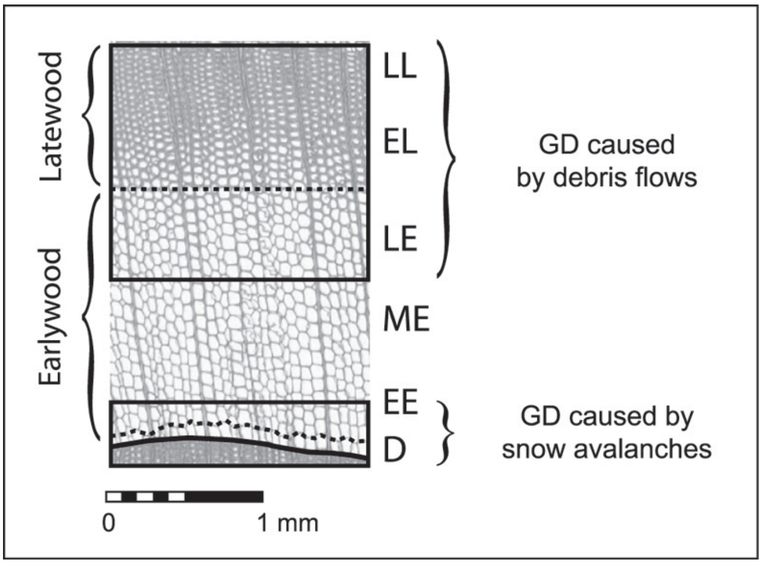

Fig. G1.3 *Growth zones within a Larix decidua tree ring and seasonal timing of debris-flow and snow avalanche events at Birchbach cone.*

al. (2005a), analysis was exclusively based on the intra-annual position of callus tissue (i.e. scars) and TRD, as other types of growth disturbances such as abrupt changes in growth or reaction wood can only be allocated within the growth ring with difficulty, or may even occur in the outer part of the tree ring of the year following an event. Figure G1.3 shows that TRD identified at the beginning of the tree ring were attributed to avalanche impacts caused during dormancy (D) or at the very beginning of the growth period of trees in earliest earlywood (EE), i.e. between the end of October and early May. In contrast, TRD located in late earlywood (LE) or within latewood cell layers (i.e. early [EL], middle [ML] and late latewood [LL]) were considered the result of debris-flow activity, as these cell layers of the tree ring are locally formed between July and early October. In order to avoid misinterpretation, TRD located between EE and EL cell layers (i.e. in middle earlywood [ME]) were disregarded.

1.3.5 Spatial distribution of trees disturbed during past debris-flow and snow avalanche events

In a final analytical step, the spatial distribution of trees showing GD at identical moments was assessed. This procedure aimed at approximating the (minimum) extent of past snow avalanche events on the cone, or at determining – based on the geomorphic map of the Birchbach cone – whether debris flows used single or multiple channels during particular events. Finally, the spatial analysis of trees showing GD also served to determine the source area (i.e. torrent or avalanche track) of reconstructed debris flows and snow avalanches.

1.4 Results

1.4.1 Geomorphic mapping and identification of forms

Geomorphic mapping permitted identification of more than 220 deposits related to past debris-flow activity on the Birchbach cone. A large majority of these forms (68%) were still easily discernible in the field as (small) deposits at the edge of abandoned flow paths or as terminal lobes. In contrast, 106 deposits (34%) were either partly overgrown with low vegetation or their shape was smoothed by subsequent snow avalanches. In addition, because large parts of the cone are used as extensive pasture land (Bachmann-Voegelin, 1984), the influence of anthropogenic activity on the current appearance of forms and deposits should not be underestimated.

Similarly, geomorphic mapping produced extensive data on abandoned flow paths and levees present on the Birchbach cone. None of these forms could, however, be identified from the apex to the base of the cone, as most of the levees and channels have, again, been largely remodelled by succeeding debris-flow events, snow avalanching or anthropogenic activity. Consequently, the number of abandoned flow paths identified was limited

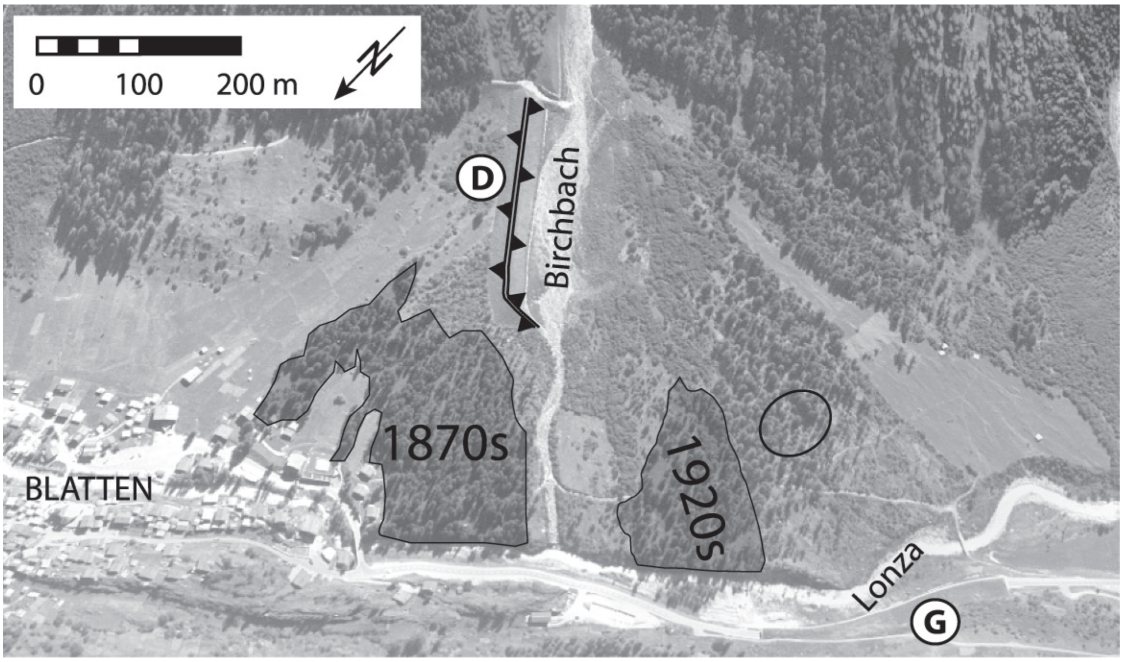

Fig. G1.4 *Age structure of stands and recolonization of selected parts of the Birchbach cone after widespread elimination of trees during major snow avalanche events. The circle indicates the area where the oldest trees were identified on the cone.*

to 18 channels with clearly visible levees over a considerably long distance on the cone.

Debris transport of snow avalanches is, by contrast, mostly limited to uprooted stems, branches or humus, while rocks and boulders are only occasionally deposited on the Birchbach cone. As a consequence, deposits of past snow avalanches were not assessed in greater detail.

1.4.2 Age structure of the stand

Data on the pith age at breast height indicate that the 251 *Larix decidua* and *Picea abies* trees growing on the Birchbach cone are, on average, 105 years old. While the oldest tree selected for analysis attained sampling height in AD 1660, the youngest sample only reached breast height in 1993. As can be seen from Figure G1.4, the age of trees as well as their spatial distribution on the cone

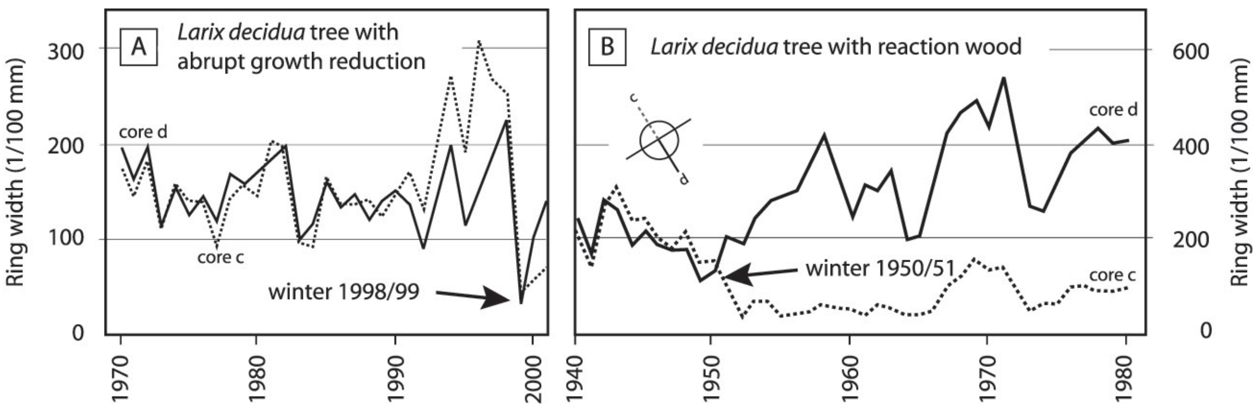

Fig. G1.5 *(A) Short, but abrupt growth reduction occurring as a result of damage caused during an avalanche in winter 1998/99; (B) After the tilting of the stem due to an avalanche in winter 1950/51, this tree started to produce reaction wood on the downslope side of the trunk (core d), whereas increment slightly dropped in core c (raw data:* Hassler*, 2004).*

suggest that parts of the stand must have been eliminated through large snow avalanches, resulting in a relatively homogenous age structure in the trees located northeast of the recently built protection dam or southwest of the current flow path of the Birchbach torrent. According to tree-ring data, seedlings started to recolonize the cone in these two areas in the 1870s and 1920s, respectively.

Figure G1.4 also indicates that the oldest trees can, in contrast, be found near the walking track crossing the cone, where they seem to be reasonably well protected from repeated debris-flow and snow avalanche activity.

1.4.3 Growth disturbances in trees and their seasonal timing

The 251 Larix decidua and Picea abies trees chosen for analysis permitted identification of 561 growth disturbances (GD). Most often, rows of traumatic resin ducts (61%) were identified in the cores, but callus tissue (7%), reaction wood (22%), abrupt growth releases or growth reductions (10%) could be identified as well. By way of example, Figure G1.5A illustrates a short, but abrupt growth reduction occurring as a result of avalanche activity in winter 1998/99, whereas Figure G1.5B shows the presence of reaction wood (i.e. compression wood) in the downslope core of a tree tilted in winter 1950/51.

In total, the grouping of GD allowed reconstruction of 30 event years between 1750 and 2002. On average, evidence for individual debris-flow or snow avalanche events is found in five trees, while 27 GD were reconstructed for a snow avalanche event in 1999. As illustrated in Table G1.2, only one abrupt GD each was used to assess six events dated during the period 1750–1842.

Year	Trees affected	Seasonality	Process
1998/99	27	D	Snow avalanche
1992	7	ML	Debris flow
1989	3	LL	Debris flow
1983/84	6	D	Snow avalanche
1983	6	LL	Debris flow
1981/82	6	D (EE)	Snow avalanche
1979	6	ML	Debris flow
1976/77	16	D (EE)	Snow avalanche
1970	3	ML	Debris flow
1958	6	LE	Debris flow
1950/51	2	D	Snow avalanche
1944	2	LL	Debris flow
1940	2	LL	Debris flow
1928	8	EL	Debris flow
1926/27	6	D	Snow avalanche
1918/19	8	D	Snow avalanche
1915	7	EL	Debris flow
1898	6	LL	Debris flow
1894	4	LL	Debris flow
1874	3	ML	Debris flow
1855	4	EL	Debris flow
1854/55	2	D	Snow avalanche
1853	4	LL	Debris flow
1843/44	5	D	Snow avalanche
1842	1	EL	Debris flow
1833	1	ML	Debris flow
1812	1	LL	Debris flow
1790	1	LL	Debris flow
1776/77	*1*	*D (?)*	*not clear*
1756/57	*1*	*D (?)*	*not clear*

Table G1.2 *Illustration of the event years with the number of trees affected, the position of rows of traumatic resin ducts (TRD) within the tree ring (i.e. seasonality) as well as the process responsible for the damage.*

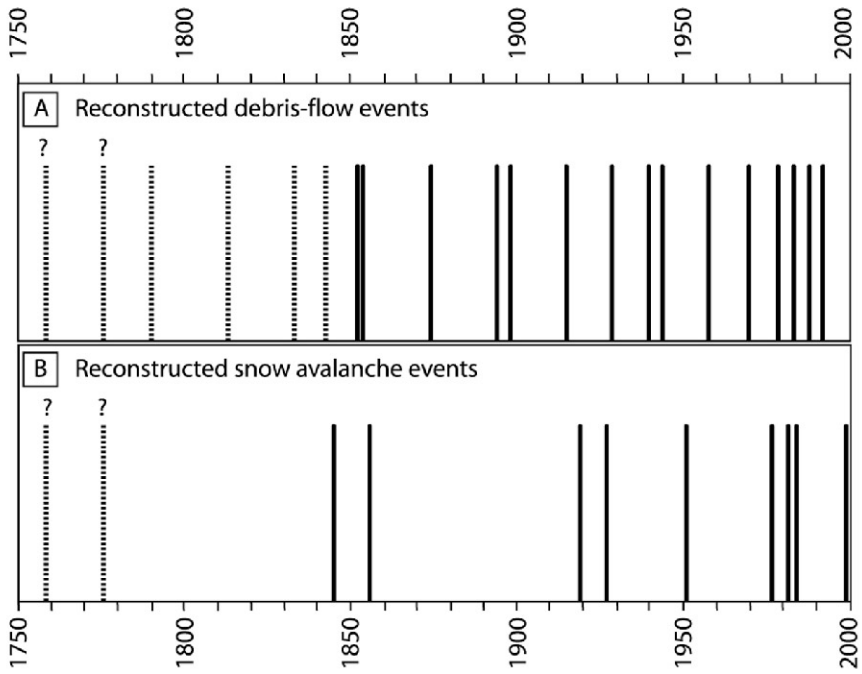

***Fig. G1.6** (A) Debris-flow and (B) snow avalanche activity reconstructed from tree-ring records of Larix decidua and Picea abies from the Birchbach cone. Dashed lines indicate past events assessed with GD in only one tree. For the event years 1756/57 and 1776/77, it is not clear whether the growth reactions were caused by debris-flow or snow avalanche activity (raw data: Hassler, 2004).*

The seasonal timing of TRD indicates that nine events (30%) occurred during the dormant season (D), leaving signs at the very beginning of the succeeding growth period of trees in earliest earlywood (EE). As the dormant season and the succeeding formation of earliest earlywood cell layers occur between the end of October and the beginning of May, we believe that the TRD associated with these nine event years are the result of past snow avalanche activity.

Table G1.2 also illustrates that in 19 event years (63%), TRD occurred in late earlywood (LE) or within latewood (L) cell layers, which are locally formed between July and early October (Fischer, 1980). This time of the year coincides with the period of local debris-flow activity.

TRD were most frequently identified within the last layers of latewood cells (LL = 30%), followed by events attributed to the segments of middle (ML = 17%) and early latewood (EL = 13%) cell layers. In contrast, only one event could be attributed to the period of late earlywood (LE = 3%) cell layers.

As illustrated in Table G1.2, a determination of seasonal timing was not possible for two event years (7%) of the 18th century. Even though the samples clearly show TRD and callus tissue at the beginning of the tree ring (EE), the signs are considered too weak to designate them as being the result of past snow avalanche activity. Consequently, the event years 1756/57 and 1776/77 are shown with a question mark and given in both the reconstructed debris-flow and snow avalanche frequencies in Figure G1.6.

1.4.4 Spatial distribution of trees disturbed during past debris-flow events

The spatial distribution of trees affected simultaneously allowed approximation of the spatial extent and the cone surface influenced by past activity as well as identification of the origin of past debris flows and snow avalanches. Figure G1.7 illustrates the spatial distribution of characteristic Birchbach debris flows. The distribution of trees affected by debris-flow activity clearly shows that signs are normally restricted to one or a few flow channels. The events reconstructed for 1928, 1915 and 1898 therefore appear to represent abnormal events, as debris-flow material was deposited in various parts of the cone. Surges apparently used or created several flow channels during these events, leaving signs in trees at different locations. Based on our data, we further suppose that debris-flow activity remained quite sparse east of the current flow path of the Birchbach torrent, where GD can only be detected in 1989 (Fig. G1.7A), 1928 and 1898. For the central part of the cone, Figure G1.7B gives the position of trees affected during the 1944 debris flow. In the north-western sector, past debris flows repeatedly caused GD to the Larix decidua

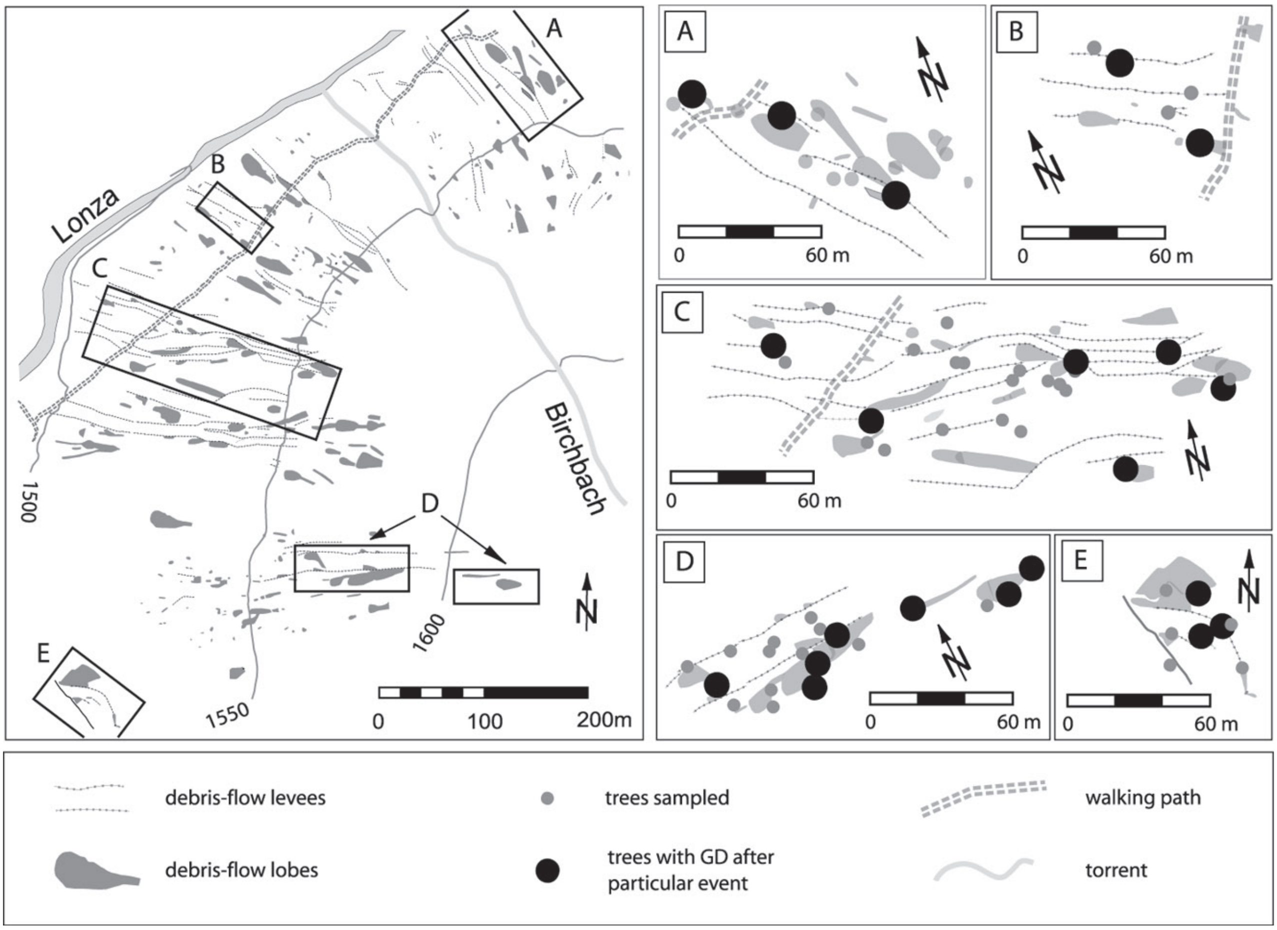

Fig. G1.7 *Spatial distribution of trees showing GD as a result of debris-flow activity (A) east of the current flow path of the Birchbach torrent (1989), (B) in the central (1944), (C) the north-western (1983) and (D) south-western (1992) parts of the Birchbach cone. Furthermore, (E) illustrates the position of three trees affected during the 1970 Nästbach debris flow.*

and Picea abies trees chosen for analysis, namely in 1983 (Fig. G1.7C), 1979, 1928, 1915, 1898, 1874, 1855, 1853, 1842, 1812 and 1790. Towards the southwestern border of the cone, GD indicate events in 1992 (Fig. G1.7D), 1958, 1940, 1915 and 1833.

Finally, the three GD reconstructed for the 1970 Nästbach debris flow illustrated in Figure G1.7E clearly show that the channels, lobes and levees identified in the westernmost edge of the cone may be the result of past debris-flow activity in either the Birchbach or Nästbach torrents.

1.4.5 Spatial distribution of past avalanches and identification of source areas

The spatial analysis of reconstructed GD attributed to the dormant season (D) and the first cell layers of early earlywood (EE) neatly shows that these reactions would, most frequently, be the result of snow avalanche activity in the 'Birchchinn' gully (see Fig. G1.2). From the nine avalanche events reconstructed on the Birchbach cone, seven would have been triggered from the northwest-facing slopes of the Bietschhorn (3934 m a.s.l.) before passing through the narrow 'Birchchinn' gully, namely in the winters 1983/84, 1981/82, 1976/77 (Fig. G1.8a), 1926/27, 1918/1919 (Fig. G1.8a), 1854/55 and 1843/44. Reconstructed data further show that during these events, major parts of the cone would have been covered with avalanche snow and a considerable number of trees affected. In contrast, the snow avalanches reconstructed for the winters 1983/84 and 1981/82, given in Figure G1.8b, appear to have been restricted to the central area of the cone, while trees located in the eastern and western parts were apparently not disturbed.

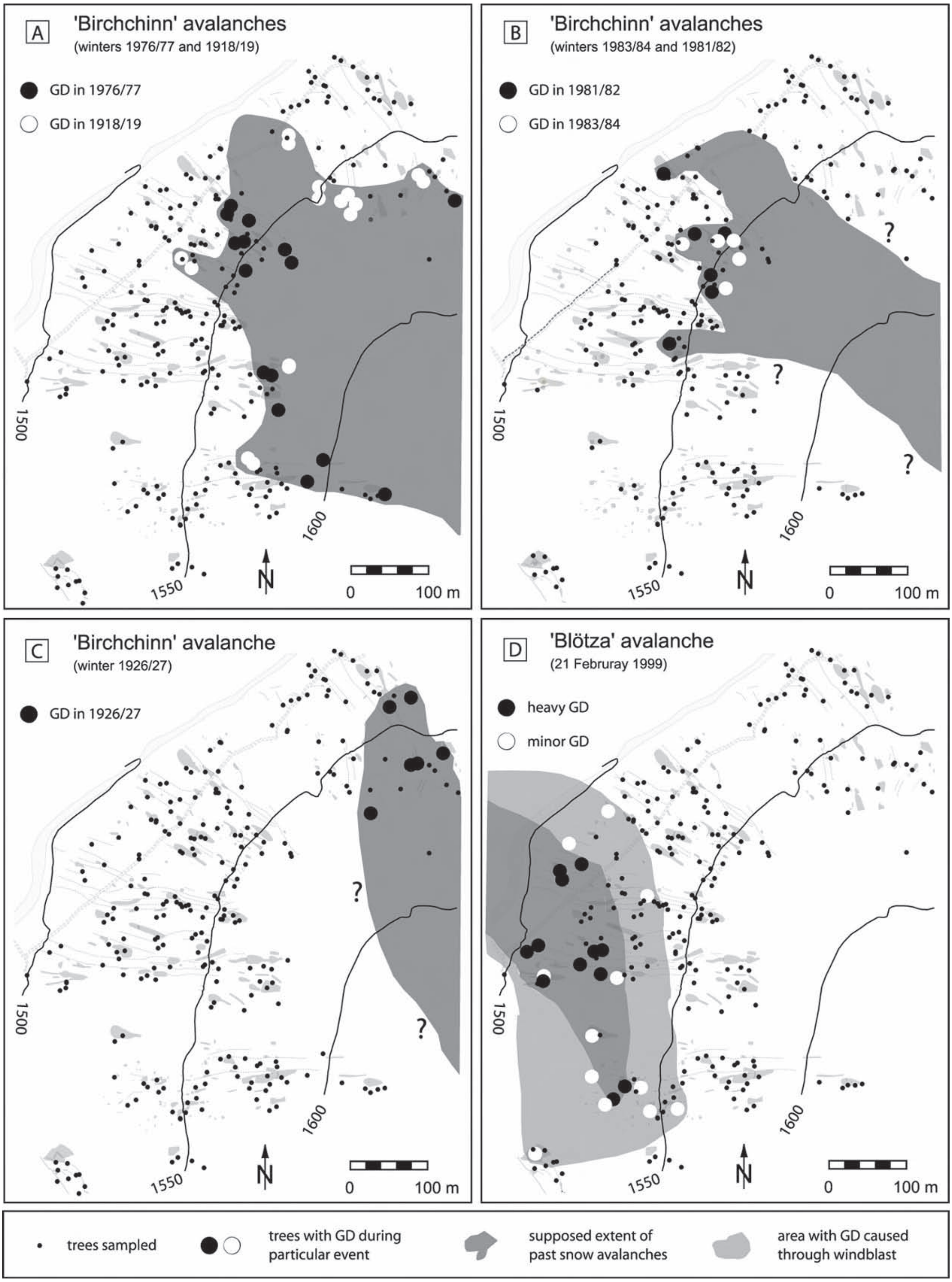

Fig. G1.8 Maps showing the distribution of trees disturbed and assumed extent of past 'Birchchinn' avalanches during (A) events affecting large parts of the Birchbach cone in 1976/77 and 1918/19, (B) comparably small events restricted to the central sector of the cone in 1983/84 and 1981/82 as well as during (C) an event presumably covering the eastern part of the slope in 1926/27. (D) Trees showing GD as a consequence of the exceptionally large 'Blötza' powder snow avalanche on February 21, 1999.

Another distribution of disturbed trees is given in Figure G1.8c, where a snow avalanche apparently caused GD to only those trees selected in the eastern part of the slope in winter 1926/27. While it is conceivable that avalanche snow would also have been deposited in the non-forested central part of the slope, dendrogeomorphological analysis indicates a complete absence of GD in the western parts of the cone.

According to our data, it also appears that past snow avalanches from the nearby 'Nästchinn' gully apparently did not cause GD in the Larix decidua and Picea abies trees selected on the cone. Nonetheless, and as observed in the winter following the sampling campaign, very large 'Nästchinn' avalanches released from the west-facing slope of the Bietschhorn summit may well disturb or even destroy trees colonizing the Birchbach cone.

Similarly, reconstructed data indicate that very large 'Blötza' avalanches descending from the southeast-facing slopes of the Tennbachhorn (see Fig. G1.1) may cause GD to the trees on the Birchbach cone as well. Figure G1.8d shows the reconstructed extent of snow masses deposited as well as the area affected by the windblast during the February 21, 1999 avalanche. Contrary to expectation, we found no evidence of former 'Blötza' events in the *Larix decidua* and *Picea abies* trees on the Birchbach cone, even though the area of possible deposition of 'Blötza' avalanche snow coincides quite well with the sector containing the oldest trees found on the cone.

Interestingly, and although dendrogeomorphological investigations allowed reconstruction of one out of five known 'Blötza' avalanches in the field, it was not possible to confirm the four snow avalanches (1808–2003) noted in chronicles (Bellwald, 2003) for the 'Birchchinn' gully.

1.5 Discussion and Conclusions

In the study we report here, dendrogeomorphology has been used to assess debris-flow and snow avalanche activity on a forested cone influenced by both processes. For the first time, an assessment of the position of rows of traumatic resin ducts (TRD) within the tree ring was used to permit attribution of tree damage to either past debris-flow or snow avalanche activity.

Tree-ring analysis of 520 increment cores sampled from 251 strongly disturbed Larix decidua and Picea abies trees allowed identification of 30 event years in the last 252 years (1750–2002). For nine of these event years, the intra-seasonal timing of TRD located within the very first cell layers of the new tree rings – which is locally formed in early May at the latest – clearly showed that signs were the consequence of past snow avalanche activity. Similarly, TRD occurring in late earlywood or latewood were found in 19 cases, indicating that damage would have been caused between July and early October and, thus, through debris flows in the Birchbach torrent. Interestingly, the seasonal timing of past debris flows as well as the great predominance of TRD within latewood cell layers widely agree with results obtained at the nearby 'Ritigraben' torrent, where dendrogeomorphological investigations suggest a peak of debris-flow activity in August and September as well (Stoffel *et al.*, 2005b).

Moreover, the complete absence of TRD identified within middle earlywood (ME) cell layers indicates that neither wet-snow avalanches very late in spring nor exceptionally early debris-flow activity at the beginning of summer occurred on the Birchbach cone during the last 250 years, thus facilitating a certain and unequivocal differentiation of past debris-flow from snow avalanche events. As documented by the snow avalanche in winter 1854/55 and a debris flow occurring in summer 1855 (see Fig. G1.6), the methodological approach introduced within this study even allows a distinction of different events occurring within the same tree ring (i.e. 1855).

While the study produced sound results on past debris flows and snow avalanches, it was also restricted by the elimination of parts of the forest stand through large snow avalanches, which led to the rather young age of trees growing on certain sectors of the Birchbach cone, averaging 105 years. Furthermore, it is possible that small debris flows remained within the flow path of the torrent without necessarily causing growth reactions in trees growing on the cone (also see Stoffel *et al.*, 2005b). Likewise, comparably small snow avalanches or events limited to the non-forested parts of the cone cannot be reconstructed with dendrogeomorphological methods. On the other hand, we also need to consider that destructive snow avalanches may not only leave easily recognisable signs (GD) in tree-ring sequences, but that they may have eliminated large parts of the forest stand at Birchbach and, therefore, blurred evidence of past events as well (Carrara, 1979; Bryant *et al.*, 1989; Schweingruber, 1996). In this sense, there seems to be evidence that tree recolonization in the north-north-western part of the slope during the 1870s (see Fig. G1.4) is the consequence of abundant tree elimination associated with the snow avalanche event in winter 1854/55. Similarly, data clearly indicate that the destructive snow avalanche – reconstructed with tree rings for the winter 1918/19 – knocked down the forest stand located in the central part of the cone. As a consequence, trees growing on the cone are much too young to show signs of, e.g., the 1808 'Birchchinn' avalanche event and the reconstructed events may only represent "minimum frequencies" of past debris-flow and snow avalanche activity.

Similarly, archival data on past snow avalanching in the 'Birchchinn' gully appear to be rather incomplete for the 19th and large parts of the 20th century, containing – most probably – only data on major destructive snow avalanches or spectacular events like the ice avalanche from the Bietschhorn slopes in December 1993. On the other hand, abundant avalanche activity with many destructive events in late February 1999 apparently led to increased avalanche awareness, giving even small and non-destructive snow avalanches access to the database in the years 2000 to 2003 (Bellwald, 2003).

Moreover, matches between archival information and reconstructed snow avalanches can be improved considerably if avalanching in other gullies within the Lötschental valley is taken into account as well: we are thus able to identify analogues for our reconstructed 'Birchchinn' avalanches in 1983/84, 1981/82, 1926/27 or 1918/19.

Interestingly, the huge 'Blötza' powder snow avalanche in 1999 apparently represents the only event from the northeast-facing slope that would have crossed the Lonza river and reached the cone on the opposite valley slope. Even though we have to admit that the 1999 avalanche has – probably – to be seen as one of the major events for this avalanche track, we nonetheless suppose that the recent construction of the road gallery illustrated in Figure G1.2 would have made it much easier for snow masses to pass over the Lonza river and, as a consequence, to cause damage to trees on the Birchbach cone.

We conclude that the approach outlined in this study proved to be a useful tool for analysing past debris flows and snow avalanches on forested cones affected by both processes. The results presented also show that dendrogeomorphological analysis of TRD clearly has the potential to allow distinction of past debris-flow from snow avalanche events. Nonetheless, replicate studies are needed to further refine the methods used within this study or to focus on wood-anatomical changes occurring with these events in greater detail. Lastly, future studies should try to identify anatomical differences related to geomorphic processes, so as to allow differentiation of events that might occur simultaneously, such as rockfall and snow avalanches (Jomelli & Francou, 2000).

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*****

Appendix 2

Some illustrations on the study site as well on trees and stem discs analyzed for the publication «Traumatic resin ducts in *Larix decidua* stems impacted by debris-flows» presented in Chapter B of this thesis.

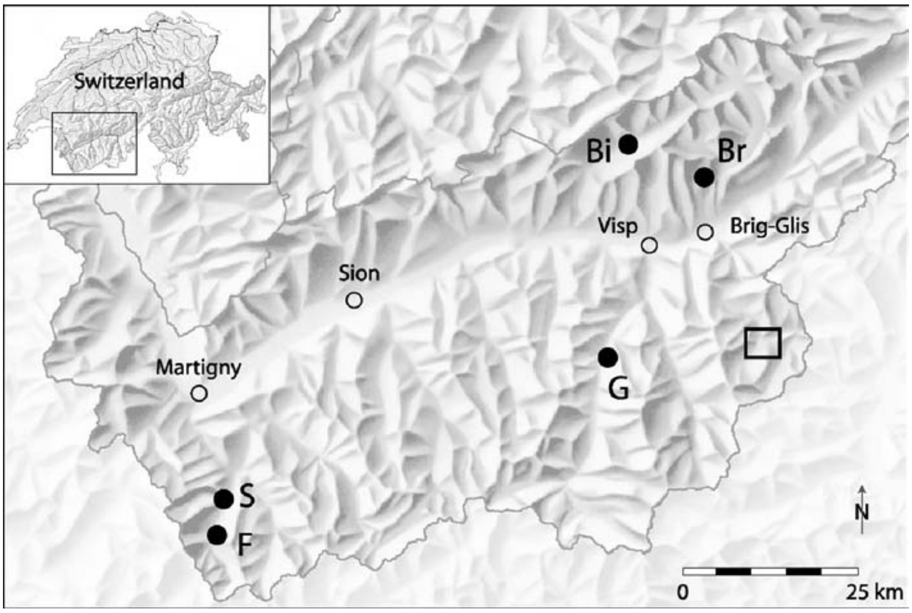
2.1 Study sites

Top

The trees presented in Chapter B were collected south of the Simplon Pass. The black rectangle on the map represents the area illustrated in the image below (map © 2007 Swisstopo).

Bottom

Satellite image of the Feergraben and part of the Laggina catchments. Trees analyzed in Chapter B originate from the fluvial terrace indicated with a red oval (satellite image: © 2007, CNES / Spot image).


Switzerland
Bi
Br
Visp
Brig-Glis
Sion
Martigny
G
S
F
N
0
25 km


Chrummbach
Doveria
Feergraben
Laggina

Top

Channel of the Feergraben (photo courtesy of Michael Graupner, used with permission).

Center

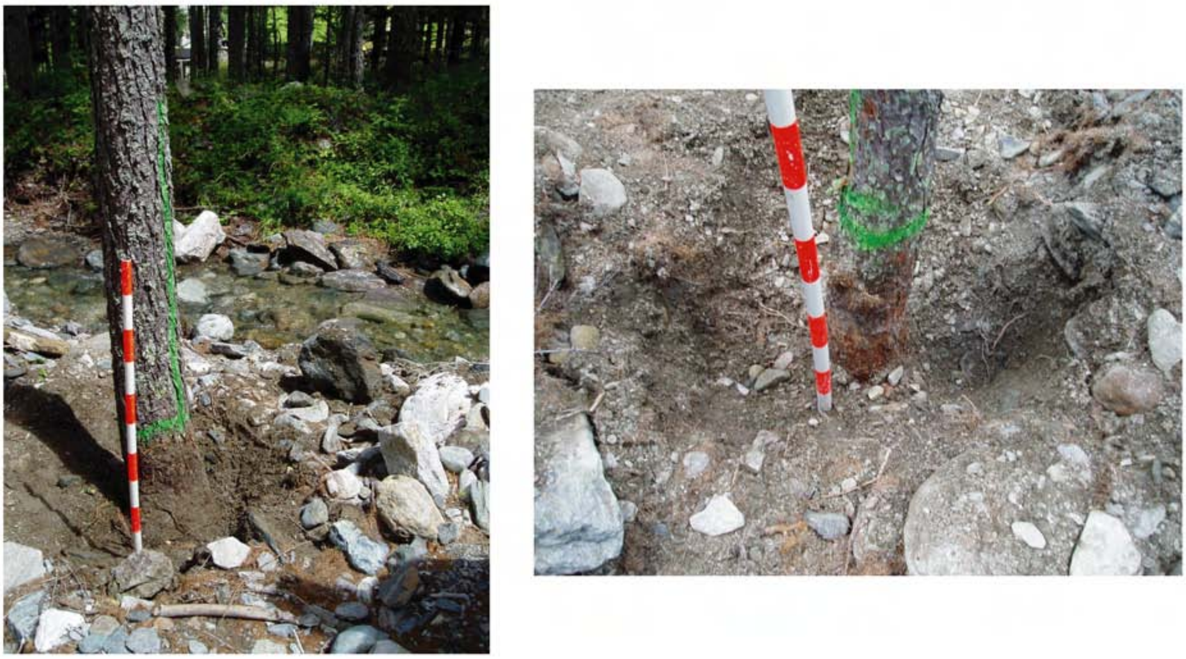
Bank erosion at Feergraben (photo courtesy of Michael Graupner, used with permission).

Bottom

Channel of the Feergraben in the upper part of the catchment (photo courtesy of Michael Graupner, used with permission).

2.2 Illustrations of the *Larix decidua* Mill. trees selected for analysis

Tree no. I



Tree no. II

Tree no. III

Tree no. IV

Tree no. V

Tree no. VI (right) and VII (left)

Tree no. VIII

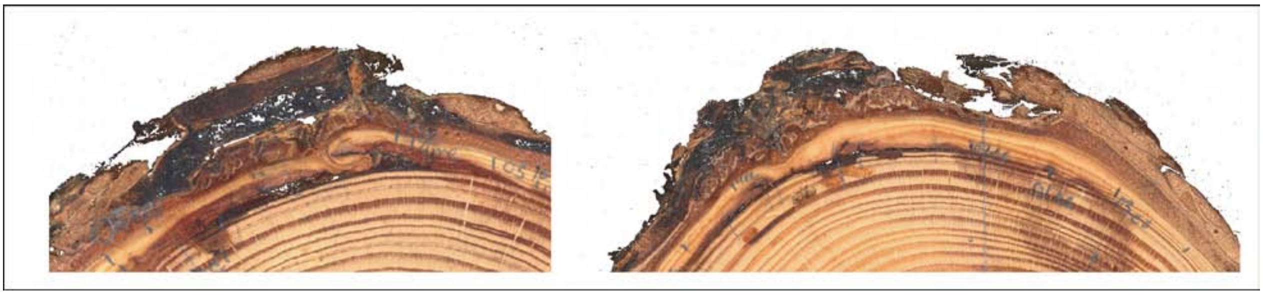
2.3 Illustrations of characteristic stem discs

Tree no. I (Ø max. 25.5 cm)

Tree no. II (Ø max. 12.5 cm)

Tree no. III (Ø max. 11.5 cm)

Tree no. IV (Ø max. 9 cm)



Tree no. V (Ø max. 18 cm)

Tree no. VI (Ø max. 13 cm)

Tree no. VII (Ø max. 6 cm)

Tree no. VIII (Ø max. 17.5 cm)

*****

Appendix 3

In this Chapter, satellite images of the study sites described in Chapters B, C, D and E are provided. Pictures of the catchment areas, the channel and the deposition cone illustrate the characteristics of the different sites.

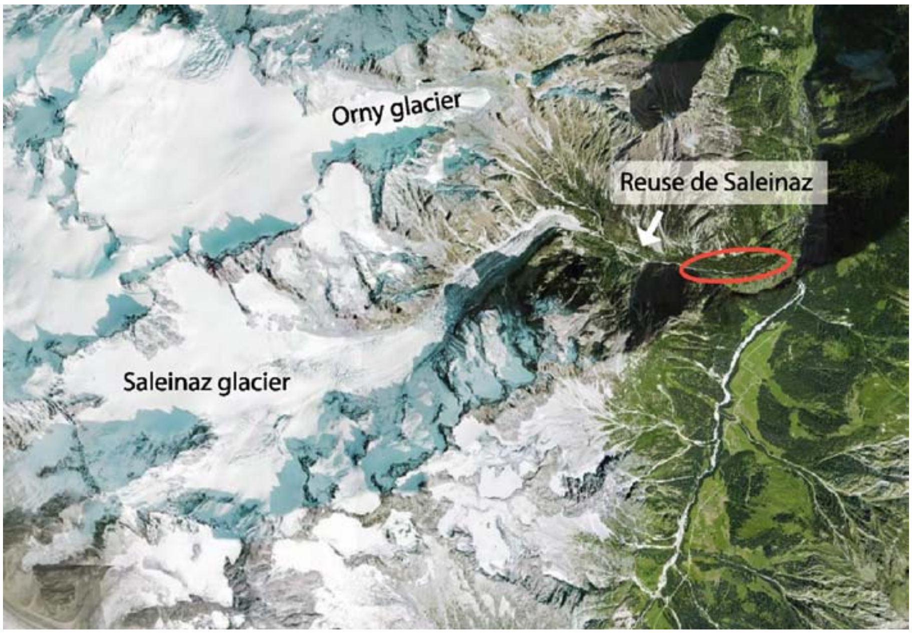
3.1 Reuse de Saleinaz (Praz de Fort, Orsières)

Top

Satellite image of the Reuse de Saleinaz catchment. The forest analyzed in Chapter C is indicated with a red oval (Satellite image: © 2007 CNES, Spot image).

Bottom

Upper part of the Reuse de Saleinaz catchment as seen from the opposite slope. The torrent originates at the Saleinaz and Orny glaciers and reaches the cone after 1.5 km.


Orny glacier
Reuse de Saleinaz
Saleinaz glacier

Top left

The tongue of the Saleinaz glacier is covered with debris (photo courtesy of Sébastien Morard - all photos used are with the permission of the authors mentioned).

Top right

The Reuse de Saleinaz just subsequent to its origin in the Saleinaz glacier (photo courtesy of Sébastien Morard).

Bottom left

Confluence of meltwater from the Orny and Saleinaz glaciers. The debris-flow cone can be seen in the background (photo courtesy of Sébastien Morard).

Bottom right

Pinus sylvestris L. with a completely overgrown wound as observed in the deposits of the debris-flow cone.

Top

Lobate debris-flow deposit on the present-day cone surface.

Bottom

On the Reuse de Saleinaz cone, only a small number of levees can be observed.

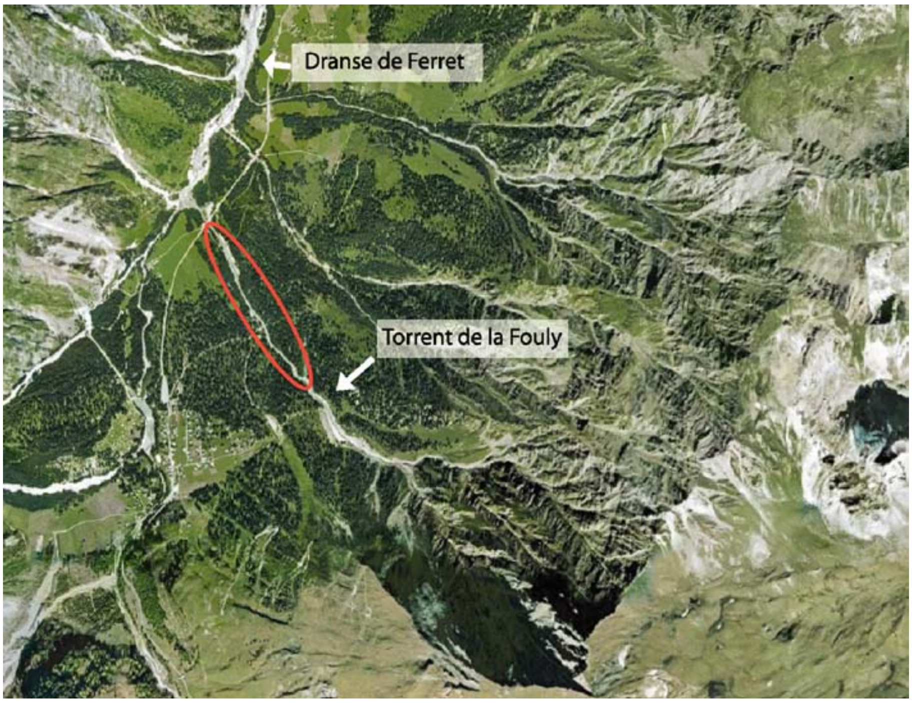
3.2 Torrent de la Fouly (La Fouly, Orsières)

Top

Satellite image of the Torrent de la Fouly catchment. The site presented in Chapter C is indicated with a red oval (satellite image: © 2007 CNES, Spot image).

Bottom

The debris-flow cone of Torrent de la Fouly as seen from the upper part of the catchment. Due to considerable logging activity, trees with obvious growth disturbances are only present along the current channel (photo courtesy of Kathrina Steffen).


Dranse de Ferret
Torrent de la Fouly

Top

The source area of Torrent de la Fouly consists of flysch, black schists, calcareous schists and quartzites (photo courtesy of Kathrina Steffen).

Bottom

View of the source area and the very short channel (250 m). Grain sizes of the heavily fractured material remain normally < 0.5m (photo courtesy of Kathrina Steffen).

Top

Debris-flow channel at the apex of the cone (photo courtesy of Kathrina Steffen).

Center

Recent debris-flow levees as observed near the apex of the cone (photo courtesy of Kathrina Steffen).

Bottom

Channel geometry on the cone. In total, 50 heavily affected trees were sampled in this sector (photo courtesy of Kathrina Steffen).

3.3 Bruchji (Blatten b. Naters, Naters)

Top

Satellite image of the lower part of the Bruchji catchment. The site presented in Chapter D is marked with a red circle (satellite image: © 2007 Digital globe).

Bottom

View of the debris-flow cone of the Bruchji torrent with the debris-retention basin and the village of Blatten b. Naters.

Top

Gneiss in the source area is heavily fractured, and material is easily eroded during rainfall and hailstorms.

Center

Rocks and boulders transported during previous debris-flow activity and deposited on the cone range in size from < 0.5 m to > 2 m.

Bottom

The banks of the current channel have been reinforced near the apex of the cone.

Top

View of the debris-retention basin with guard.

Center

On 4 July 2001, a debris flow completely filled the retention basin.

Bottom

During the event in July 2001, overbank sedimentation occurred on the road below the basin.

Top

The Bruchji torrent below the debris-retention basin as it was before the event of 4 July 2001.

Center

The Bruchji torrent below the debris-retention basin as it was after the event of 4 July 2001. Erosion in the channel caused deepening of approximately 1 m.

Bottom

Bank reinforcement near the apex of the cone was partially eroded by the debris flow.

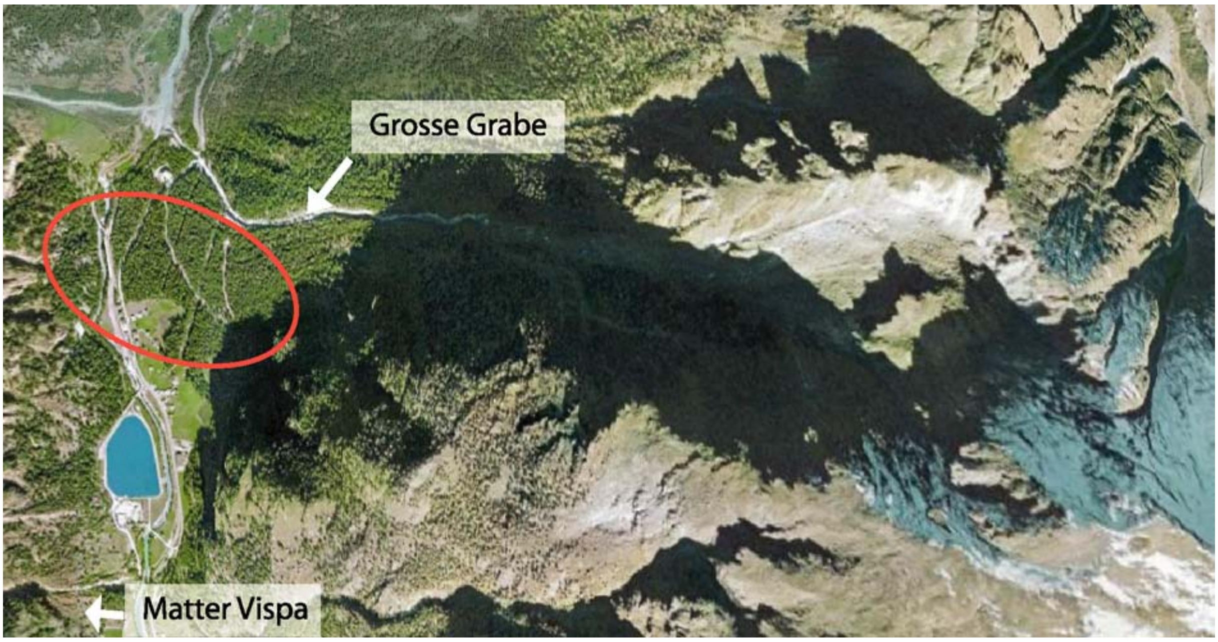
3.4 Grosse Grabe (Mattsand, St. Niklaus)

Top

Satellite image of the Grosse Grabe catchment. The site presented in Chapter E is marked with a red oval (satellite image: © 2007 Digital globe).

Bottom

Gneissic rocks of the Mischabel unit dominate the source area of the Grosse Grabe.


Grosse Grabe
Matter Vispa

Top

The currently active debris-flow channel near the apex of the cone. The largest boulders are several meters in diameter.

Center

The banks in the lower part of the cone have been reinforced, as the channel changes its direction from east-west to southeast-northwest.

Bottom

The lower part of the cone: Here, the main road tunnels underneath the channel (photo courtesy of Nathalie Chanez).

Top left

Previously active debris-flow channel as observed on the present-day cone surface.

Top right

Logging activity has been, and still is, important on the Grosse Grabe cone. Therefore, only a small number of trees was of sufficient age to show signs of past debris-flow activity.

Bottom left

Larix decidua Mill. injured by a debris-flow surge.

Bottom right

Front of a debris-flow lobe deposited against this *Larix decidua* Mill. trunk during an event in 1917. After tilting, the tree produced compression wood on the downslope side to regain its vertical position.

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Curriculum vitae

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1985-1991	Primary school in Unterägeri, ZG
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1998-2003	Studies of Geography at the Department of Geosciences, University of Fribourg Major Field Geography, Minor Fields Geology, Biology and Environmental Sciences
2003	Diploma in Geography Diploma thesis (MSc thesis): “Frequenzanalyse von Murgangereignissen anhand dendrogeomorphologischer Methoden – Murkegel Bruchji, Blatten bei Naters, Wallis, Schweiz“ under the supervision of Prof. M. Monbaron
2003-2007	Diploma assistant and PhD student, Groupe de Recherches en Géomorphologie (Prof. M. Monbaron), Department of Geosciences, Geography, University of Fribourg (teaching and coaching of students within the scope of their BSc, MSc and diploma theses, organization of excursions and fieldtrips).

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