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Tree Rings and Natural Hazards

A State-of-the-Art

Springer

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Cover illustration: Front cover (top to bottom): New leaders formed in tilted sub-alpine fir after snow avalanche impact (© BH Luckman); European larch destroyed by rockfall (© DM Schneuwly); Cross-section of a freshly cut European larch stem with multiple injuries (© M Stoffel); microsection of a European larch tree-ring with tangential rows of traumatic resin ducts (© M Bollschweiler). Back cover: European larch tilted by snow pressure (© M Bollschweiler).

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To our families for their understanding
and support during our absences over
many field seasons

Foreword

Dendrogeomorphology Beginnings and Futures: A Personal Reminiscence

My early forays into **dendrogeomorphology** occurred long before I even knew what that word meant. I was working as a young geoscientist in the 1960s and early 1970s on a problem with slope movements and deformed vegetation. At the same time, unknown to me, Jouko Alestalo in Finland was doing something similar. Both of us had seen that trees which produced annual growth rings were reacting to geomorphic processes resulting in changes in their internal and external growth patterns. Dendroclimatology was an already well established field, but the reactions of trees to other environmental processes were far less well understood in the 1960s. It was Alestalo (1971) who first used the term, *dendrogeomorphology.* In the early 1970s, I could see that active slope-movement processes were affecting the growth of trees in diverse ways at certain localities. I wanted to learn more about those processes and try to extract a long-term chronology of movement from the highly diverse ring patterns.

As a graduate student in Utah I was encouraged to gain expertise in disciplines outside geology and geography with which I was comfortable. All non-biology majors in the botany course did term papers that combined some aspect of plants with their main disciplines. I wrote an original paper on plants as **geoindicators**, mainly because I had discovered in my readings that some endemic species only occur in soils developed from certain lithologies. That choice of botanical **geoindicators** as a term-paper eventually opened doors I had never dreamed of and exposed me to a diverse literature that I would normally never have read. In this research I discovered a few early papers on various surficial processes that had been studied in some fashion through use of plants. A decade later, when studying ice- and water-driven slope failures on mountain slopes in Utah, I found a slope covered with distorted trees and remembered that term paper. Then, upon trying to cut down one of the inclined trees, my small camp saw stuck irretrievably in its dense reaction wood. This annoying event wonderfully focused my mind upon the solution to two problems; how to extract my saw and how to find out what had happened to distort those trees into curved trunks, even into corkscrew spirals. We later discovered that the geotrophic growth response in these trees curved them ever upward as they were slowly rotating as they simultaneously tipped over and were carried downslope. I needed some way to assess these processes quantitatively.

Searching the literature anew, I discovered the work of the Tree-Ring Laboratory at the University of Arizona. Discussion of my samples with Val Lamarche, Wes Ferguson and Hal Fritts convinced me that it should be possible to obtain a chronology of slope movements from my tree-ring data, although it certainly could not simply be by using simple ring-width measurements. These scientists impressed upon me the complexity of extraneous factors that can affect tree growth, and the need to identify and differentiate the desired 'signal' from the profuse 'noise'. Fritts' (1976) five basic concepts of dendrochronology became my mantra, especially the fact that robust replication was essential. Ferguson, LaMarche, and Fritts sent me home to renew my efforts on better understanding how the trees reacted to the disturbance of the soil in which they were rooted. Little by little, after examining many cores and cross sections, I saw a way to extract the particular signal I was interested in from the enormous clutter of other irrelevant tree-ring data. The event-response methodology (Shroder 1978, 1980; Giardino et al. 1984) of tree-ring dating and geomorphology emerged from this work.

In Tucson I had met Gordon Jacoby when he was working on detecting past seismicity from tree-rings and he later invited me to give a keynote presentation on dendrogeomorphology at the International Tree-Ring Conference in Tarrytown in 1986. At the same time, when he was my student, David Butler and I (Fig. 1) had frequently discussed the problems with missing and interannular ('false') rings that gave dubious chronologies to the uninitiated. I was especially concerned with published work that took unreplicated ring counts as gospel and uncritically accepted chronologies with little thought as to whether or not the ring count was correct. I had encountered this problem in New Zealand with Val LaMarche in 1974 where I tried unsuccessfully to extract the timing of debris-flow events from roots of the Southern Hemisphere silver beech (*Nothofagus menziesii*). Back in Nebraska my students and I encountered similar lack of replication in dating the roots of Ponderosa pine (*Pinus ponderosa*) in gullies in the Nebraska panhandle. Clearly more work was required. Apparently the conversion of rootwood to stemwood and development of a new callus margin over corrosion scars as roots are exposed was not straightforward. Perhaps some species reacted in predictable fashions and on an annual basis, and others did not. Interannular rings or missing rings in disturbed roots remain a significant problem that continues to need attention. Great care and rigorous replication were indicated then and are still just as important. With those experiences in mind, David Butler and I wrote the paper for Jacoby's conference (Shroder and Butler 1987).

Off and on over the next two decades I periodically revived my interest, read the newest literature, got out my increment borers, and taught my students a few old and new tricks of the trade. Avalanche-stricken trees and landslides in the La Sal Mountains of Utah (Shroder and Sewell 1985), landslides on the Pierre Shale of north-central Nebraska, conifer germination on the landforms of the Himalaya (Shroder and Bishop 1995), trees falling on railroad rights of way, terracette development in the Loess Hills of Iowa; all were fair game and chronologies were developed.

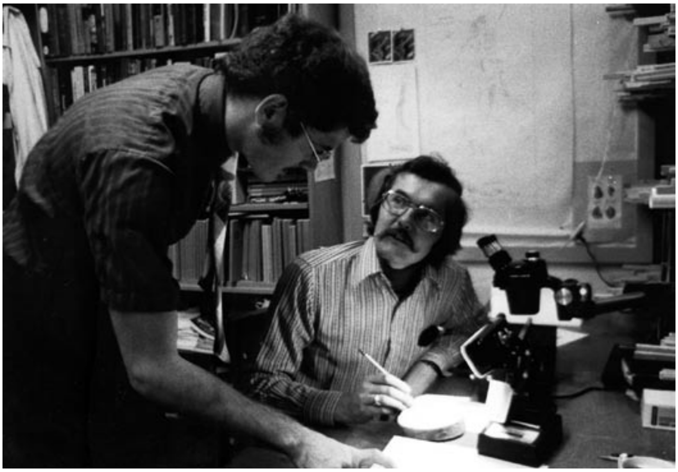

Fig. 1 Jack Shroder (seated) at the University of Nebraska at Omaha in the middle 1970s explaining some of the principles of dendrogeomorphology to David Butler while he was a student. The cross-cut tree-trunk section that Shroder is pointing to was sampled from a tree knocked flat by rapid-wet debris-flow that occurred some decades previously in the High Plateaus of Utah. Such cross sections were easy to use to explain basic principles to new students, but the preferred method of data collection was from the many multiple cores stacked on the shelves to the right, mainly because fewer trees were killed in the process of data collection

It is gratifying over these past years to see the field develop so robustly, especially when I remember sterile arguments as to whether dendrogeomorphology should ever be included in geography or geology! I considered such stultifying disciplinary debates irrelevant – all that mattered was that the science was solid and the dendrogeomorphic investigations were productive. In recent decades tree-ring laboratories have sprung up in universities across the world, the methods of dendrochronology and dendrogeomorphology have continued to be refined and real progress is being made on the use of tree-ring dating to study various environmental problems. A glance at the internet or Henri Grissino-Mayer's "Ultimate Tree-Ring Pages" certainly shows abundant new publications and on-going projects. I must admit that I am proud to have had a small part in the beginnings of this tree-ring endeavor and was humbled to be offered the opportunity to reflect upon that fact.

The science of dendrogeomorphology has come a long way in the past half century, and as long as sufficient care is used in the future assembly of tree-ring based chronologies of surficial processes and natural hazards, the methodology should continue to be a useful procedure in our geo-toolkits. Nonetheless, strong attention to the principles of Fritts (1976), especially cross dating and replication, are as germane now as they were decades ago. This new volume on **Tree Rings and Natural Hazards** contributes essential studies to ongoing hazard problems that continue to plague so many people worldwide. The history and periodicities of natural processes are critical, necessary data to reduce and evaluate future hazard.

In the absence of documentary records, relevant periodicities are best established from tree rings and this book presents studies of some of those periodicities and possibilities. This assembly of a critical collection of classic and ongoing tree-ring studies offers a wide range of examples of the study of natural hazards and possible applications to solutions to the management of those hazards.

Omaha, NE John (Jack) F. Shroder, Jr.

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Part I
Tree Rings and Natural Hazards – An Introduction

European larch (*Larix decidua*) destroyed by rockfall (© D. M. Schneuwly)

Tree Rings and Natural Hazards: An Introduction

Markus Stoffel, Michelle Bollschweiler, David R. Butler, and Brian H. Luckman

1 Introduction

Each year, natural disasters claim thousands of lives and lead to economic losses of several billion US dollars worldwide. In 2008, natural disasters caused 240,500 fatalities and losses of more than US$250 billion (SwissRe 2009), making it one of the largest annual amounts ever recorded. More than 90% of people killed by catastrophic events in 2008 were during two tropical cyclones (Myanmar and Philippines) and the 7.9 moment-magnitude earthquake hitting China's Sichuan region in May 2008 (Rodriguez et al. 2009). In February 2009, severe bush fires destroyed several villages in Victoria (Australia), killing more than 90 people and leaving 700 houses in ashes (Shaban 2009).

The aim of this book is to demonstrate how tree-ring studies can further our understanding of the nature, magnitude and frequency of more frequent, smaller scale natural hazards. Although they have less spectacular impacts, floods, windstorms, volcanic eruptions, landslides, rockfall, debris flows and snow avalanches have contributed to more than 10% of hazard-related deaths over the twentieth century (e.g., Wisner et al. 2003; EMDAT 2009; Rodriguez et al. 2009). As small disasters are by

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definition, more frequent than mega-events, we may be able to appreciate and examine their causes, frequency and magnitude, in both space and time (including the potential impacts of future climatic changes) and, thereby, develop a better understanding of these hazards and possibly mitigate future impacts.

A major key to the assessment of ongoing hazard is the documentation of the number and size of past events at a site. In many cases, because of the absence of documentary records, this information must be developed from natural archives or "silent witnesses" (Aulitzky 1992) that remain in the landscape after the event. In addition to the geomorphic or sedimentological evidence, key information is required on the dating and history of past events. The significant contribution of tree rings to these endeavors lies in their capacity to both preserve evidence of past events and to provide critical information on their dating with annual or sub-annual resolution. Therefore, in many climates, the tree-ring record may represent the most valuable and precise natural archive for the reconstruction and understanding of past events over the last several centuries. This book will illustrate how tree-ring analysis has been used to reconstruct natural hazards and provide information that may be used to understand potential future incidence of these events.

The book offers an overview of tree-ring based reconstructions of natural hazards that result from mass-movements, water, weather and fire. This introduction provides a brief background to hazard and disaster research and outlines the impact of these events on tree morphology, tree growth and wood anatomy. It clarifies the approaches used for the tree-ring reconstruction of past events and suggests standards and definitions. It also offers an overview of state-of-the-art principles of dendrogeomorphology and a short illustration of recent methodological developments.

2 Natural Hazards, Disasters and Risk: Some Definitions

The contributions in this edited book will deal with different types of natural hazards and the description of applications of tree rings to studies of past events. In addition, terms like risk, frequency, magnitude, recurrence intervals or return periods will be used by the authors and therefore deserve a short description here.

1. A **natural hazard** is a natural process or phenomenon that may result in the loss of life, injury or health impacts, property damage, livelihood, injury or health impacts, property damages, social and economic disruption, or environmental damage (UNISDR 2009, p. 9). Rodriguez et al. (2009) define five sub-groups of natural hazards: namely geophysical (i.e. earthquakes, volcanic activity, landslides, rockfall, avalanches and subsidence and other mass movements), hydrological (floods, flash floods), meteorological (tropical, extra-tropical, and local storms), climatological (extreme temperatures, drought, wildfires), and biological hazards (epidemics, insect infestation, animal stampede). This book focuses on the first three sub-groups and wildfires, but disregards biological hazards, extreme temperatures and drought.

2. A **natural disaster** represents a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts. A natural disaster may be defined as a situation where the ability of a community or society to cope using its own resources is exceeded. Disasters normally result from a combination of an existing exposure to hazard, the presence of conditions of vulnerability and insufficient capacity or measures to reduce or cope with the potential negative consequences of an event (UNISDR 2009). Other definitions stipulate quantitative thresholds for a natural event to become a disaster. For the Centre for Research on the Epidemiology of Disasters (CRED; Rodriguez et al. 2009), at least one of the following criteria must be fulfilled: ten or more people reported killed; more than 100 people reported affected; declaration of a state of emergency or a call for international assistance.
3. The term **risk** describes the probability of an event and its negative consequences (UNISDR 2009). In contrast to popular usage, the emphasis of the word “risk” is not based on chance or probability in technical settings, but on the consequences, i.e. potential losses for a particular reason, location or time.

Natural hazard events can be characterized by their magnitude or intensity, their frequency, speed of onset, duration, and areal extent. The number of occurrences per unit time is often described as **frequency** or **temporal frequency**. The size or intensity of an event is defined as **magnitude**, allowing for a differentiation of larger from smaller incidences of the same process at the same site. Based on the analysis of frequencies and magnitudes, **return periods** – also known as **recurrence intervals** – can be derived. They represent an estimate of the average interval of time between events of a certain intensity or size. They are statistical measurements denoting the average number of occurrences relative to a period of time or number of observations (Wolman and Miller 1960).

3 Tree Rings and Natural Hazards

3.1 Basic Patterns of Tree Growth

Dendrochronology depends on the fact that trees growing in areas with strong seasonal climates can form distinct annual growth rings. In conifers (*gymnosperms*), reproductive cambium cells form large, thin-walled earlywood tracheids during the early stages of the growing season (Camarero et al. 1998; Rigling et al. 2002), which primarily serve the transport of nutrients and water. Later in the season, smaller and denser latewood tracheids are developed. These layers are darker in appearance due to thicker cell walls and serve to increase the stability of the tree. Tissue formation in broadleaved trees (also called *angiosperms* or flowering plants) is more complex and diverse than in gymnosperms. In addition to the tracheids found in gymnosperms, the dividing cambium of broadleaved trees also produces vessels. Figure 1 illustrates the appearance of tree rings in conifers (a, b) and broadleaved trees (c, d).

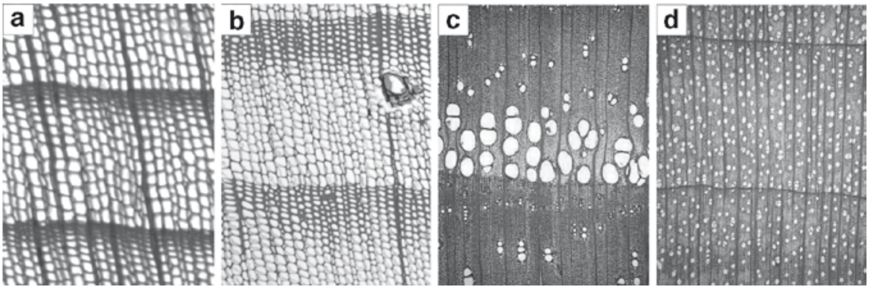

Fig. 1 Micro-sections of tree rings prepared from conifer and broadleaved trees: In (**a**) Norway spruce (*Picea abies*) and (**b**) Cembran pine (*Pinus cembra*), bands of tracheids form the individual increment rings. In broadleaved trees, tracheids and vessels are formed by the dividing cambium. Depending on the distribution of vessels in the ring, we distinguish between (**c**) ring-porous (European Ash, *Fraxinus excelsior*; photo: Schoch et al. 2004) and (**d**) diffuse-porous angiosperms (Sycamore Maple, *Acer pseudoplatanus*; photo: Schoch et al. 2004)

The width and character of each tree ring is influenced by biotic and abiotic factors. Biotic factors include the genetic makeup as well as the aging of trees and are individual for each species and each tree. Abiotic factors include a wide range of environmental factors, e.g. light, temperature, water, nutrient supply or the influence of strong wind, that are more or less common for all trees growing at a specific site (Fritts 1976). Therefore, trees growing at the same site can record the same environmental impacts and fluctuations (e.g., temperature or precipitation) in their tree-ring series. More details on tree growth can be found in Fritts (1976), Cook and Kairiukstis (1990) or Schweingruber (1996).

3.2 How Do Natural Hazards Affect Tree Growth?

In addition to site-specific information common to all trees at a location, individual trees also record the effects of mechanical disturbance caused by external processes. Trees can be injured, their trunks inclined, suffer breakage of their crown or branches, burial of the basal trunk or exposure of roots. Evidence of these events can also be recorded in individual tree-ring series. The analysis of geomorphic processes through the study of growth anomalies in tree rings is called dendrogeomorphology (Alestalo 1971). Dendrogeomorphic research is normally based on the "process–event–response" (Fig. 2) concept as defined by Shroder (1978). The "process" is represented by any geomorphic agent, e.g., debris flows or snow avalanches. Individual geomorphic "events" that affect the tree may result in range of growth "responses". These "events" and associated "responses" are illustrated in the following paragraphs.

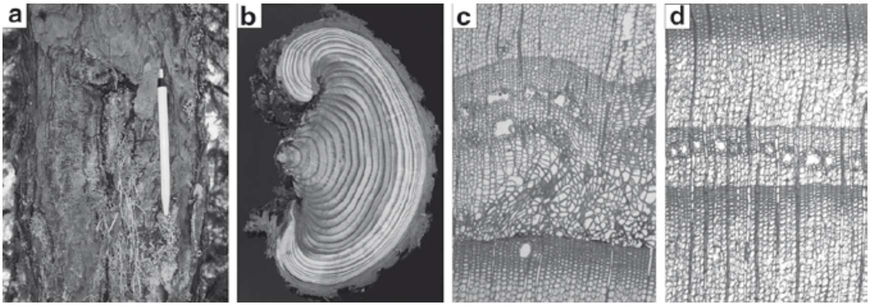

Fig. 2 Injuries in European larch (*Larix decidua*): (**a**) Injured trunk (**b**) Cross-section with overgrowth starting from the lateral edges of the injury. (**c**) Callus tissue as observed in the overgrowing cell layers bordering the injury. (**d**) Tangential row of traumatic resin ducts migrating from earlywood towards later portions of the tree ring with increasing distance from the wound (Bollschweiler 2007)

3.2.1 Wounding of Trees (Scars) and Resin-Duct Formation

Scratches on the outer bark and injuries are a very common feature in trees affected by geomorphic processes (Lundström et al. 2008). Wounds can be observed on the tree's trunk (Fig. 2a), branches or roots. When impact locally destroys the cambium, increment cell formation is disrupted and new cell formation ceases in the injured segment of the tree. In order to minimize rot and insect attacks after damage, the injured tree will (i) compartmentalize the wound (Shigo 1984) and (ii) almost immediately start production of chaotic callus tissue at the edges of the injury (Fig. 2c; Schweingruber 2001). Through the production of callus tissue, cambium cells will continuously overgrow the injury from its edges (Fig. 2b; Larson 1994; Sachs 1991) and ideally can lead to the complete closure of the wound. The extent of healing of the wound greatly depends on the annual increment rate, the age of the tree, and on the size of the scar.

Following injury, tangential rows of traumatic resin ducts (TRD) are produced in the developing secondary xylem of certain conifer species e.g., European larch (*Larix decidua*), Norway spruce (*Picea abies*) or Silver fir (*Abies alba*; Fig. 2d). They extend both tangentially and axially from the injury (Bannan 1936; Bollschweiler et al. 2008b; Nagy et al. 2000). When wounding occurs during the vegetation period of the tree, resin production will start a few days after the event and ducts emerge within 3 weeks after the disturbing event (Luchi et al. 2005; McKay et al. 2003; Ruel et al. 1998). Therefore, when analyzing cross-sections, the intra-seasonal position of the first series of TRD can be used to reconstruct previous events with monthly precision (Stoffel 2008; Stoffel and Beniston 2006; Stoffel et al. 2008; Stoffel and Hitz 2008; Stoffel et al. 2005b), provided that the incidence occurred during the vegetation period. With increasing axial and tangential distance from the impact, however, TRD tend to migrate to later portions of the tree ring, which is why intra-seasonal dating with monthly precision has to be based on a large number of samples when working with increment cores (Bollschweiler et al. 2008a; Schneuwly and Stoffel 2008a, b; Schneuwly et al. 2009). This technique cannot be used in pines as this genus does not produce traumatic and tangential rows of resin ducts: it can produce copious amounts of resin that is unrelated to mechanical wounding (Phillips and Croteau 1999).

Depending on the impact energy and the relative size of the damage, an injured tree will concentrate the formation of tree rings to those parts essential for survival and limit growth in other segments in the years succeeding the impact (Bollschweiler 2007). This may result in missing or partial rings from certain areas of the trunk.

3.2.2 Tilting of Trunks

Tilting (or inclination) of trees may result from the sudden pressure induced directly by geomorphic impacts or by the associated deposition of material (e.g., avalanche snow, debris-flow material) as well as by the slow but ongoing destabilization of a tree through landslide activity or erosion (Lundström et al. 2007, 2008). Tilted trees are common in many areas affected by geomorphic processes (Fig. 3a) and have therefore been used in many dendrogeomorphic studies to date previous events (e.g., Braam et al. 1987a, b; Casteller et al. 2007; Clague and Souther 1982; Fantucci and Sorriso-Valvo 1999).

The trunk of a tilted tree will always try to regain its vertical position. The reaction will be most clearly visible in that segment of the tree to which the center of gravity has been moved by the inclination of the stem axis (Mattheck 1993). In the tree-ring series, eccentric growth will be visible in the cross-section after a tilting event and thus allow accurate dating of the disturbance. In coniferous trees, compression wood (also known as reaction wood) will be produced on the underside of the trunk. Individual rings will be considerably larger here and slightly darker in appearance as compared to the upslope side (Fig. 3b). The difference in color is due to the much thicker and rounded cell walls of early- and latewood tracheids (Schweingruber 2001; Timell 1986; Du and Yamamoto 2007). In contrast, trunk tilting in broadleaved trees leads to the formation of tension wood (Schweingruber 1983; Schweingruber et al. 1990; Schweingruber 1996; Westing 1965) and the eccentricity will occur on the upper side facing the tilting agent. Broadleaves trees also react upon tilting with ultrastructural modifications (e.g., a gelatinous layer oriented nearly parallel to the fibre axis) that are only visible when studied on micro-sections (Pilate et al. 2004).

In addition to the formation of different types of reaction wood, trees may also respond with reduced growth after tilting (Bollschweiler 2007). It is believed that such reductions in annual tree-ring width are related to the destruction of roots resulting from the abrupt or severe tilting. It is worthwhile to note that the growth decrease will be normally less visible on the side where the reaction wood (i.e. compression or tension wood) is being formed. Figure 3c provides an example of the appearance of differing yearly increments in a *Picea abies* tree tilted by a debris flow in 1922.

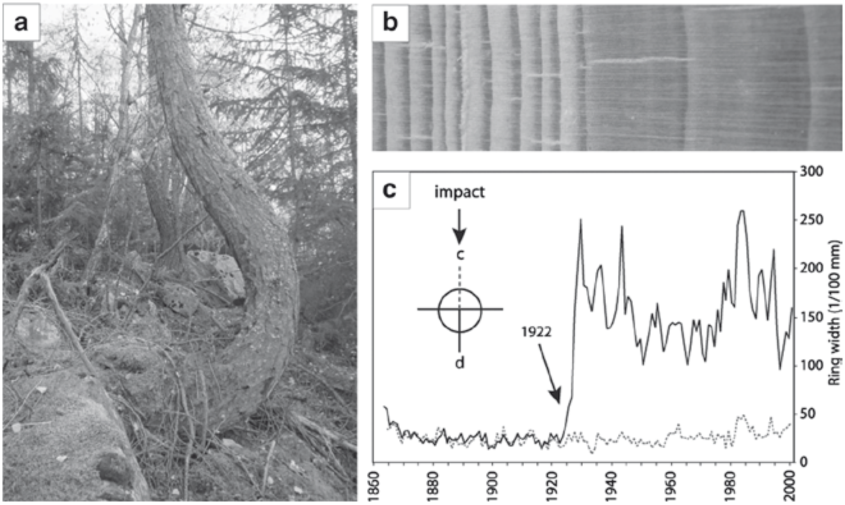

Fig. 3 (**a**) Tree morphology and (**b**) cross-sections of a tilted *Larix decidua* (D. M. Schneuwly). (**c**) Increment curves of a *Picea abies* tree tilted by a debris flow in 1922 (Stoffel et al. 2005b)

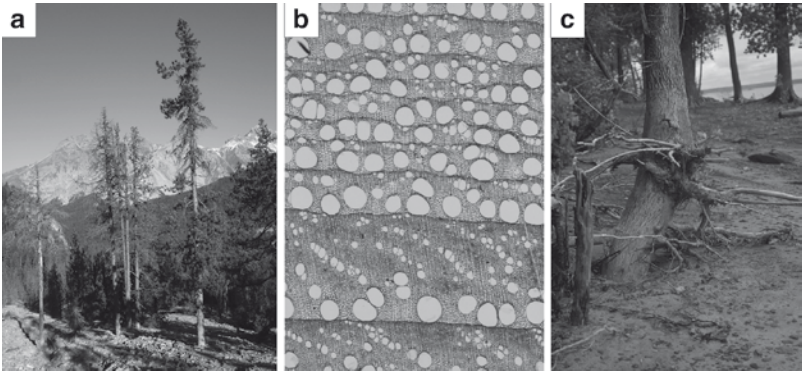

Fig. 4 (**a**) Sedimentation and subsequent die-off of trees after sedimentation. (**b**) Micro-section showing an abrupt growth decrease in Sweet Chestnut (*Castanea sativa*) following an event (F. H. Schweingruber). (**c**) Several levels of adventitious roots in Eastern Cottonwood (*Populus deltoids*) (F. H. Schweingruber)

3.2.3 Trunk Burial

Debris flows, hyperconcentrated flows, floods or landslides may bury trees by depositing material around their trunk base (Fig. 4a). Growth in these trees will normally be reduced as the supply of water and nutrients will be temporarily disrupted or at least limited (Fig. 4b; Friedman et al. 2005; Hupp et al. 1987; LaMarche 1966). Exceptionally, the burial of a trunk can cause a growth increase if the material deposited is rich in nutrients, the water supply guaranteed and the depth of the deposited material is not too important (Strunk 1995).

If trunk burial exceeds a certain threshold, trees will die from a shortage in water and nutrient supply (Fig. 4a). According to case studies from the Italian Dolomites (Strunk 1991), *Picea abies* may tolerate a maximum burial depth of 1.6–1.9 m in environments dominated by fine-grained debris flows composed of calcareous and dolomitic material (Strunk 1997). Although there are no data available for other species or lithologies, it is believed that survivable burial depths will be (much) smaller in regions where debris flows are composed of massive and large crystalline blocks.

Occasionally, buried trees produce adventitious roots close to the new ground surface (Fig. 4c; Bannan 1941). As adventitious roots are normally formed in the first years succeeding burial (Strunk 1995), the moment of root sprouting can be used for approximate dating of the sedimentation processes, as shown by e.g., Strunk (1989, 1991) or Marin and Filion (1992). When a tree has been repeatedly buried and formed several layers of adventitious roots, it is possible to estimate the thickness of sedimentation from individual events at the location of the tree (Strunk 1997).

3.2.4 Decapitation of Trees and Elimination of Branches

Bouncing rocks and boulders, debris in flowing water, debris flows and lahars or the windblast of snow avalanches may decapitate trees (Fig. 5a) or remove branches. The loss of the crown or branches is more common in bigger trees, where trunks have lost their suppleness. Apex loss has also been observed as a result of rockfall impacts close to the ground level. In such cases, the sinusoidal propagation of shockwaves in the trunk results in the break-off of the crown. This phenomenon has been described as whiplash or "hula-hoop" effect (Dorren and Berger 2006; Stoffel et al. 2005b).

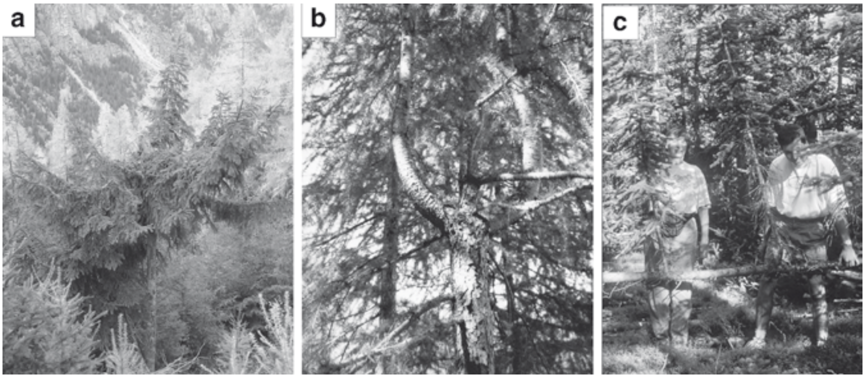

Fig. 5 (**a**) *P. abies* topped by rockfall. (**b**) Candelabra growth in *Larix decidua* following apex loss. (**c**) Engelmann Spruce (*Picea engelmannii*) with two "leaders" developed from a prostrated trunk knocked to the ground by a snow avalanche

Following decapitation, trees react with distinct radial growth suppression in the years following the impact (see Fig. 5b). One or several lateral branches will form a "leader" that replaces the broken crown, resulting in a tree morphology called "candelabra" growth (Fig. 5b; Butler and Malanson 1985; Stoffel et al. 2005c). In addition, it is not unusual that the shock of the impacting material causes injuries and provokes the formation of TRD as well (see Section 3.1). "Leaders" may also be formed from prostrated trunks knocked over by mass wasting events (Fig. 5c).

3.2.5 Root Exposure and Damage

Erosional processes and the (partial) denudation of roots may generate different growth reactions, both in the trunk and in the exposed roots. The type and intensity of the reaction(s) will depend on the nature of the erosive event, which may be instantaneous or progressive and gradual. If several roots are completely denuded during a sudden erosive event (e.g., debris flow, lahar, flood or landslide), they are no longer able to fulfill their primary functions and quickly die. The tree subsequently suffers from a shortage in water and nutrient supply, resulting in suppressed tree growth and the formation of narrow rings in the trunk (see Fig. 4b; Carrara and Carroll 1979; La Marche 1968; McAuliffe et al. 2006).

In cases where only part of a root is exposed (Fig. 6a) and its outer end remains in the ground, the root will continue to grow and fulfill its functions. In the exposed part, however, anatomical changes will occur and individual growth rings similar to those in the trunk or branches will be formed. The localization of this change in the tree-ring series may allow determination of the moment of exposure (Fig. 6b–d; see Bodoque et al. 2005; Gärtner et al. 2001). The continuous exposure of roots is usually caused by gradual processes and relatively low denudation rates, e.g. by overland

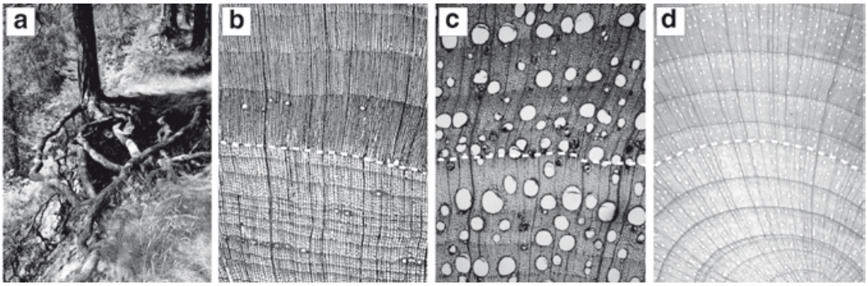

Fig. 6 (**a**) Exposed roots of Scots Pine (*Pinus sylvestris*). (**b**) Larger increment rings with distinct latewood formed in Silver fir (*Abies alba*) after sudden exposure (*dashed white line*). (**c**) Following sudden exposure, the arrangement of vessels in *Fraxinus excelsior* change from diffuse-porous to ring-porous. (**d**) In addition to cell changes, tension wood is formed in this root of *Acer pseudoplatanus* (Hitz 2008)

flow of rain water, the slow opening of cracks in soils (e.g., soil creep, landslides) and in disintegrated bedrock (e.g., preparation of rockfall, thrusts), along rivers, streams, lakes and oceans (floods, shore erosion) as well as with faulting activity and displacements in relation with earthquake activity. Provided that the roots are gradually exposed with time, it is also possible to determine the erosion rates (Carrara and Carroll 1979).

Root shearing and root damage frequently occurs in areas affected by landsliding or along earthquake faults (Allen et al. 1999; Vittoz et al. 2001). As a result of root damage, tree-ring growth will be suppressed or eventually cease (Fig. 7). Previous studies using ring-width series to determine landsliding and earthquake activity include Meisling and Sieh (1980), Lin and Lin (1998), Carrara and O'Neill (2003), or Papadopoulos et al. (2007). Rizzo and Harrington (1988) showed that periods of decreased growth of red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) trees from the northern Appalachian Mountains were significantly correlated with wind exposure and related root and crown damage variables.

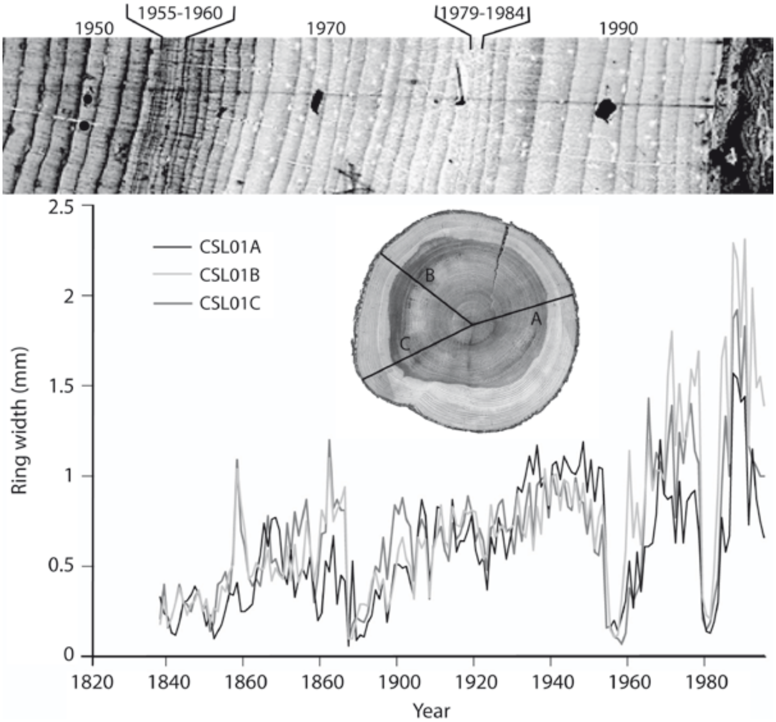

Fig. 7 Radial growth suppression caused by landsliding. This tree was growing on a slope destabilized by downwasting of Columbia Glacier, Alberta. The abrupt radial suppressions in 1887–1894, 1955–1960 and 1979–1984 are thought to result from root damage as a landslide block moved downslope three times. The tree was cut in 1996. The enlargement shows part of radius A (B.H. Luckman, unpublished data)

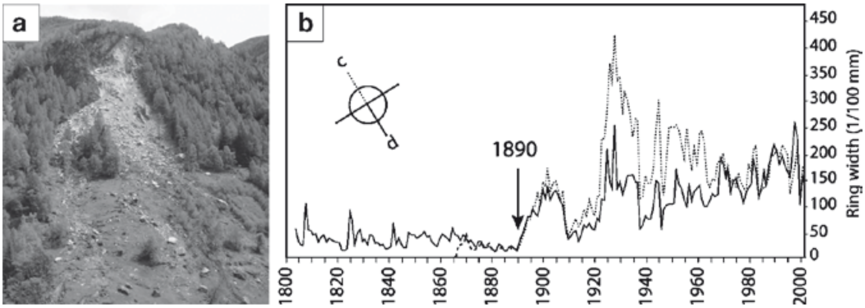

Fig. 8 (**a**) Part of this forest stand has been eliminated by a rockslide event, leaving survivor trees uninjured at both sides of the scar. (**b**) Increment curves of a survivor tree (*Larix decidua*) remaining intact after a major debris flow in 1890 (Stoffel et al. 2005b)

3.2.6 Elimination of Neighboring Trees

Geomorphic processes can also eliminate trees along channels or couloirs through uprooting and stem breakage and leave neighboring trees intact (Fig. 8a). This phenomenon can be observed with e.g., rockfalls, debris flows, lahars, extreme floods, landslides or snow avalanches (Butler 1979, 1985; Stoffel et al. 2005c).

In their new environment the uninjured survivor trees have less competition, more light, nutrients and/or water (Schweingruber 1996). As a consequence, they will start to produce larger increment rings. However, several observations indicate that this growth release in survivor trees can be delayed and therefore this reaction cannot always be used to date past destructive events with yearly precision (Fig. 8b). Nevertheless, the growth release in survivor trees can corroborate the dating of events that have been identified in other trees at the same site, e.g., from scars, tilted trunks, etc. (Stoffel et al. 2005a).

3.2.7 Colonization of Landforms After Surface-Clearing Disturbances

Many natural processes can eliminate surface vegetation including entire forest stands, leaving no direct dendrogeomorphic evidence. In such cases, germination ages of trees growing on the bare surfaces can be used to estimate the time of creation of the new landforms and/or surface-clearing disturbances to existing landforms. This approach provides a minimum age for that surface and has been used repeatedly to date landforms or assess the minimum time elapsed since the last devastating event in snow avalanche couloirs, debris-flow channels or floodplains (Bollschweiler et al. 2008a; McCarthy and Luckman 1993; Pierson 2007; Sigafoos and Hendricks 1969; Winter et al. 2002). It involves estimating the time between the exposure of the surface and the germination of the first surviving seedling on that surface. This "ecesis" estimate varies with the environment, substrate, available seed sources and several other factors. Problems of ecesis determination have been extensively discussed in studies that attempt to date the formation of glacier moraines (see Koch 2009; McCarthy and Luckman 1993) where ecesis estimates may vary from a few years to several decades.

3.3 Sampling Design and Laboratory Analyses

3.3.1 Field Approach and Sampling Design

The types of damage to trees described in the preceding section may result from a wide variety of natural processes. Linkage between the damage and the causative process depends on a critical evaluation of the sampling site. In many cases, hazard investigations are undertaken with a specific context where the process or processes involved are known and appropriate sampling methods and sampling design may be applied. These vary considerably with the nature of the process or investigation and are best discussed in the specific context of individual processes. For example, the sampling network needed to define past earthquake activity may be very different than trying to reconstruct the history of snow avalanches and debris flows on a large debris cone.

At an individual site the choice of sampling design and selection of the trees to be sampled will depend on the purpose of the investigation and the processes or hazards being sampled. The sampled area and number of trees sampled may be very small and specific e.g. on a small landslide or may involve systematic sampling of a larger area (e.g. within a large run-out zone of a snow avalanche) or target trees damaged at the margins of an event. The choice of individual trees is based on (i) an inspection of the trunk surface (i.e. does the tree show obvious signs of past disturbance?) and (ii) the location of the trees with relation to the processes/ hazards studied i.e. is the tree located on or adjacent to the area influenced by the process studied? (e.g. a debris flow levee). A detailed description on the documentation and numbering of trees in the field is provided by Stoffel et al. (2005a).

The tree-ring record of growth disturbances created by past events is analyzed with cross-sections or increment cores. Cross-sections are normally taken at the location of the growth disturbance and provide an excellent and very complete insight into the tree's history. However, in many locations (e.g. protection forests, National Parks) felling may be prohibited or ill-advised for aesthetic or safety reasons. Most tree-ring studies therefore use cores extracted with an increment borer. Grissino-Mayer (2003) provides a technical description on the correct use of increment borers. In some cases useful information may also be obtained from the analysis of cross-sections sampled from tree stumps remaining on the slopes after logging (Hughes and Brown 1992; Swetnam 1993; Stoffel and Perret 2006).

The nature of visible growth defects observed in the tree's morphology will strongly influence the sampling height, sampling directions and the minimum number of samples to be taken per tree. In trees with visible **scars**, previous geomorphic events are most easily dated through the destructive sampling of trees and the preparation of cross-sections taken at the location where the injury is largest. This approach will facilitate an accurate and intra-seasonal identification of the onset of **callus tissue** production (and **TRD** formation in certain conifer species) and therefore allows a reconstruction of the impacting event with a very high temporal resolution. Alternatively, wedges can be sawn from the overgrowing callus and an increment core extracted from the side opposite of the wound. In this case, the sampled tree will survive and a reconstruction of the wounding event will be possible. When cross-sections and wedges cannot be taken from the injured trees, at least two increment cores need to be extracted, one from the overgrowing callus and the other from the side opposite to the wound. Internal scars that have been completely healed over cannot be sampled with cores, except fortuitously. Special attention needs to be addressed to the sampling of cores from the overgrowing callus: Samples taken inside the overgrowing tissue will provide an incomplete tree-ring record, as wounds are closed from their edges. On the other hand, samples taken too far away from the callus growth will not show any signs of the disturbing event at all and thus prevent dating of the event. Figure 9 illustrates the recommended position for the extraction of increment cores in injured trees. In addition and in the case of certain conifer species, TRD formation will be delayed with increasing distance from the wound and improper core location may influence the intra-seasonal dating quality (Bollschweiler et al. 2008b; Schneuwly and Stoffel 2008b).

Tilted trunks are best analyzed with at least two increment cores extracted per tree, one in the direction of the tilting and the other on the opposite side of the trunk. The reaction wood will be visible on the tilted side in conifer trees (= compression wood) and on the side opposite to the tilting direction in the broadleaved trees (= tension wood). Individual cores are best extracted at the location where the tilting is strongest based on an outer inspection of the tree morphology.

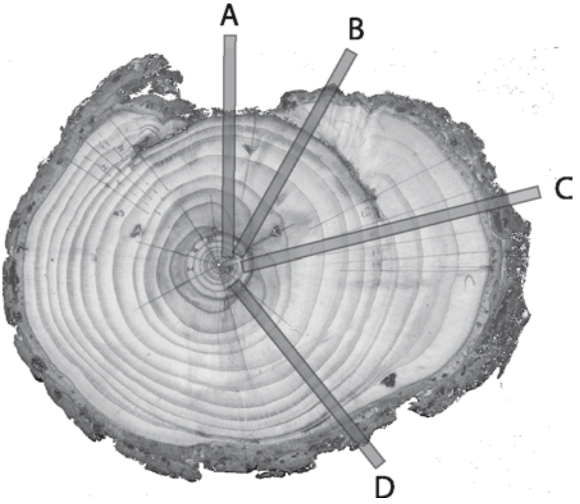

Fig. 9 When sampling injured trees, special attention needs to be addressed to the sampling position. Samples taken inside the wound (**a**) or from the overgrowing callus tissue (**b**) will provide an incomplete tree-ring record, as wounds are closed from their edges. Ideally, increment cores are extracted just next to the injury (**c**) where the presence of overgrowing callus tissue and TRD will allow accurate dating. Cores taken too far away from the wound (**d**) will not necessarily show signs of the disturbing event and thus prevent dating