TREE RINGS AND NATURAL HAZARDS: PRINCIPLES AND APPLICATIONS II

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ABSTRACT .- Tree rings and natural hazards: principles and applications. A detailed understanding of how the earth surface is being continuously shaped and why it looks the way it does are essential prerequisites for an appraisal of geomorphic processes and related changes in space and time. Data on the occurrence of past geomorphic events remains, however, scarce and predictions on how the expected climate change may affect the frequency and volume of earth-surface processes have to be based on limited datasets. Tree rings have on varied occasions proved to be a reliable tool for the acquisition of data on past events. In this paper, examples are provided on how the recurrence of events can be assessed (*how often?*) or their timing determined with yearly and sometimes even monthly precision (*when?*). Based on the mapping of trees on the study site, it is also possible to determine the reach and lateral spread of events (*how far?*). Movement rates can be reconstructed (*how fast?*) or the magnitude of incidences assessed (*how big?*). In combination with meteorological, hydrological and/or seismological data, results from tree-ring studies can be consulted to identify triggers of previous events (*why?*).

Key-wors: natural hazards, principles, applications, dendrochronology

3. Tree-ring analysis of earth-surface processes – selected applications

As shown in the previous section, trees react to the impact of geomorphic processes with different "anomalous" growth responses. Through the analysis of these reactions, the moment of the event can be determined and the recurrence of incidences accurately assessed (*how often?*). The position of the growth anomaly within the tree ring allows for an assessment of the moment of events with yearly and sometimes even with monthly precision (*when?*). Based on a mapping of geomorphic forms and trees, the reach and lateral spread of events can be

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determined (*how far?*), movement rates identified (*how fast?*) or the magnitude assessed (*how big?*). In combination with meteorological, hydrological and/or seismological data, results from tree-ring studies can be consulted to identify triggering factors of previous events (*why?*). In the following, we provide examples on how tree-ring analyses can be used for the reconstruction and the understanding of geomorphic processes and their dynamics.

3. 1. How frequently did events occur in the past?

The primary goal of most dendrogeomorphic studies usually resides in the reconstruction and assessment of temporal frequencies of past debris flows. Pioneering work in the field has been realized by Hupp (1984) or Hupp et al. (1987) documenting the past occurrence of debris flows on the slopes of Mount Shasta in California (United States). Subsequent studies were realized in North America as well, for instance by Wilkerson and Schmid (2003), who used tree rings as one of several methods to assess the frequency and magnitude of debris-flow events in Glacier NP. May and Gresswell (2004) in contrast used dendrochronology to estimate the time since the previous debris flow and therefore to calculated the rate of sediment and wood accumulation in low-order streams to understand the temporal succession of channel morphology following.

Most of the more recent research activities, however, clearly focused on the European Alps. Strunk (1989, 1991, 1995) was the pioneering researcher who used tree rings extensively to reconstruct debris-flow activity in the Italian Dolomites. Strunk also investigated the germination of adventitious roots in buried stems to reconstruct burial depths and the history of debris flows. Similarly, Baumann and Kaiser (1999) established a 500-year chronology of debris-flows on a fan in the Swiss Alps. More recently, the frequency of past events was

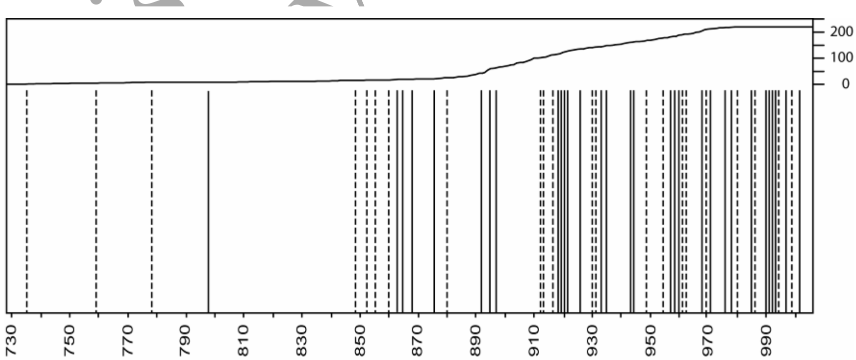

Figure 8. Reconstructed frequency of debris flows in the Geisstriftbach torrent *(Valais Alps, Switzerland; adapted from Stoffel et al. 2010b).*

reconstructed for over 30 torrents in the Alps (Bollschweiler, 2007; Bollschweiler and Stoffel, 2007; Bollschweiler et al., 2008a; Stoffel et al., 2008b). By way of example, the frequency of the Geisstriftbach torrent in the Swiss Alps is shown in Fig. 8 (Sorg et al., 2010; Stoffel et al., 2010b). On the basis of 252 disturbed *Larix decidua* and *Picea abies* trees, 53 events could be reconstructed for this torrent between A.D. 1736 and 2008, as compared to three events identified in archival records (SRCE, 2007).

Most frequently, analyses focused on the reconstruction of debris-flow activity in individual torrents, with reconstructed time series often spanning several centuries. While most reconstructions were rather based on the investigation of conifer trees, Arbellay et al. (2010) or Szymczak et al., (2010) were successful in using different species of broadleaved trees for the determination of past event years. In the recent past, the focus in frequency reconstructions shifted away from isolated at-site analyses to regional approaches covering entire valleys (Jomelli et al., 2003; Pelfini and Santilli, 2008). Such an integration of several torrents in a single reconstruction provides a much completer picture of debris-flow activity at the regional level. In addition, the large amount of data on past debris-flow events contained in regional chronologies – for instance 296 debris flows since A.D. 1850 in the case of the Zermatt valley, Swiss Alps (Bollschweiler and Stoffel, 2010) – tend to yield much clearer and univocal results. In addition and through their representation as decadal frequencies, it also becomes possible to identify changes and trends in regional debris-flow occurrences and to relate these changes to changing climatic conditions. By way of example, Fig. 9 illustrates that increased debris-flow activity in the Ritigraben – one of the torrents investigated in the Zermatt valley – became apparent after the end of the Little Ice Age around 1900(Grove, 2004) and in the early twentieth century when warm-wet conditions

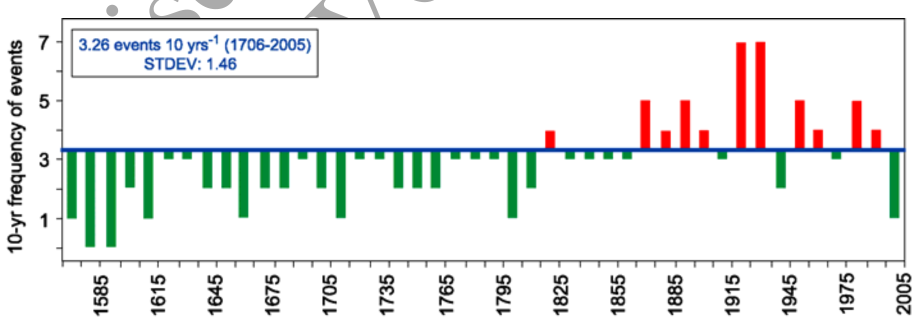

Figure 9. Reconstructed 10-year frequencies of debris-flow events between 1566 and 2005 for the Ritigraben torrent (Switzerland). Data are presented as variations from the mean decadal frequency of debris flows of the last 300 years (1706-2005), corresponding to the mean age of trees sampled. (modified from Stoffel & Beniston, 2006).

prevailed during summers in the Swiss Alps (Pfister, 1999). On the other hand, we observe a considerable decrease in debris-flow frequency over the past decades which would be the result of changes in atmospheric circulation patterns and a decrease in the frequency of triggering precipitation events (Schmidli and Frei, 2005).

The recurrence of past events can be assessed for other earth-surface processes as well, like flooding (Friedman et al., 2005; Jones et al., 1984; Shapley et al., 2005; St. George & Nielsen, 2000), snow avalanches (Boucher et al. 2003; Butler, 1979; Butler & Malanson, 1985; Butler & Sawyer, 2008; Corona et al., 2010; Muntán et al., 2004), volcanic (Yamaguchi, 1983, 1985) or rockfall activity (Fig. 10), Perret et al. 2006; Schneuwly & Stoffel, 2008a, b; Stoffel et al..,2005a, b).

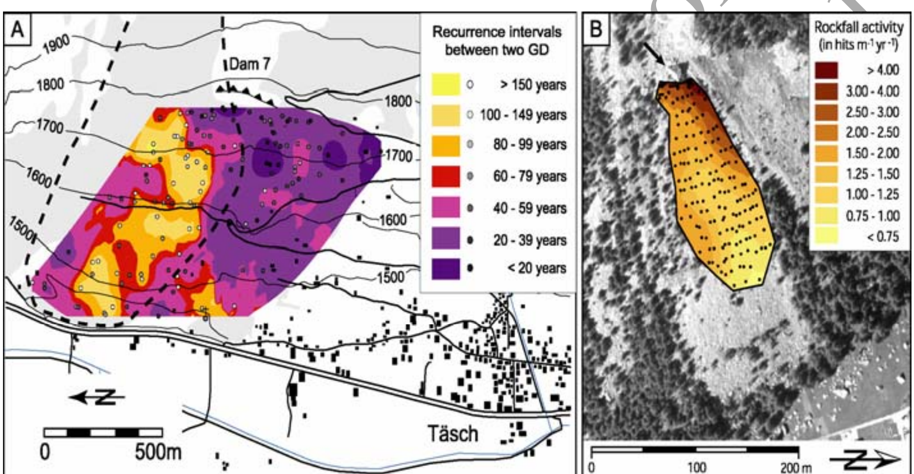

Figure 10. Rockfall activity as reconstructed from tree-ring analyses at (a) Täschgufer and (b) Schilt (both Valais Alps, Switzerland). Recurrence intervals designate the number of years passing between two reconstructed growth disturbances in a single tree (adapted from (a) Stoffel et al., 2005 b and (b) Schneuwly and Stoffel, 2008 b).

It is important to stress that tree-ring based reconstructions of past incidences provide minimum frequencies. Small-scale events occurring within channels or on slopes do not always affect trees and large-scale events may eliminate entire stands. In both cases, an exhaustive reconstruction of past incidences will not be possible.

3. 2. At what time of the year did events occur?

In temperate regions with distinct seasons, tree-ring analysis allows dating with yearly precision. Provided that data exists on the onset and timing of the local growing season of trees, the position of the growth anomaly within a tree ring can be used to refine the dating of the event. As injuries, bordering callus tissue and tangential rows of resin ducts are being produced almost immediately after an event, they allow a more accurate dating, sometimes to the degree of a monthly precision (Stoffel, 2008).

In rockfall research, the intra-seasonal dating can be used to identify periods with higher activity during the year. In the Swiss Alps, the dormant season lasting from approximately October to May has proved to be the period with the largest rockfall activity (Fig. 11; Perret et al., 2006; Schneuwly & Stoffel ,2008 a, b; Stoffel et al., 2005b). This culmination in activity during winter and spring is due to repeated and surficial freeze-thaw cycles in the rockwalls and the seasonal thawing of locally existing permafrost in April and May (Stoffel, 2006).

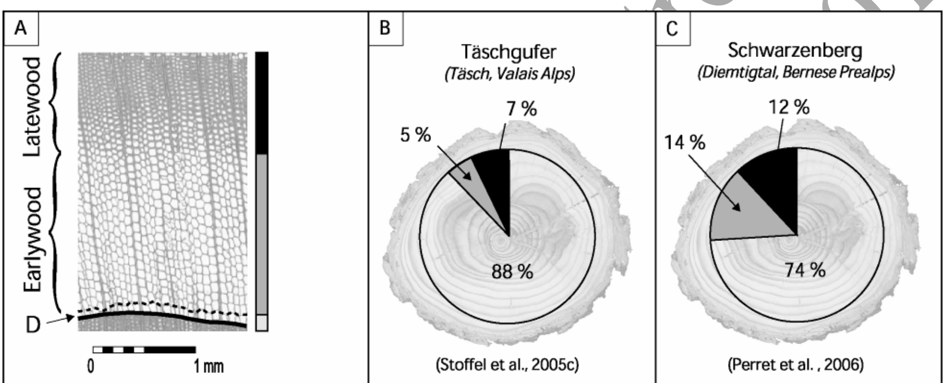

Figure 11. (a) During the period of cell growth, conifer trees first form thin-walled earlywood cells (E) before they start to produce thick-walled latewood (L) cells. At the end of the growing season, cell formation ceases and dormancy (D) sets in. The seasonal timing of rockfall activity was assessed on two different slopes in Switzerland, namely on the (b) Täschgufer (Swiss Alps) and the (c) Diemtigtal (Swiss Prealps) slopes. While permafrost exists locally at Täschgufer, seasonal frost occurs during the winter months at Diemtigtal (Stoffel 2006).

Based on the intra-annual position of injuries and bordering callus tissue in the tree ring, Kazcka et al. (2010) used 240 discs of trees impacted by a known debris-flow event in Quebec to identify the timing of growth disturbances (i.e. injuries, tangential rows of traumatic resin ducts and density fluctuations) within the tree ring. In the Swiss Alps, Stoffel et al. (2008 b) have used the intra-seasonal position of debris-flow damage in trees, local rainfall records and data on floods in neighboring catchments to reconstruct more than four centuries of debris-flow activity at Ritigraben with monthly resolution. Results of this study are illustrated in Fig. 12 and clearly demonstrate that the main debris-flow season at the study location shifted from June and July during the second half of the 19th century to August and September over the last fifty years (Stoffel & Beniston, 2006; Stoffel et al., in press).

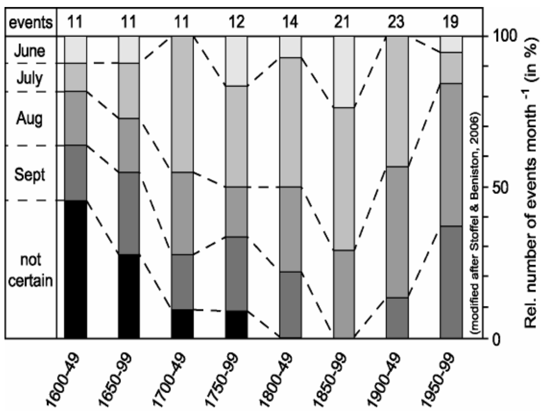

Figure 12. Seasonality (JJAS) of past debris-flow activity as inferred from the intra-annual position of tangential rows of traumatic resin ducts in the tree ring, archival data on flooding as well as meteorological data since AD 1864 (adapted from Stoffel et al. 2008).

In the French Alps, Lopez Saez et al. (in review) have recently demonstrated that dating with subannual precision is also possible for landslides and based on the analysis of compression wood formation in *Pinus nigra* stems.

Jacoby (1997) used tree rings to refine the dating of an earthquake in northwestern USA. The Cascadia earthquake was known to have occurred at the end of the seventeenth or the beginning of the eighteenth century along the Cascadia subduction zone west of Oregon and Washington as well as in northern California. However, neither radiocarbon nor other dating approaches could yield a precise year or month of the earthquake. Through the investigation of tree-ring widths and anatomical changes in the increment rings, Jacoby (1997) was able to date the event to the very restricted time slot between late 1699 and early 1700. The analysis also provided evidence that this earthquake event in North America was the cause of a tsunami recorded on 27 January 1700 in Japan (Satake et al., 1996).

3. 3. How far did past events reach?

When records on the temporal occurrence of earth-surface processes are coupled with spatial data, the reach of such processes can be determined. In particular, the application of detailed geomorphic mapping and the accurate positioning of trees considerably increase the information on the reach and spread of mass movements. For example, the spatial patterns of past debris-flow activity were reconstructed on the cone of a debris-flow torrent in the Swiss Alps, using a detailed geomorphic map (1:1000) of the debris-flow deposits and tree-ring analyses (Bollschweiler et al., 2007). The position of trees showing growth responses following an event was used to identify spatial patterns of past

Figure 13. Spatial patterns of past debris-flow events at Bruchji torrent. (A). Example for event affecting the western and central part of the cone as in 1907. (B) The event of 1980 influenced only the eastern part of the cone (adapted after Bollschweiler et al. 2007).

incidences. Examples for two different types of incidences are provided in Figure 13: Type A events affected the western and central part of the cone whereas type B events were restricted to the eastern part of the cone. From the data, a clear shift of the main channel was observed. While the main channel passed on the western part of the cone until the 1930s, it started moving its bed to its current position on the eastern part of the cone. In a similar way, spatial analysis of trees affected by a debris-flow event allows identification of outbreak locations and overbank sedimentation (Mayer et al., 2010; Sorg et al., 2010; Stoffel et al., 2008a). The definition of breakout locations and the activity of channels over the past decades and centuries receives key importance as soon as it comes to hazard assessment and risk analysis on debris-flow cones (Bollschweiler et al., 2008a).

The application of tree-ring techniques in hydrogeomorphic research has recently been expanded to include debris floods in the Austrian (Mayer et al., 2010) and hyperconcentrated flows (i.e., debris floods *sensu* Hungr et al. 2001) in the Swiss Alps (Bollschweiler et al., 2007). In the Spanish Central System, Ballesteros et al. (2010 a, b) documented flash flood signatures in riparian trees to determine the occurrence of past hydrogeomorphic events. It has been assumed in the past that the extent of disturbance by hydrogeomorphic processes to vegetation can be indicative of the energy of the water and of physical impact by materials transported by hydrogeomorphic processes (Johnson et al., 2000). Based on this assumption and on data on flash-flood frequency (Ruiz et al., 2010) and vertical distribution of impact scars on the stem surface, Ballesteros et al. (in press) were able to accurately reproduce flow heights in a two-dimensional hydraulic model and to derive data on stream power, flow velocity and discharge of past flash-flood events (Fig. 14). Similarly, growth-ring series from injured and buried trees were used at high-elevation sites in the Mexican Volcanic Belt (*c.* 3300 – 4000 m a.s.l.) to reconstruct the temporal occurrence and disturbance extent of past lahars from the Popocatépetl volcano (Bollschweiler et al., 2010).

Likewise, spatial information obtained from tree-ring records are also crucial for the reconstruction and understanding of snow avalanche activity (Boucher et al. 2003; Butler 1979, 1987; Butler & Sawyer 2008; Hebertson & Jenkins 2003). In the Spanish Pyrenees, Muntan et al. (2004; 2009) depicted the importance of tree-ring reconstructions for the determination of the spatial reach of snow avalanches. Several events were noted in the archives for the investigated avalanche path and an avalanche map was published indicating the runout zone of avalanches. Dendrogeomorphological analyses revealed, however, that a snow avalanche in winter 1971–1972 (Fig. 15) has surpassed the maximum runout distance indicated in this map by more than 200 meters (Muntan et al. 2009).

Similarly, tree rings are widely used in glacier research (dendroglaciology), where they assist the reconstruction of glacier advances and retreats through the determination of death dates of trees killed by advancingglaciers, the moment of inclination of tree stems close to a glacier or the age of successor trees colonizing the surfaces cleared by retreating glaciers (Luckman 1995, 1998, 2000; Smith & Lewis 2007). Extensive dendroglaciological investigations, coupled with radiocarbon dating as well as lichenometry (Innes 1985), have mainly been performed in North America. The spatial and temporal complexity of LIA glacier activity has been reconstructed for several regions including the Canadian Rocky Mountains (Luckman, 2000), coastal Alaska (Calkin et al., 2001; Reyes et al., 2006) and more recently for the Coast Mountains of British Columbia (Allen & Smith, 2007; Larocque & Smith, 2003; Lewis & Smith ,2004; Smith & Desloges, 2000).

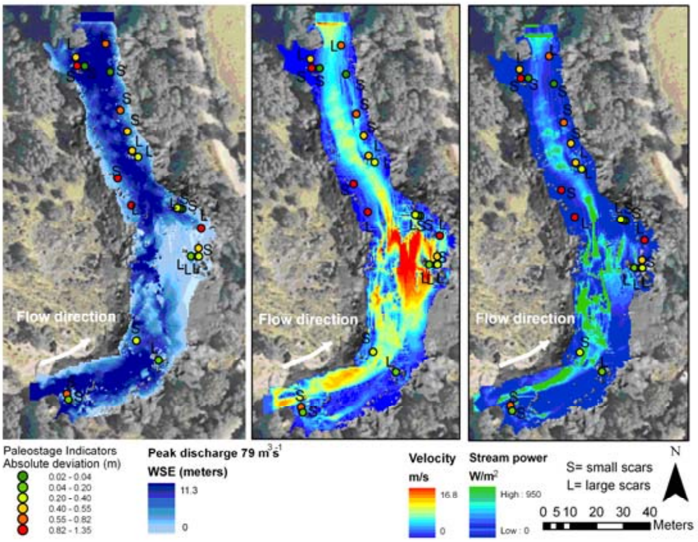

Figure 14. Deviation (in meters) between observed scar heights on tree trunks and modeled (2D hydraulic model Mike 21) flood stage. Scar data was used to calibrate peak discharge and to derive information on flow velocity and stream power of the 1997 flash-flood event at Venero Claro (Spanish Central System). S=small scar (< 800 cm^2); L=large scar (≥ 800 cm^2). (adapted from Ballesteros et al. in press)

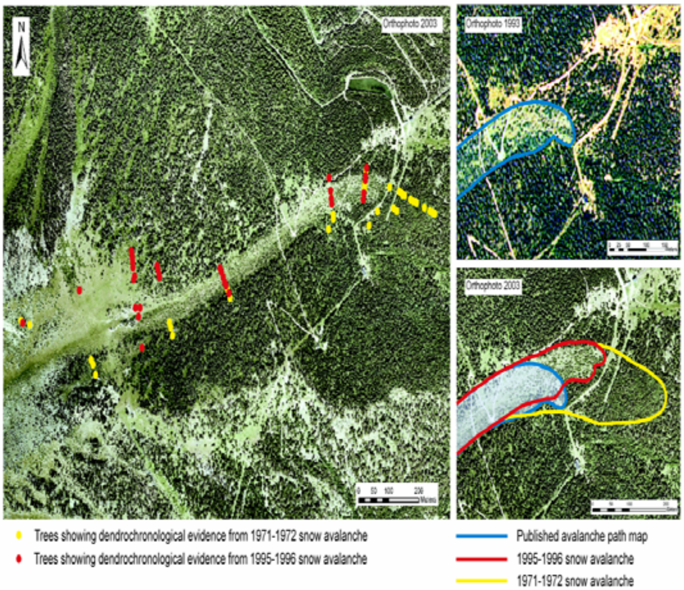

Figure 15. Avalanche map improvement. In an avalanche track in the Southeastern Pyrenees, the dendrogeomorphological analysis revealed the occurrence of an event in 1971-1972. Notice that the published avalanche map did not have detailed knowledge about the actual extent of exceptional events such as those in 1995-1996 or 1971-1972 (1993 and 2003 ortophotoimages, ICC; modified from Muntan et al. 2008).

3. 4. How fast did the landscape change?

Tree-ring dating can not only provide information on the time of occurrence or on the spatial spread of a geomorphic event, but it can also be used to determine movement rates of different earth-surface processes. The cell-structural change in the roots of trees and growth reactions in stem rings can be used for the reconstruction of sudden or continuous erosion rates in torrents, gullies or on slopes (LaMarche, 1961). For instance, Bégin et al., (1991) have studied the recent shoreline forest degradation caused by erosion occurring during high-water events along the upper St. Lawrence estuary (Canada). Similarly, Fantucci (2007) assessed horizontal shore-erosion rates at different locations around Lake Bolsena in central Italy. McAuliffe et al. (2006) coupled hillslope erosion in the Colorado Plateau with climate variations during the past 400 years. Marin & Filion (1992) have used radial growth patterns in white spruce (*Picea glauca*) to calculate rates of accumulation, erosion and migration of cold-climate sand dunes along the eastern coast of Hudson Bay (Québec, Canada).

Slow movements in periglacial environments can be studied with tree rings as soon as forest cover exists. The movement rates of gelifluction lobes have been studied by Jonasson (1988) and Jakob (1995). Similarly, dendrogeomorphology has been used to study the rise and evolution of thermokarst bodies in Western Siberia (Agafonov et al., 2004).

In addition, rock glaciers were documented in several case studies. In his pioneering investigation of a glacier-like boulder deposit on Table Cliffs Plateau (Utah), Shroder (1978) documented 200 years of movements and suggests that precipitation would possibly be the trigger for the main episodes of movements. Other studies on movements in permafrost complexes have been performed in North America ever since (Bachrach et al., 2004; Cannone & Gerdol 2003; Carter et al. 1999; Giardino et al., 1984), but are inexistent in other alpine regions.

3. 5. How big was the event?

Based on the height or dimension of visible growth defects on the stem surface, the spatial distribution of trees showing simultaneous signs of disturbance in their tree-ring record or the dating of individual deposits, it is sometimes also possible to assess magnitudes of past events.

Following the approach of Sigafoos (1964), flood-scar heights on trees have been used to provide minimum estimates of peak flood stages in rivers and streams. In subarctic Québec (Canada), Bégin (2001) has used ice-push scars on trees and tilted stems to reconstruct major ice floods and wave-erosion events resulting from extreme lake levels.

In the Swiss Alps, reconstruction of rockfall activity at two different locations allowed identification of more than 1500 small magnitude–high frequency events consisting of one or a few rocks and boulders since AD 1394

(Schneuwly & Stoffel, 2008 a, b; Stoffel et al., 2005 b). At the same time, only one high magnitude–small frequency event (i.e. rockslide) was reconstructed per site, namely in 1720 (Fig. 16) and in winter 1960/61. While a quantification of material transported during incidences is not feasible with tree-ring analysis, it is possible to determine event magnitudes and to distinguish rockslide from rockfall events.

While there is a plethora of data available on sites being affected by landslides and on periods of landslide activity (Bégin & Filion, 1988; Corominas & Moya 1999; Fantucci & Sorriso-Valvo, 1999), there is, in contrast, very limited knowledge available on volumes involved.

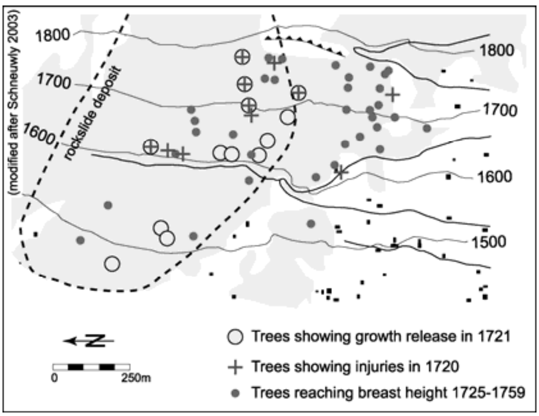

Figure 16. Damage resulting from the 1720 rockfall. Thirteen trees have been injured (red crosses) and 11 trees show an abrupt growth release starting in 1721 (yellow circles). The (re-)colonization of the rockfall slope (blue dots) in the succeeding decades (1725-1759) most probably represents a reaction to the 1720 rockfall event (adapted from Stoffel et al. 2005b).

The amount, type, size, condition, and distribution of vegetation on snow avalanche paths can reveal an abundance of information about past avalanche events (Butler, 1979). Based on the position of injured trees or the height of damage on the stem surface, it is possible to infer the extent, depth or size of past occurrences (McClung, 2003). The assessment of high-magnitude avalanches is often based on index numbers (Shroder 1978; Butler & Malanson, 1985), meaning that a certain percentage of all sampled trees must show signs following snow avalanche activity. Butler & Sawyer (2008) have set the threshold to 40%, arguing that only during years where their index number was exceeded, there was also some historical documentation available for avalanches in the Glacier National Park region.

Based on the nature of damage in trees, it is also possible to determine the type of and forces involved in snow avalanches, which in turn have different impact loads on buildings and the assessment of hazards: Mears (1975) has used data on tree-trunk failures to calculate velocities and impact pressures of dense-snow avalanches, whereas Stoffel et al. (2006) were distinguishing the extent of snow deposits from the area affected by windblast for dry- or powder-snow avalanches.

The size of debris flows has rarely been assessed, as signs of previous activity are often eroded or overridden by subsequent events and as it is very difficult to assess the size of individual debris-flow deposits on cones. In his pioneering work about debris flows at Mount Shasta (California), Hupp (1984) states that events of small magnitudes have shorter recurrence intervals than do large-magnitude discharges. Strunk (1988) has coupled tree-ring data with stratigraphic investigations (i.e. layer thicknesses) and presents a rough volume estimate for episodic debris-flow events in the Italian Dolomites. Based on (i) the height or dimension of growth defects on stems, (ii) the spatial distribution of trees showing signs of disturbance to a specific debris flow in their tree-ring record or (iii) the dating of individual deposits, it is sometimes also possible to determine magnitudes of past events. In his pioneering tree-ring work on debris flows at Mount Shasta (California), Hupp (1984) states that events of small magnitudes have shorter recurrence intervals than do large-magnitude ones. Strunk (1988) coupled tree-ring data with stratigraphic records (i.e. layer thickness) and presented rough volume estimates for episodic debris-flow events in the Italian Dolomites. On the basis of the spread of individual surges, amount of material left on the cone during specific events, seasonality of incidences, rainfall intensities and mean rock sizes, Stoffel (2010) determined four magnitude classes of debris flows for 62 events in a small, periglacial watershed of the Swiss Alps since AD 1863 (Fig. 17).

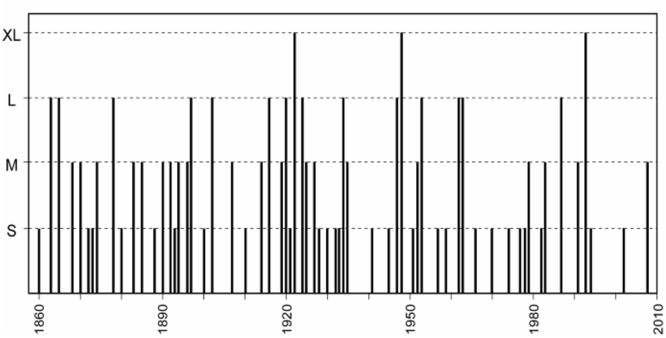

Figure 17.: Reconstructed time series of debris-flow magnitudes, in five classes, for the period from 1858 to 2008. Note the clustering of important events in the early decades of the twentieth century and the absence of class XL debris flows before 1922. S = 10^2–10^3 m^3; M = 10^3–5×10^3 m^3; L = 5×10^3–10^4 m^3; XL = 10^4–5×10^4 m^3 (adapted from Stoffel 2010).

3. 6. Why did it happen?

The occurrence of geomorphic events depends on the presence of triggers in the form of precipitation, snow melt, changes in mean and extreme temperatures or earthquakes. A coupling of tree-ring based event chronologies with meteorological or seismological records helps the understanding of contemporary process activity and dynamics and may be used for the prediction of potential future events occurring under greenhouse climate conditions.

In subarctic Québec (Canada), Bégin (2001) observes that heavy snowfalls in winter between the 1930s and 1980s have had a significant influence on spring ice-flood events. In the Swiss Alps, meteorological data indicates that the frequency of convectional rainfall in summer (thunderstorms) has decreased over the last decades and that important precipitation sums are more frequently due to cyclonic rainstorms in late summer and early autumn today. As a result, Stoffel & Beniston (2006) observe a clear shift of reconstructed debris-flow activity from summer (June, July, August) to late summer and early autumn (August and September).

Fantucci & McCord (1995) state a correlation between increased landslide activity and particularly wet summer conditions on an unstable slope in Viterbo (Italy). At the same time, Fantucci & Sorriso-Valvo (1999) did not find comparable reactions in a landslide in Calabria (Italy). Here, extreme meteorological events could only explain one third of all landslide incidences, whereas 80% of historical earthquakes had an impact on landslide activity. The presence of earthquake-triggered landslides was also analyzed by Carrara & O'Neill (2003) in south-western Montana, where they could link multiple periods of landslide re-activation following regional earthquake activity during the twentieth century. The influence of earthquakes on earth-surface processes has also been demonstrated on a rockfall slope in the Swiss Alps, where Schneuwly & Stoffel (2008 a) observe a partial destruction of the forest stand and a large number of scars in surviving trees as a result of co-seismic rockfall activity.

A regional analysis of torrents producing simultaneous debris flows can help the assessment of triggers. Bollschweiler and Stoffel (2010 b) have recently demonstrated that debris flows occurring in single torrent are most probably the result of very local (convective) rainfalls or originating from geomorphic particularities in the catchment area such as outbreaks of water pockets or the formation of temporary landslide dams. In contrast, debris flows occurring in several torrents of a region at a time often pinpoint to more regional rainfalls (advective storms). In addition, the comparison of event frequencies in a torrent with data on floods in neighboring watersheds may considerably help identification of triggers and synoptic weather patterns (Stoffel et al., 2005 c).

For the Ritigraben torrent (Swiss Alps), Stoffel et al., (in press) compared tree-ring based event frequencies with meteorological data to determine debris-flow triggering rainfall thresholds. At their study site, precipitation totals recorded during individual debris-flow events greatly differed and ranged from 10 to 179 mm (mean: 40.1 mm; SD: 29.8 mm) over the last 150 years. While there is a certain dependency of debris-flow magnitude from precipitation inputs, it becomes also quite obvious that rainfall thresholds needed for the release of events increase over the debris-flow season and will depend on the state of the rock-glacier body (i.e. active layer thickness of the permafrost; Lugon & Stoffel 2010) located in the source area of debris flows. Stoffel et al. (in press) also demonstrate that the changes in the temporal occurrence and size of debris flows were clearly the result of modified atmospheric circulation patterns (i.e. North Atlantic Oscillation or NAO) and a related decrease in the number of potentially triggering rainfalls (Schmidli and Frei, 2005) rather than reflecting sediment supply limitations in these catchments (i.e., "transport-limited" conditions *sensu* Bovis and Jakob, 1999).

4. Outlook

The surface of planet Earth is continuously subjected to external forces and drivers and landscapes are, as a result, continuously changing. A detailed comprehension of process dynamics, landscape history and of the reasons why the present-day earth surface looks the way it does are crucial for an accurate assessment and reliable predictions on how earth-surface processes might influence our environment in a future greenhouse climate (Collison et al., 2000; Dehn et al., 2000; Goudie, 2006; Soldati et al., 2004).

Trees may register signs of past earth-surface processes in their increment rings and therefore represent a valuable tool for the analysis of past, contemporary and potential future process activity. The method has been widely used in the analysis of snow avalanche, debris-flow, landslide or flood analysis. In contrast, tree-ring based reconstructions of past rockfall activity have been scarce so far, yet yielded promising results. Based on the physics of the processes involved and the nature of damage observed in the trees' morphology, we believe that there is also a potential for the tree-ring based analysis of other processes, such as glacier-lake outburst floods, ice avalanches or the occurrence of volcanic lahars.

Further, tree-ring based research on geomorphic processes has largely focused on mountain regions in general and the North American chains and European Alps in particular. Although there seems to be potential for dendrogeomorphological studies, tree rings have only rarely been used in other regions of the world to assess past geomorphic process activity, such as the analysis of landslides in subtropical Argentina (Paolini et al., 2005) or the reconstruction of snow avalanches in Patagonia (Casteller et al., 2008; Mundo et al. 2007). We therefore call for more dendrogeomorphological research in South America, the Indian subcontinent, Africa, Northern and Eastern Europe (Surdeanu et al., 2010) or Russia.

The past is the key to the future and a detailed knowledge of process dynamics will help the understanding and management of contemporary as well as the forecasting of future incidences. It is therefore important to realize that besides the pure dating of events and the creation of valuable event chronologies, dendrogeomorphological data should also be used as a tool and as the most complete database for the assessment of hazards and risks.

Essential progress has been made in dendrogeomorphology over the last few years, but more work is needed to further promote this unique technique. Research performed with new species or parts of trees needs to go beyond simple ring counting and should include more rigorous statistical comparisons of ring chronologies or event-response replications. Otherwise, investigations can lead to spurious errors. At the end, tree-ring research will help to even better understand the complex dynamics, mechanisms or triggering factors of geomorphic processes and to mitigate or reduce the problems they may pose.

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