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META-ANALYSIS OF DENDROCHRONOLOGICAL DATING OF MASS MOVEMENTS

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Abstract: Absolute dating of mass movements is crucial for disentangling possible release factors and determining the frequency of events. Here, we present an overview of a recent approach to dendrochronological dating of rockfalls, flows, landslides and avalanches. The results, based on 69 case-studies, show that methodological approaches to sampling and material processing differ considerably for different types of mass movements. Landslides are usually detected through abrupt growth changes and changes in stem eccentricity, whereas high-energy events as avalanches and flows are mostly identified by the formation of traumatic resin ducts, reaction wood, growth injuries and eccentricity changes. Cross-dating of dead wood is applicable as well. The dating of most mass movements except landslides is common, even with sub-annual resolution. In comparison to other methods of absolute dating, the main benefit of dendrochronology still lies in the high temporal resolution of the results. If living material is accessible, on-going research progress makes absolute dating of most mass-wasting events possible with sub-annual precision.

Keywords: dendrogeomorphology, disturbances, meta-analysis, mass-movement, absolute dating

1. INTRODUCTION

Slope movements are one example of natural processes that can pose a serious risk to human beings and their possessions (Kukal and Pošmourný, 2005). Data regarding former mass-movement events are very useful for producing reliable estimates of their frequency and spatial extent (Stoffel and Bollschweiler, 2009a). If there are written records or eye-witness accounts of former reactivations in a given location, they can be very easily used as a source of information. The problem is that memories of an individual are very subjective and underestimate events that may have (i) occurred in unpopulated areas and (ii) did not lead to material losses or injuries (Bollschweiler *et al.*, 2011). In comparison, the application of relative or absolute dating techniques provides more objective results (Lang *et al.*, 1999). Dendrochronology represents an appropriate method for dating mass-movements on decadal to millennial time scales. The fundamental principle of dendrochronological dating is the reconstruction of former events using tree rings and other anatomic structures of trees and shrubs growing in the affected area (Alestalo, 1971; Gärtner, 2007b; Stoffel and Bollschweiller, 2008). In particular, debris flows, avalanches, rockfalls and landslides (**Table 1**) can be dated with at least one-year resolution using this method (Lang *et al.*, 1999; Kaczka *et al.*, 2010).

Because tree rings represent the typical structure of wood (xylem) used for dating purposes, we find it important to briefly describe their basic anatomy. Xylem is

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Table 1. *Typology of catastrophic slope-movements based on Varnes (1978) and Kukal and Pošmourný (2005); edited by the authors to fit the prevailing focus and terminology of current dendrogeomorphological case studies.*

Type of catastrophic slope-movement	Characteristic features	Subtypes	
Landslide	Distinct slip surface(s), where shear strain takes place, is formed between transported material and underlying layers.	Rockslide Debris-slide Earthslide	Translational Rotational
Flow	The deformation of transported material (which usually partly consists of water) takes place in whole masses. Surfaces of shear are short-lived, closely spaced and usually not preserved.	Debris flow Debris flood Earth flow Soil and rock creep Slope sagging	
Fall	Falling, rolling and bouncing of single stones or layers; at least some part of the transport is carried out by free fall.	Rockfall Debrisfall Earthfall	
Avalanche	Abrupt movement of snow downhill with a path longer than 50 m and speed of at least 10 $m.s^{-1}$	x	

formed as a result of the activity of cambium – the lateral meristem – which is responsible for the secondary growth of trees (Pallardy and Kozlowski, 2008). For a strong seasonal climate (e.g., boreal or temperate climatic zone, semiarid climates), the activity of cambium is restricted only to a specific part of the year – the growing season – and for the rest of the year (dormancy), it ceases (Schweingruber, 1996). The onset and duration of cambial activity is hormonally driven, and the production of hormones is governed by temperatures and photoperiod (Rossi *et al*., 2006; Pallardy and Kozlowski, 2008). Xylem cells created at the beginning of the growing season have a primarily transporting function, which results in their unique shape; along their transversal cross-section, they are isodiametric and thin-walled. On the other hand, cells formed during summer months serve as mechanical support for trees and are flattened and thick-walled (Schweingruber, 1996). The formation of alternating layers of these two types of cells creates the typical structure of tree rings. There are three different functional types of cells present in the xylem structure (Pallardy and Kozlowski, 2008): parenchyma (transports water horizontally and stores substances), schlerenchyma (mechanical support) and trachea (vessels) and tracheids (transport water and nutrients upward from the roots to the crown). The spatial structure and proportion of the previously mentioned types of cells differs greatly between angiosperms and gymnosperms. Tracheae are not present in the xylem of gymnosperms, which makes their structure simpler and tree rings often more optically distinguishable (Schweingruber, 2007).

The fundamental principle of mass-movement dating is that the energy of an event leads to a change in local ecological conditions, which has a strong influence on plant growth. Trees affected by this change have to adapt, which means changing their growth parameters (Gärtner, 2007a). This idea was originally defined by the so-called Process-Event-Response principle (Shroder, 1978). In this case, the Process indicates geomorphological factors (e.g., mass-movement, earthquake, flood, erosion), which are very important Events in the life of a tree (it can cause, e.g., tilting, mechanical damage to cambium, or competition-pressure decrease). Wooden plants adapt to new conditions by changing their rate of cambial activity and xylem structure. Because there is a clear logical link between Process, Event and Response, these abrupt changes can be used to reconstruct the original Process (Shroder, 1978), and different reactions of trees can therefore serve as a good tool for the estimation of the time of occurrence of a geomorphological event.

The aim of this article is to provide a comprehensive review of (i) the macroscopic and microscopic reactions of trees to mass-movement disturbance and (ii) recent dendrochronological research of rapid mass movements in terms of type of mass movement, regional focus, methods used and dating resolution achieved.

2. METHODOLOGY

We attempted to build the most complete list of case studies focused on mass-wasting dating through dendrochronological methods. However, our effort barely reached total completion because the number of studies using dendrochronological methods is enormous, and in many studies, dendrochronology is combined with other dating techniques and serves only as a supplementary tool. Moreover, any complete list would gradually lose its value over time because new articles are rapidly being published. Our meta-analysis is therefore based on as broad sample of dendrochronological case studies focusing solely on the dating of mass-wasting events as possible. Only case studies *sensu stricto* in which dendrochronology was the dominant dating method were involved.

The principle parameters of the involved studies that were evaluated were the mechanism of slope processes, analysed growth reactions, temporal extent and resolution of results, geographical locality, species and sampling strategy. To identify and analyse the relationships between the processes and dating methods used (including data resolutions and covered time spans), we used redundant discriminant analysis implemented in CANOCO software (Ter Braak and Šmilauer, 1998). Because most of the variables were categorical, they were transformed into "dummy" variables (Lepš and Šmilauer, 2003).

To enhance the validity of the results, a special rule had to be set for the inclusion of analysed types of mass movement and markers. To do this, the requirement of a minimum of 10 studies for mass movement types was set – if fewer than ten studies focused on a single type of movement, they were not involved in the meta-analysis because that type of research activity was not adequately represented. An exception to this rule was made only if (i) the research was focused on areas with the concurrent origin of two or more different types of slope processes or (ii) if the mechanism of the process and procedures used for dating were very similar to that used to study another type of the event. In this case, two similar groups were merged. The same rule, with a threshold of only 5 studies, was set for markers of disturbances because the number and variability of the markers used are higher than those of mass-wasting type.

3. RESULTS

Overview of macroscopic and microscopic markers of mass movements in tree rings

Irregular shape of tree-rings

Eccentrically shaped tree rings are characteristic of trees growing on slopes, where trees are subjected to soil creep or mass movement processes. Their stems are usually deflected toward the direction of mass movement, and during subsequent growth, they become curved near the bottom of the trunk (Schweingruber, 1996). This curvature occurs because the imbalanced position of the deflected tree forces the formation of elliptical tree rings during the following growing seasons. Tree-ring shape and the rate of ring eccentricity can serve as tools to determine the year when a tree was inclined (**Fig. 1a**).

Tree-ring eccentricity can be quantified and analysed by means of so-called eccentricity indices, whose specific form differs among researchers (**Table 2**).

An abrupt increase in the value of indices indicates the year of the inclination of a tree.

The main advantage of Schweingruber's (1996) formula is its simplicity. However, tree rings are usually very narrow along the upper part (R_u) of the inclined stem (in conifers), which makes their measurement very difficult and very often leads to mistakes (Braam *et al*., 1987). The application of the equation developed by Braam *et al*. (1987) faces this problem but requires the core to be extracted in a direction perpendicular to the inclination (which is not always performed). All of the equations listed can be used for the quantification of the eccentricity of coniferous tree rings; if angiosperms are used for dendrochronological research, the equations must be adjusted with regard to the specific form of tension wood formed by these species (Pallardy and Kozlowski, 2008).

Abrupt growth changes

Because tree-ring width is *inter alia* driven by external factors affecting trees (Cook and Kairiukstis, 1990; Schweingruber, 1996), this parameter has traditionally been the main and principle indicator of disturbances.

Masses transported during events on a slope usually have huge kinetic energies. Although the majority of mature trees are destroyed, juvenile trees are usually not damaged to the same extent due to the flexibility of their stems. In the following spring, the survivors can use more of the local resources because of the decrease in competition pressure. As a result, a sudden increase in tree-ring width occurs (Stoffel *et al*., 2005a, 2005b; Casteller *et al*., 2007; Šilhán and Pánek, 2008). Other ways in which a mass-movement event can induce wider tree-ring formation are, for example, the accumulation of fertile soil near trees (Gärtner, 2007a) or the increase in water content in accumulated layers (Fantucci and Sorriso-Valvo, 1999).

Some trees affected by the energy of mass movement can be seriously damaged (e.g., decapitation, tearing of roots) but not killed, which results in the reduction of their cambial activity in the following years (**Fig. 1b**).

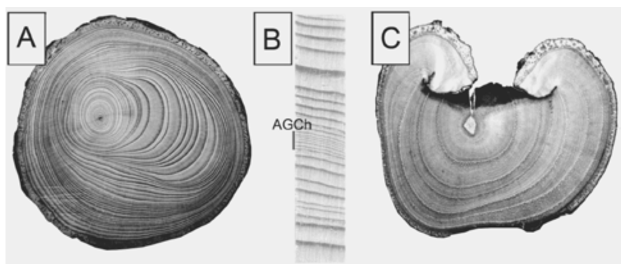

Fig. 1. *Macroscopic changes in tree rings: (a) changes in eccentricity; (b) abrupt growth change (reduction) in tree-ring width (AGCh), and (c) growth injury (scar).*

Table 2. *Different equations used for quantification of eccentricity of a single tree-ring; R_D – tree-ring width measured in downslope orientation, R_U – tree-ring width measured in upslope orientation, R_P – tree-ring width measured in orientation perpendicular to slope.*

Equation	Citation	Value of a circle
$I_{ex\,1} = \dfrac{R_D}{R_U}$	Schweingruber, 1996	1
$I_{ex\,2} = \dfrac{R_D - R_P}{R_D + R_P}$	Braam *et al*., 1987	0
$I_{ex\,3} = \dfrac{R_D}{R_D + R_U}$	Alestalo, 1971	½

Additionally, the burial of stem bases with the huge masses transported and accumulated by an event can lead to the formation of narrow tree rings (Gärtner, 2007a) as a result of strong mechanical pressure on the cambium and reduced access to air for roots (Strunk, 1997). The inclination of the tree stem can also result in abrupt growth reduction if tree-ring widths are measured perpendicularly to the inclination (measurements should not be performed in the up- and downwards directions because the tree-ring width can be eccentrically deformed there). This is because the formation of reaction wood and lignification of cell walls is energy-consuming (Schweingruber, 2007).

Reaction wood formation

If a tree stem is affected by mechanical stresses (such as pressure or tension), the anatomical structure of wood changes, and so-called tension wood (angiosperms) or compression wood (gymnosperms) is formed. Together, these are termed reaction wood (Schweingruber, 1996). Because their formation is usually the result of stem inclination, the relationship between tree-ring eccentricity and reaction wood is very explicit (Duncker and Spiecker, 2008).

Compression wood is formed in the area of the cambial zone of gymnosperms that is affected by compression, i.e., on the lower side (Stoffel and Bollschweiler, 2009a). The cells are usually isodiametric, typically with thickened cell walls (Schweingruber, 1996), which macroscopically results in an apparently darker colour. Intercellular spaces occur between cells frequently (**Fig. 2a**). Another typical feature is the vast amount of lignin impregnating cell walls, which allows for the straightening of tree stems but decreases the permeability of the walls (Pallardy and Kozlowski, 2008).

On the other hand, the tension wood of angiosperms is usually formed on the upper part of the inclined stem, where the increased activity of the cambium usually occurs after inclination (Heinrich and Gärtner, 2008; Stoffel and Bollschweiler, 2009a). Typical features are low lignin content and the presence of gelatinous fibres (Heinrich and Gärtner, 2008). Unfortunately, tension wood is very difficult to recognise macroscopically – as a result, and if possible, the reaction wood of gymnosperms is more frequently used for dendrochronological purposes.

Using reaction wood as an indicator of disturbance has some important advantages. First, if the disturbance occurred during the growing season, results with a resolution of better than one year can be obtained by analysing the position of the first reaction wood cells inside a tree ring. However, the risk of delayed reaction wood formation is also very important; if a tree is damaged by mass movement, different adaptations can proceed first after the event (such as an abrupt decrease in growth), and the formation of reaction wood can be delayed for a few years (Carrara and O'Neill, 2003). Significant potential also lies in the possibility of estimating mass-movement intensity and direction (Heinrich and Gärtner, 2008; Duncker and Spiecker, 2008).

Exposed tree roots

Although the use of exposed tree roots (as well as adventitious roots) was infrequent in studies directly focused on mass-wasting dating (fewer than 5 studies), we provide a short explanation of the principles of dating based on them because exposed roots have proved very useful in other geomorphological situations, e.g., the dating of gully evolution (Malik and Matyja, 2008) or estimation of erosion rates (Bodoque *et al*., 2005).

The exhumation of roots occurs in the transport and source zones as a result of mass-movement events. These roots are then affected by different ecological conditions, which results in changes in the anatomical structures of wood (Hitz *et al*., 2008).

Normally, tree rings in roots are often hardly distinguishable, narrow and feature indistinct layers of latewood (Schweingruber, 1996) and the cells forming them are usually larger (higher vessel lumen area) with thinner walls (Hitz *et al*., 2008) (**Fig. 2c**). In contrast, the wood of exposed roots resembles the wood of stems and branches. However, the presence of very narrow or missing rings is very common in roots, which makes the measurement of tree-ring width difficult and cross-dating almost impossible (Bodoque *et al*., 2005); therefore, only

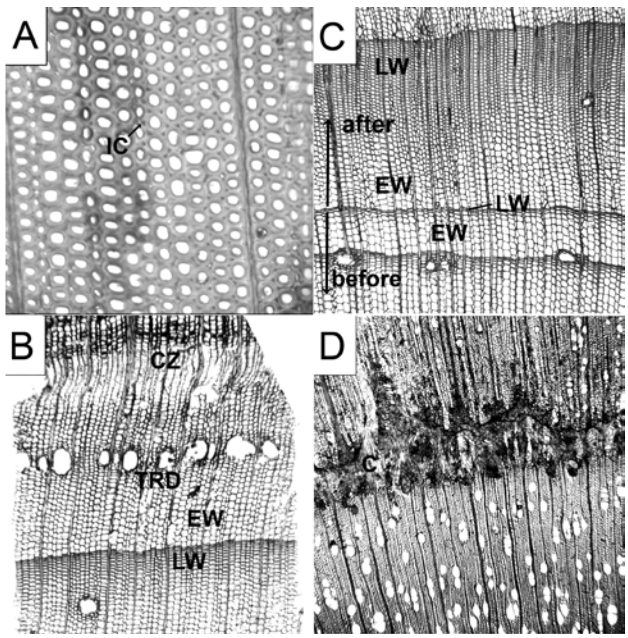

Fig. 2. *Response of tree-ring anatomy to disturbances: (a) reaction wood; (b) traumatic resin ducts formed several weeks (2-4) after experimentally induced injury; (c) comparison of wood anatomy in roots before (thin late-wood cells zone) and after (broad late-wood cells zone); (d) callus tissue; (a-c:* Picea abies*, d:* Betula pendula*; magnification of "a": 200×, "b-d": 50×). Abbreviations: IC – intercellular spaces; EW – early wood; LW – late wood; CZ – cambial zone; TRD – traumatic resin ducts; C – callus.*

living exhumed tree roots should be sampled (Malik and Matyja, 2008).

The risk in analysing exposed tree roots is that they could be exposed only because of their gradual radial growth, without the effects of external forces. The methodology proposed by Gärtner (2007b) can be used to differentiate these two situations. To avoid the sampling of tree roots exposed due to stem growth, samples should be taken at least 1.5 m from stem base (Bodoque *et al*., 2005). This distance cannot be dogmatically accepted; it strongly depends on the specific conditions of the associated microtopography and the sampled tree. For example, if the estimation of gully erosion intensity is the aim of the dendrochronologist, very special care must be given to the selection of the position of root cutting to avoid the under- or overestimation of erosion rates and volumes (Vandekerckhove *et al*., 2001). Very useful information, which can be achieved by studies of exposed tree root, is whether it was exposed all at one time (one fast event) or gradually part-by-part (slow continuous process – e.g. gully erosion). Taking more samples in different positions from one exposed root can help to differentiate these two situations (Malik and Matyja, 2008).

Tree response to a burial event – adventitious tree roots

Trees growing in area where the accumulation of transported masses takes place are usually exposed to frequent burials, which results in changes in tree-ring widths and wood anatomy. These are mainly dependent on the amount of burial material, physical and chemical structure, the periodicity of burial and also on the phenological phases during which the burials occurred (Kent *et al*., 2001).

The situation is analogous to the exhumation of tree roots – after burial, we can expect the formation of cells with larger vessel lumen areas and thinner cell walls (Friedman *et al*., 2005). If samples are taken from the level of the former stem base, tree rings may be hardly distinguishable and very narrow (Friedman *et al*., 2005). *Picea abies* (L.) Karst. reacts by an apparent shortening of tree rings after burial by fine-grained material of 10 cm thickness and dies if it is covered by 1.6-1.9 m of material (Strunk, 1997). If burial exceeds a critical level, dead tree stumps can then be used to estimate the minimum age of an event (Yoshida *et al*., 1997).

The main consequence of a burial event is the reduction in the roots' access to air; as a result, a tree forms new roots in accumulated layers near the soil surface. These tree roots are called adventitious and can be used by dendrochronologists for dating purposes (Gärtner, 2007a). The cross-section of the stem in a vertical layer of adventitious root is taken and the first anatomical sign of its formation is identified (Strunk, 1997). The problem is that there can be a prolonged lag between the event and the beginning of the formation of these tree roots. Therefore, the results obtained from adventitious tree roots should normally be interpreted as minimum ages only (Gärtner, 2007a).

Traumatic resin ducts (TRD)

Resin is a chemical substance that is produced by conifers under active stress, and resin ducts, the cellular formations responsible for its production, can be found scattered in the wood of many coniferous species (Schweingruber, 2007; Pallardy and Kozlowski, 2008). In the case of a strong external factor inducing their formation, some species (*Picea abies*, *Larix decidua* Mill., *Abies alba* Mill.) form coherent tangentially oriented traumatic resin ducts (TRDs) (Stoffel, 2008), which can be used for dating purposes (**Fig. 2b**).

The most important information recorded in TRDs is their position inside a tree ring; therefore, they are very often used to achieve better than one-year resolution in dating (Stoffel *et al*., 2006; Szymczak *et al*., 2010). The basic principle is that the TRDs in one of the first layers of cells of a specific tree ring indicate mechanical damage to the tree during the previous dormancy; TRDs occurring in the second half of the tree ring indicate that a disturbance took place during the growing season (Stoffel *et al*., 2006; Szymczak *et al*., 2010). However, a tree's response to disturbances seems to be complex and species-specific (Gärtner and Heinrich, 2009). While some species form TRDs after winter disturbance events immediately at the beginning of the growing season (e.g., larch), others respond with a lag, and TRDs are detectable only in a part of their tree-ring area (Stoffel and Hitz, 2008; Gärtner and Heinrich, 2009). Additionally, the persistence of TRD formation in tree rings following the year of the damage depends on species and mass-movement type (Schneuwly *et al*., 2009).

Growth injuries

Clastic material, logs and other objects transported by the energy of mass movements hit, abrade and injure tree stems, which can result in local damage to cambium and xylem. Nearby surviving cambium reacts by forming irregularly shaped cells (callus) (**Fig. 2d**), which serve to fill the damaged segment (Gärtner, 2007a). Tree rings formed after injury have a very typical and "incomplete" shape (**Fig. 1c**).

The speed at which injuries are healed depends on the size and the speed of the moving clast, the speed of tree growth and specific features and processes of secondary bark (e.g., peeling; Stoffel and Perret, 2006). Problems for the dendrochronologist appear when an entire injury is healed with callus and any obvious signs of injury are no longer externally visible on the stem. Healed injuries can be studied effectively only through the sampling of cross-sections (Bollschweiler *et al*., 2007) because if cores are extracted, the identification of injury is difficult.

Colonisation

If a mass-movement event is very strong and destructive, it is capable of destroying all vegetation in the affected area, which makes the utilisation of the above-mentioned indicators of disturbance almost impossible. In this case, the age structure of the established stand can be useful – if an event truly destroyed all surrounding trees, the age of the oldest tree now growing in the area provides the minimum age of the event (Bollschweiler *et al*., 2008). The same presumption can also be used for the minimal dating of fresh surfaces created in accumulation zones, e.g., rockslide cones (Van der Burght *et al*., 2012). The length of the lag between the event and the germination of the first seedling (ecesis) depends on the climatic and edaphic conditions of the area (mainly grain-size of substratum) and the availability of seeds (Sorg *et al*., 2010). The species composition of the surrounding source forest sites plays a crucial role because different species have different eceses (Van der Burght *et al*., 2012). The frequency of events can also be indirectly assessed by the age distribution of trees and shrubs growing in the area affected by the mass movement (Voiculescu and Ardelean, 2012).

Mass movement dating characteristics

A total of 69 scientific studies dealing with the dendrochronological dating of various types of mass movements were evaluated (Appendix and **Fig. 3**). Most of them address debris flows (including debris floods and lahars – 22), avalanches (17) and landslides and rockslides (17). The highest number of studies are from Switzerland (19) and the Alps. A preference for gymnosperms for sampling purposes is clearly visible – at least one species was a gymnosperm in 52 (more than 75%) case studies. From this point of view, the most "popular" were *Picea* sp. (27), *Pinus* sp. (20) and *Larix* sp. (19). Angiosperms were more common only in the case of landslide dating, and the most used species were *Alnus* sp. (7), *Betula* sp. (6) and *Fagus sylvatica* L. (6). The markers used to date events were typically growth injuries and the onset of callus formation (51) and abrupt growth changes (51). Reaction wood (45) and TRD (27) are also common

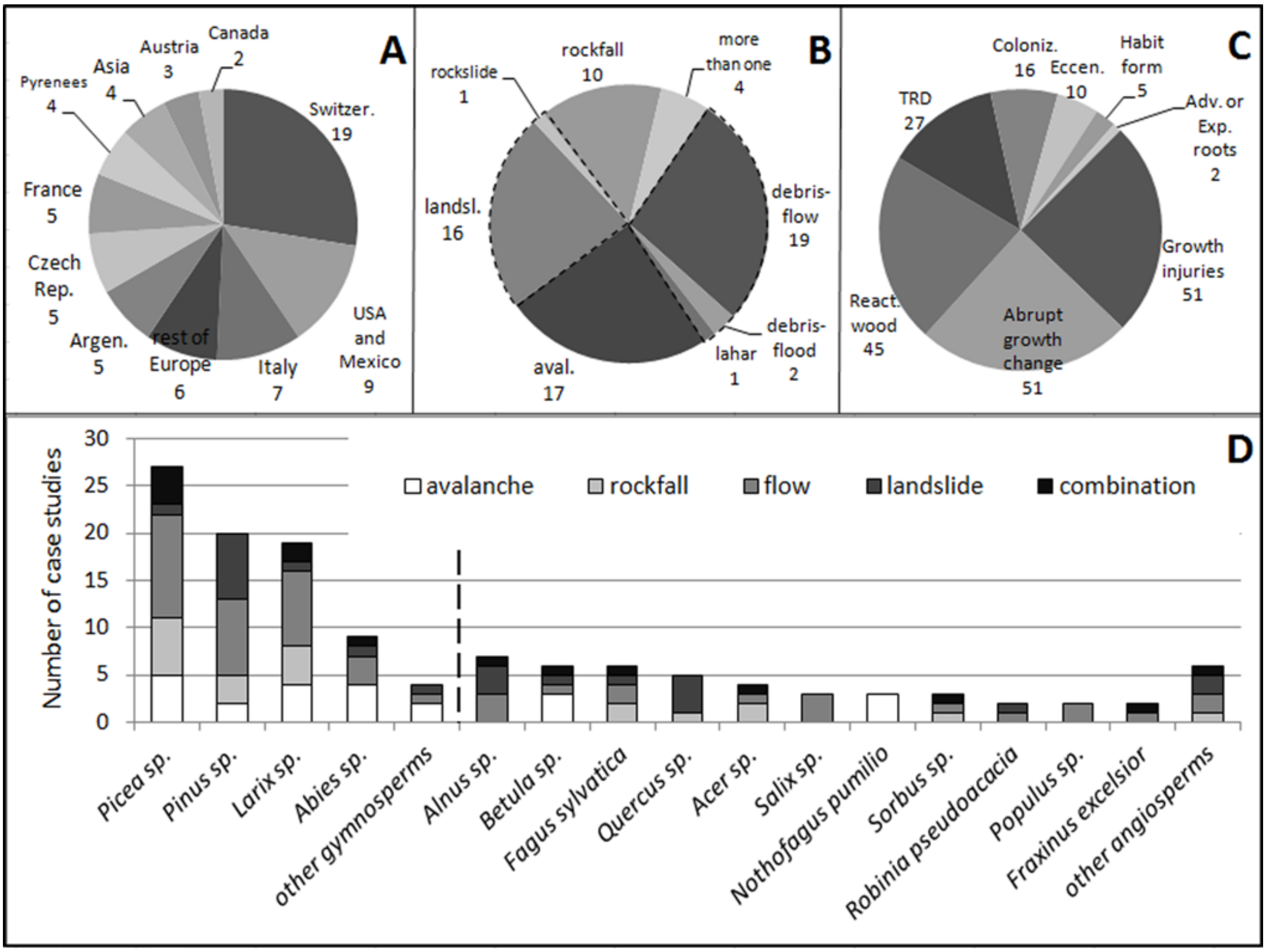

Fig. 3. *Parameters of studies according to (A) country, (B) type of the event, (C) microscopic and macroscopic markers used for dating and (D) dated species. For detailed characteristic of studies see Appendix.*

in the analyses. Although a resolution of better than one year can be achieved through these last two markers of disturbance, this great potential of modern dendrogeomorphological analyses was only rarely (11) used by researchers, so the majority of the results exhibit one-year resolution.

Taking cores is generally preferred over the destructive sampling of wedge-cuts or cross-sections (discs). However, if eccentricity is the key marker of mass-movement, the problem of missing the pith of core can be especially important. The third "sampling strategy" is simply the evaluation of the external habit (appearance) of trees and shrubs; specific forms (e.g., candelabra tree form, decapitated trunks) are typical evidence of former slope disturbances. However, the dating of events cannot be achieved in this way.

The ordination plot of redundant discriminant analysis (**Fig. 4**) shows correlations between mass-wasting types and their dating characteristics. As the score on a given axis increases, a higher correlation between the corresponding mass-wasting type and dating method can be expected. Flows and rockfall are mostly dated using TRDs and growth injuries (high negative scores on Axis 1), whereas landslides are usually identified by abrupt growth changes and changing eccentricity (high positive scores on Axis 1). Colonisation is mostly used as a data source for dating flows. Avalanches are most frequently determined through reaction wood formation and injuries (correlated along third axis of RDA scheme – not shown). While angiosperms are mainly used for landslide dating, gymnosperms are frequently sampled in cases of flow and rockfall.

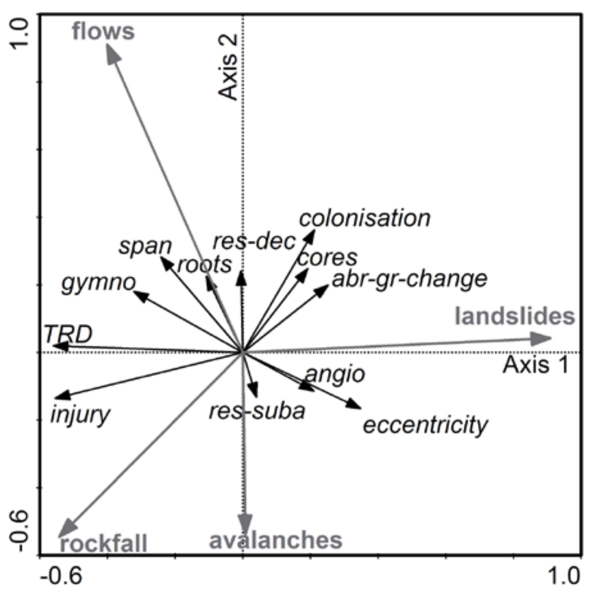

Fig. 4. *Redundant discrimination analysis ordination plot. Arrows indicate directions of variance; the longer they are and the more acute angle they have with corresponding axis or with other variable (e.g. arrow), the more are correlated. Axes represent the main directions in variability of the given set of variables. First two axes cover 75% of mass-wasting type – methodological characteristics variance. For the sake of simplicity, variables with the lowest scores on both axes are suppressed (reaction wood, habit, annual resolution, cross sections). Abbreviations: gymno – gymnosperms; angio – angiosperms; res-dec – decadal resolution; res-suba – subannual resolution; abr-gr-change – abrupt growth change.*

Snow avalanches

Early studies regarding snow avalanches have been performed in the northern U.S., particularly in Wyoming, Colorado and especially Glacier National Park (Montana) (Butler and Malanson, 1985), which still attractive for researchers (Reardon *et al*., 2008; Butler and Sawyer, 2008). However, since the turn of the millennium, attention has also been aimed at other mountains, e.g., the Alps (Casteller *et al*., 2007; Corona *et al*., 2010), the Pyrenees (Muntán *et al*., 2009) and the Andes (Mundo *et al*., 2007; Casteller *et al*., 2011).

The goal of the study of avalanches is to determine the frequency of avalanche events and the extent of their paths; dendrochronology can use information about ages and the density of trees for this purpose. Paths usually record lower average ages of trees (Casteller *et al*., 2007) and lower tree density (Mundo *et al*., 2007). For the proper dating of an event, almost all of the markers mentioned in the previous chapter, except for adventitious roots, can be used (Casteller *et al*., 2007), depending on the specific situation.

The most traditional way to statistically analyse data for dating purposes was first described by Shroder (1978) and requires finding the proportion of disturbed trees among all the trees growing in an area (with a one-year resolution). Due to temporal changes in sample depth (meaning that the number of analysed trees is not the same for all the years of the analysis because the years of germination are usually not the same), this is effectively necessary; the method based only on the absolute count of affected trees would strongly underestimate avalanches in years when there were only few sampled trees growing (this usually means older periods). Shroder's (1978) procedure can also be used to study landslides (Stefanini, 2004) or debris floods (Mayer *et al*., 2010). The threshold value should usually be set, in the case of avalanches, between 10 and 40% (Butler and Sawyer, 2008); traditionally, it has been set at 10% (Reardon *et al*., 2008). Very detailed methodological research on the problem of setting the appropriate level of this index performed by Corona *et al.* (2012) pointed to the need to increase the threshold with decreasing sample size; otherwise, many past avalanches can be omitted and potential noise (identification of "false" events) can occur. The other statistical analysis approach is based on a special "scoring" scheme, which assigns points to years according to the number and severity of indicators of the avalanche and the total amount of disturbed trees (Casteller *et al*., 2011).

The dating of avalanches can broadly use loads of dead wood (i.e., the broken trunks of trees growing in the path before the fall) to estimate the ages of their breakage by means of cross-dating. To determine whether their death was really avalanche-induced, the analysis of the azimuth of their deposition in relation to the expected azimuth of the avalanche can be used (Reardon *et al*., 2008; Corona *et al*., 2010).

Rockfall

Research activities focused on rockfalls are mostly restricted to Europe (predominately the Alps). Data about frequencies of rockfall derived from tree rings spans across the last four centuries (Stoffel *et al*., 2005b).

Falling clasts can have huge kinetic energies and the capacity to seriously damage trees. As a result, decapitated habits and surface injuries are typical features of trees in an affected area (Stoffel *et al*., 2005b). If a crown is broken, two adventitious shoots usually emerge and continue vertical growth. After a few years, the habit closely resembles a street light, which is why it is called a "candelabra tree form" (Schweingruber, 1996). These adventitious shoots can be very easily used to estimate the minimum age of an event (Schweingruber, 1996). The breaking of the crown is usually the consequence of a frontal hit to the upper parts of a tree, but it can also be caused by the vertical sinusoidal transmission of kinetic energy affecting the lower parts of the stem (Dorren and Berger, 2006; Stoffel and Bollschweiler, 2008). In addition to habit form, many other dendrochronological pointers of the timing of an event can be used to accurately date a rockfall, e.g., abrupt growth changes, scars, reaction wood and (in the case of conifers) TRDs. Because this type of mass movement can occur both during dormancy and a growing season, the last three mentioned indicators of rockfall can be particularly useful for dating with better than one-year resolution (Stoffel *et al*., 2005c; Schneuwly and Stoffel, 2008b; Moya *et al*., 2010).

The dendrochronological dating of rockfall must take into account the fact that this slope movement transports single clasts differing in size rather than some type of compact layer. One clast can damage more than one tree during transport, but on the other hand, it can pass a forest belt without inflicting any hits. The probability of the second situation decreases with the increasing average DBH of trees; thus, the area where samples are collected should be belt-shaped with different widths depending on the average DBH (for specific values of width/DBH see Moya *et al*., 2010). Additionally, the number of growth reactions per year reveals almost nothing about the changes in the frequency of events because it also depends on changes in DBH. To obtain accurate data, DBH, should be used as a weighting tool, as shown in the following equation (Stoffel *et al*., 2005b):

$$RR_{dt} = \frac{\sum GR_{dt}}{\sum ED_{dt}} = \frac{\sum GR_{dt}}{\left(\frac{DBH}{A} T_{dt}\right)} \tag{3.1}$$

where RR_{dt} stands for rockfall rate, GR_{dt} is the number of documented rockfall events during decade t, ED_{dt} is the exposed diameter of the tree at the beginning of decade t, DBH is the diameter at the breast height, A is the number of tree rings formed at the breast height in the year of the sampling and T_{dt} is the number of tree rings formed at the breast height at the beginning of the decade. This equation can be modified if necessary to obtain a resolution of better than one decade (Perret *et al*., 2006; Schneuwly and Stoffel, 2008a).

Flows

Pioneer studies were performed during the 1980s in California (Hupp, 1984) and during the 1990s in the Dolomites (Strunk, 1997). Currently, the highest density of research activity occurs in Switzerland, where up to four-century-long chronologies of debris flows have been established (Stoffel *et al*., 2005a).

Usually, there are huge masses of sediments accumulated in the depositional zone of flows, which can cover stem bases. Consequently, the formation of adventitious roots often occurs. Their analysis, together with the evaluation of the ages of trees colonising specific layers, is a strong tool used to date several generations of flows (Sorg *et al*., 2010). Additionally, exposed tree roots, scars, abrupt growth changes and TRDs can be successfully used for dating purposes (Bollschweiler *et al*., 2007; Sorg *et al*., 2010; Stoffel and Bollschweiler, 2009b).

Scars, reaction wood and other growth reactions are, in the case of flows, usually concentrated near the stem base, not higher than the thickness of the flow during the event. This is the main difference from a rockfall, where injuries can occur vertically along the whole stem (Stoffel and Perret, 2006). The activity of different types of flows also affects spatially compact zones (this means almost all trees in their way), which holds potential for the dendrochronological analysis of temporal changes in the extent of an affected area (Bollschweiler *et al*., 2011). However, special attention must be paid if debris contains an excessive amount of water (so-called hyperconcentrated flows); some trees growing inside an event trajectory may report no anomalies because they have been affected not by clasts but only by water (Bollschweiler *et al*., 2007).

Landslides

The typical manner in which the majority of landslides affect trees is by inclination. The azimuth of inclined stems is a very good indicator of mass-movement type; due to translational movement, almost all trees are inclined toward the valley. On the other hand, if rotation was the dominant mechanism, trees should register a bimodal or multimodal distribution of stem directions (Fantucci and Sorriso-Valvo, 1999; Van Den Eeckhaut *et al*., 2009). Almost all of the growth reactions mentioned in the previous chapter can be used to date landslides, but in the case of abrupt growth changes, typically only sudden reductions in tree-ring widths occur (Van Den Eeckhaut *et al*., 2009) because a landslide only rarely results in the total destruction of trees and a related decrease in competition. Because the majority of case studies involved in the meta-analysis focused on landslides in areas covered by angiosperms (or *Pinus* sp., which does not form resin ducts traumatically), TRDs are also rarely used.

4. DISCUSSION AND CONCLUSIONS

The dendrochronological dating of a mass-movement event involves important differences in the types of movement addressed. While high-energy events causing severe debris impacts to trees are mainly dated by TRDs and growth injuries (callus), relatively slower mass-movements (landslides) are mostly detected by changes in growth rate and changes in eccentricity. Avalanches are in most cases indicated by reaction wood and growth injuries. Only the dating of avalanches and to some extent also debris flows can use loads of dead wood (Yoshida *et al.,* 1997; Reardon *et al*., 2008). From a conceptual point of view, the direct markers resulting from the impact of mass movements on trees record events immediately. On the other hand, several indirect markers are formed with a lag. Their relation to certain events ranges from very strong (e.g., TRDs, reaction wood) to more-or-less questionable. For instance, eccentricities or exposed roots are usually frequent in a given area as a result of soil creep or the radial growth of roots, irrespective of mass movement (Gärtner 2007b). It is obvious that the use of a given marker depends on the nature of the mass-movement type. Therefore, high-energy, rapid events are often dated using direct markers and markers with strong links to the events, whereas landslides can be dated mostly by using indirect markers, often with relatively weaker relations to the events (e.g., eccentricity).

It is not only the methods used but also the sampling strategy employed that differs between types of mass movement. If dating an avalanche, landslide or flow is the aim of the researcher, two cores per tree are usually extracted (one in the downslope direction and one perpendicular to the slope azimuth). The exceptions are some recent studies focusing on landslides attempting to record successive changes in eccentricity (Lopez Saez *et al*., 2012b, 2012c), which are based on 3 to 4 cores per tree. On the other hand, in the case of rockfall, four cores are almost always taken from a stem because the number of tree rings overgrowing scars and forming callus and the difference in the number of tree rings on the scar side and opposite side of the trunk must be determined (Schneuwly and Stoffel, 2008a). Usually, a core along the perpendicular direction is also taken. As a result, the dendrochronological dating of rockfalls (which is often based on scars) is usually based on a greater number of samples than that of other types of mass movement. Because the impact energy can abrade some tree rings, this dating method can provide only the maximum age of an event.

Great "irregularities" also exist in the geographical distribution of research activities. Although the potential of tree rings as proxy data for mass movement events was first revealed in the U.S. (Butler and Malanson, 1985), these methods have expanded from North America and currently a second "core" of dendrochronological research has been established in Europe. Although research activities focusing on avalanches and landslides are dispersed all around the world, dendrochronological research on rockfalls and flows in particular has become greatly concentrated in the Swiss Alps over the last 5-10 years.

The high temporal resolution of dating is an important advantage of dendrochronology; however, there is still some risk associated with the misinterpretation of the causal processes that induce the formation of a given marker. First, many non-geomorphological processes (e.g., biotic, meteorological) can leave apparently similar marks in tree-ring structures. Filtering out of this noise constitutes a very important challenge for dendrochronologists. For abrupt growth changes, comparison with reference tree-ring curves constructed from adjacent undisturbed trees is traditionally applied (Cook and Kairiukstis, 1990). However, for other markers, there are no such well-established procedures. For microscopic dating (TRDs, reaction wood, injuries) and eccentricity-based techniques, the position/orientation of markers with respect to the direction of impact may be indirectly useful (Duncker and Spiecker, 2008) but only in the case of landslides, avalanches and flows. Rockfall involves the irregular bouncing of single rocks and some impacts on the lower (i.e. opposite) side of a stem result from the rebounds of clastic material (Stoffel *et al*., 2005b).

Because abrupt growth changes are some of the most common markers used for dating mass-movement events, the risk of mistakes caused by poor measurement must be taken into account. Using dendrochronological cross-dating principles, most of these errors can be identified (Grissino-Mayer, 2001). Trees and shrubs seriously damaged by mass movement can form number of very narrow tree rings during subsequent years, which can hardly be distinguished if a sample is prepared for traditional macroscopic analysis (i.e., sanded and measured on a positioning table under a binocular microscope). Some tree rings may be overlooked by the dendrochronologist, and mistakes in the estimated years of the slope activity can be made. The risk of poor measurement can be greatly reduced if permanently stained sections of whole cores are prepared first and the ring widths on them measured. The preparation of these long sections is the same as that for "traditional" sections of a fractional part of a sample described elsewhere (Schweingruber, 2007); the former, however, requires (i) a microtome that is long enough to mount a whole core (Gärtner and Nievergelt, 2010) and (ii) laboratory slides that are also sufficiently long. Unfortunately, most producers of laboratory equipment distribute thin (0.1 cm) slides that are maximally approximately 8 cm long, but we have also had very good experience with thicker glass (0.2 and 0.3 cm), which is readily available in most glazier shops. If tree-ring widths are measured on these sections under a binocular magnifying glass (magnification 20×), tree rings measuring nearly 4 μm can be very easily distinguished and measured (**Fig. 5**).

Because "the past is the key to the future", data regarding former mass-movement events can be very useful and are of special importance. One of the main advantages of dendrochronology in comparison to other methods of absolute dating is the temporal resolution of results (Lang *et al*., 1999). Traditional methods of the macroscopic analysis of tree-rings can achieve one-year resolution; in the case of the microscopic evaluation of anomalies in cell anatomy, more accurate results can be obtained. In the case of avalanches (which occur almost exclusively during dormancy), microscopic growth reactions can help to filter out years when a tree may have been affected by summer disturbances (e.g., storms), leaving markers similar to those left by an avalanche. In the case of other types of mass movements, growth reaction can help achieve one-month resolution if the associated events took place during the growing season. In this case, special care must be taken to reduce the risk of underestimating or (more frequently) overestimating the time of an event (Kaczka *et al*., 2010). Many studies have used TRDs, reaction wood or the microscopic analysis of scar formation. However, the majority have produced analytical results with only one-year resolution, and the main potential of microscopic growth reactions has been neglected. On the other hand, both the lag in and persistence of TRD and reaction wood formation are species-specific and differ along the stem, which is a source of uncertainty in dating (Heinrich and Gärtner, 2008; Gärtner and Heinrich, 2009; Schneuwly *et al*., 2009). Mainly in places where two or more types of mass movements are common and differ only in the season of their occurrence does this type of sample analysis play a key role (Stoffel *et al*., 2006; Szymczak *et al*., 2010; Kogelnik-Mayer *et al*., 2011).

As shown, the entire range of dendrogeomorphological methods and procedures can be used for dating and analysing landslides, flows, avalanches and rockfalls. The current state of the art indicates that the number of studies with sub-annual dating resolution is increasing. This is especially important in matching a given event to its triggering cause. However, further experimental research focused on growth reactions along disturbed trees should be performed to increase the reliability of sub-annual dating. Because every marker of a mass movement event has its own limitations, their combination is recommended. On-going dendrogeomorphological research mainly faces an increasing use of anatomical markers of disturbances and an increasing quantity of analysed samples.

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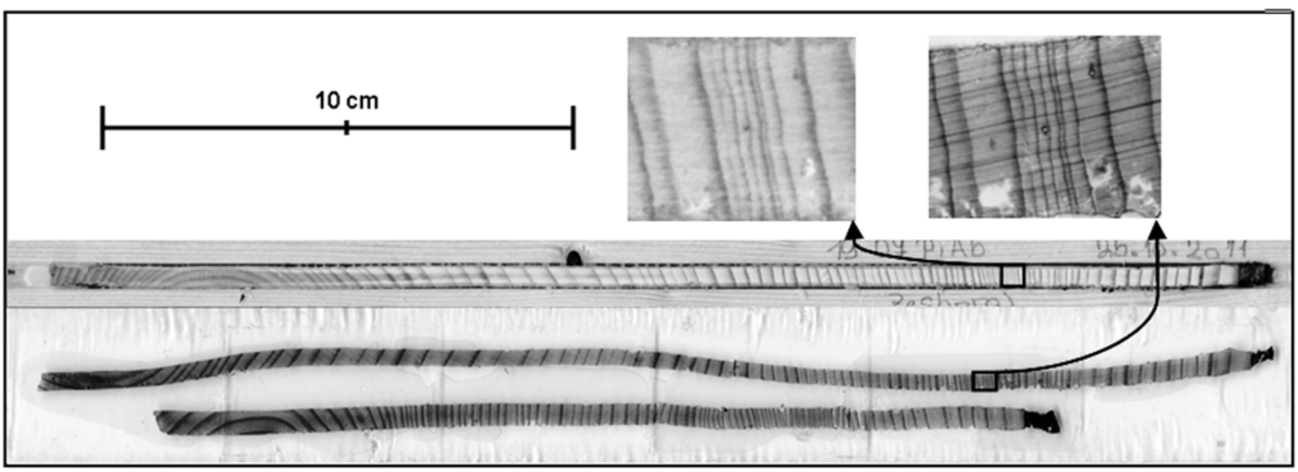

Fig. 5. *Long (~25 cm) and relatively thick microsections (~50 μm) enable precise ring-width measurements of gymnosperm wood and semi-automatic analysis of digital images.*

APPENDIX

Overview of involved studies

Citation	Locality	Type of process	Species*	Sampling strategy*	Growth reactions	Temporal extent	Temporal resolution
Butler and Malanson, 1985	Glacier National Park, Monatana (USA)	avalanche	40 *Pseudotsuga menziesii* 17 *Picea engelmanii* 11 *Pinus contorta* 9 *Abies lasiocarpa* 1 *Larix occidentalis*	cores, cross-sections	reaction wood abrupt growth changes growth injuries	1924-1985	year
Hebertson and Jenkins, 2003	Wasatch plateau Utah (USA)	avalanche	261 { *Picea engelmannii*, *Abies lasiocarpa* }	cores, wedge-cuts	abrupt growth change reaction wood growth injuries	1870-1996	year
Dubé *et al.*, 2004	northern Gaspé peninsula, Quebec (Canada)	avalanche	110 { *Thuya occidentalis*, *Abies balsamea* }	cross-sections	growth injuries reaction wood	1860-1997	year
Casteller *et al.*, 2007	Suchs, canton Grisons (Switzerland)	avalanche	61 *Picea abies* (9 †) 14 *Larix decidua* (5 †) 4 *Betula pendula*	cross-sections, 20 cores	average age of trees reaction wood eccentricity growth injuries TRD abrupt growth changes	avalanches confirmed in 1951 and 1977	year
	Monbiel, canton Grisons (Switzerland)	avalanche	65 *Picea abies* (17 †) 1 *Larix decidua*	cross-sections, 32 cores, 10 wedge-cuts			
Mundo *et al.*, 2007	valley of Martial, Tierra del Fuego (Argentina)	avalanche	*Nothofagus pumilio*	40 cores, 20 wedge-cuts	growth injuries abrupt growth changes eccentricity	avalanche confirmed in 1976	year
Reardon *et al.*, 2008	Glacier National Park, Montana (USA)	avalanche	109 (69 †)[1]	91 cross-sections, 64 cores	growth injuries reaction wood abrupt growth changes	1936-2003 1910-2003[2]	year
Decaulne and Sæmundsson, 2008	valley of Fnjóskadalur (Iceland)	avalanche	10 *Betula pubescens*	28 cores	structure of habit growth injuries reaction wood	40s-2006	year
Muntán *et al.*, 2009	6 localities Catalan Pyrenees (Spain)	avalanche	448 *Pinus uncinata*	cores	abrupt growth changes reaction wood growth injuries	1758-2008 (depending on the locality)	year
Casteler *et al.*, 2009	Loma del Las Pizaras, Santa Cruz (Argentina)	avalanche	117 *Nothofagus pumilio*	58 cross-sections, 112 cores, 1 wedge-cut	growth injuries abrupt growth change eccentricity reaction wood	1870-2003	year
Laxton and Smith, 2009	Ratoli, region Lahul, Himálaj (India)	avalanche	36[3]	cores, cross-sections	growth injuries TRD	1972-2005	year
Corona *et al.*, 2010	Massif de l'Oisans French Alpes (France)	avalanche	181 *Larix decidua* (about 30% †)	150 cross-sections, 328 cores	TRD reaction wood callus abrupt growth changes	1912-2007	year
Germain *et al.*, 2010	8 low-elevation paths 12 paths in highlands Gaspé peninsula, Quebec (Canada)	avalanche	1049 not specified	1592 cross-sections	growth injuries reaction wood	1838-2000 (the path with the longest chronology)	year
Köse *et al.*, 2010	Topçular Küre-Kastamonu (Turkey)	avalanche	61 *Abies bornmuelleriana* (some of them †)	122 cores	reaction wood growth injuries abrupt growth changes	avalanche confirmed in 1992	year
Garavaglia and Pelfini 2011	Val Mala Trentino (Italy)	avalanche	88 *Picea abies* (17 †)	17 cross-sections, cores	reaction wood TRD growth injuries eccentricity	avalanche confirmed in 2001	year

* without trees used for reference chronology building
† deadwood
[1] sampled species aren't specified in the article; *Pseudotsuga meziensii* dominates in the region with spots of *Populus tremuloides*, *Pinus contorta* a *Larix occidentalis*
[2] combined with historic written records
[3] sampled species aren't specified in the article; *Cedrus deodara, Pinus wallichiana, Abies pindrow, Betula utilis* a *Picea smithiana* grow in the locality

Casteller *et al.*, 2011	Lago del Desierto Santa Cruz (Argentina)	avalanche	95 *Nothofagus pumilio*	105 cross-sections, 3 wedge-cuts	growth injuries eccentricity reaction wood abrupt growth changes	1885-2004	year
Corona *et al.*, 2012	Arve Valley Northern French Alpes (France)	avalanche	175 *Larix decidua* 34 *Picea abies*	452 cores	abrupt growth change reaction wood TRD growth injuries	1771-2010	year
Decaulne *et al.*, 2012	valley of Fnjóska-dalur (Iceland)	avalanche	39 *Betula pubescens*	22 cross-sections, 17 cores	eccentricity abrupt growth changes	1906-2009	year
Stoffel *et al.*, 2005b	Täschgufer canton Valais (Switzerland)	rockfall	135 *Larix decidua*	564 cores	TRD structure of habit growth injuries reaction wood	1600-2002	decade (1600-1980) year (1950-2002)
Stoffel *et al.*, 2005c	Täschguber canton Valais (Switzerland)	rockfall	18 *Larix decidua*	270 cross-sections	growth injuries TRD	1977-2001	part of growing season
Perret *et al.*, 2006	Diemtigtal, Bernese Oberland (Switzerland)	rockfall	33 *Picea abies*	33 cross-sections	growth injuries TRD	1881-2000	year part of dendro-chronological year in case of injuries
Schneuwly and Stoffel, 2008a	Saas Balen, canton Valais (Switzerland)	rockfall	176 *Larix decidua* 14 *Picea abies* 1 *Pinus cembra*	796 cores, 141 cross-sections	TRD growth injuries abrupt growth changes callus reaction wood	1957-2006	year
Schneuwly and Stoffel, 2008b	Saas Balen canton Valais (Switzerland)	rockfall	23 *Larix decidua* 8 *Picea abies* 1 *Pinus cembra*	123 cross-sections	growth injuries TRD	1975-2006	part of growing season
Migoń *et al.*, 2010	Włostova-Suchawa, Kamienne hory (Poland)	rockfall	32 *Picea abies*	32 cross-sections, 30 cores	growth injuries reaction wood TRD	1859-2007	year
Moya *et al.*, 2010	Solà d' Andorra (Andorra)	rockfall	227 *Quercus robur* 49 *Quercus ilex*[4]	cross-sections, wedge-cuts	growth injuries	1959-2001	part of dendro-chronological year
Šilhán, 2010a	Smrk, Moravskoslezské Beskydy Mts.	rockfall	39 *Acer pseudoplatanus* 12 *Picea abies* 6 *Fagus sylvatica*	168 cores	growth injuries abrupt growth changes TRD	1951-2008	year
Šilhán, 2011	Lysá Hora, Moravskoslezské Beskydy Mts.	rockfall	35 *Ulmus glabra* 11 *Fagus sylvatica* 9 *Acer pseudoplatanus* 3 *Picea abies*	cores	abrupt growth change TRD reaction wood growth injuries	1905-2011	temporal and spatial variation of event frequency
	Ropice, Moravskoslezské Beskydy Mts.	rockfall	106 *Picea abies* 4 *Acer pseudoplatanus* 4 *Fagus sylvatica* 1 *Sorbus aucuparia*			1899-2011	
Stoffel *et al.*, 2011	Rodadero, Iztaccíhuatl volcano (Mexico)	rockfall	24 *Pinus hartweigii*	4 cross-sections, 82 cores	abrupt growth change growth injuries reaction wood	1924-2008	year
Yoshida *et al.*, 1997	Ochiushinai, Rishiri island (Japan)	flow	6 *Abies sachalinensis* (all †)	cross-sections	year of germination year of death	1849-1979	decade
Baumann and Kaiser, 1999	Multetta, Val Müstair (Switzerland)	flow	57 *Pinus mugo* (6†)	cores, cross-sections	abrupt growth changes growth injuries adventitious roots	beggining of 16th century – 1990	year
Santilli and Pelfini, 2002	Valle della Casina, Lombardy (Italy)	flow	53 *Pinus montana* (1 †)	cores, cross-sections	reaction wood growth injuries	1837-1998	year – 5 years
Wilkerson and Schmid, 2003	Glacier National Park Montana (USA)	flow	?	40 cores, 13 cross-sections	year of germination	1857-2000	minimum age estimation
May and Gresswell, 2004	Oregon Coast Range (USA)	flow	*Pseudotsuga menziesii* *Tsuga heterophylla*	cores	year of germination	>90 years	minimum age estimation

[4] only 22 individuals of *Quercus ilex* were finaly used for the analysis, because of very frequent presence of false-rings (evergreen species)

Stoffel *et al.*, 2005a	Ritigraben, canton Valais (Switzerland)	flow	>1200 *Larix decidua* *Picea abies* *Pinus cembra*	2450 cores	reaction wood abrupt growth changes TRD	1605-2002	year
Bollschweiler and Stoffel, 2007	Reuse de Saleinaz, canton Valais (Switzerland)	flow	148 *Larix decidua* 49 *Pinus sylvestris* 31 *Picea abies*	cores	TRD abrupt growth changes reaction wood growth injuries	1743-2003	year
	La Fouly, canton Valais (Switzerland)	flow	42 *Picea abies* 8 *Larix decidua*			1862-2003	
Bollschweiler *et al.*, 2007	Blatten b. Naters, canton Valais (Switzerland)	flow	401 *Picea abies* *Larix decidua*	802 cores	TRD reaction wood abrupt growth changes growth injuries	1867-2005	year
Pelfini and Santilli, 2008	Valle del Galo Lombardy (Italy)	flow	757 *Pinus montana*	cores, cross-sections	abrupt growth change growth injuries reaction wood	1875-2003	year part of the year in some cases
Bollschweiler *et al.*, 2008	Grosse Grabe, canton Valais (Switzerland)	flow	261 *Larix decidua* *Picea abies*	222 cores	year of germination TRD reaction wood abrupt growth changes growth injuries	1782-2005	year
Šilhán and Pánek, 2008	Travný, Ostrý, Smrk, Moravskoslezské Beskydy Mts. (Czech Republic)	flow	*Picea abies* *Fagus sylvatica* *Alnus glutinosa*	52 cores, 21 cross-sections	abrupt growth changes growth injuries	1939-2002	year
Stoffel and Bolschweiler, 2009b	Péterey canton Valais (Switzerland)	flow	35 *Larix decidua*	70 cores	TRD growth injuries reaction wood abrupt growth changes	1862-2007	year
Sorg *et al.*, 2010	Geisstriftbach, canton Valais (Switzerland)	flow	26 *Larix decidua* 2 *Picea abies*	54 cores, 7 cross-sections	year of germination growth injuries exposed tree roots decapitation TRD reaction wood abrupt growth changes	1913-2006	year
Arbellay *et al.*, 2010	Illgraben canton Valais (Switzerland)	flow	80 *Alnus incana* 29 *Populus* sp. 28 *Betula* sp. 15 *Salix caprea* 2 *Sambucus nigra*	104 cores, 118 wedge-cuts, 93 cross-section	growth injuries abrupt growth changes	1917-2008	part of growing season
Bollschweiler and Stoffel, 2010	Birchbach, canton Valais (Switzerland)	flow	201 *Larix decidua* 9 *Picea abies*	cores	TRD growth injuries reaction wood abrupt growth changes	1752-2006	year
Owczarek, 2010	Wedel Jarlsberg Land, Svalbard (Norway)	flow	*Salix reticulata* *Salix polaris*	cross-sections	reaction wood year of germination growth injuries	1955-2010	year
Šilhán, 2010b	Slavíč, Moravskoslezské Beskydy Mts. (Czech Republic)	flow	6 *Picea abies* (1 †)	3 cross-sections, 3 cores	abrupt growth changes growth injuries on roots	debris-flows confirmed in 1972 and 1997	year
Procter *et al.*, 2011	Gamperdonatal, Voralberg (Austria)	flow	268 *Pinus mugo* ssp. *uncinata* 164 *Picea abies* 10 *Abies alba* (some †)	779 cores, 69 cross-sections, 2 wedge-cuts, 4 root samples	abrupt growth change TRD growth injuries reaction wood	1839-2010	year
Mayer *et al.*, 2010	Gratzental, Tyrol (Austria)	„debris-flood“	224 *Picea abies* 3 *Larix decidua*	490 cores, 10 cross-sections	abrupt growth changes TRD reaction wood growth injuries	1800-2008	year
Bollschweiler *et al.*, 2011	torrent de la Greffe canton Valais (Switzerland)	„debris-flood“	44 *Picea abies* 55 angiosperms[5]	159 cores, 31 wedge-cuts, 16 cross-sections	TRD abrupt growth changes reaction wood growth injuries	1900-2007	year

[5]*Fraxinus excelsior, Fagus sylvatica, Acer* sp., *Ulmus glabra, Robinia pseudoacacia, Viburnum lantana, Salix caprea, Alnus incana, Populus tremula, Sorbus aria*

Bollschweiler *et al.*, 2010	Popocatépetl (Mexico)	lahar	22 *Pinus hartwegii* 21 *Abies religiosa* 19 *Pinus ayacahuite*	137 cores, 3 cross-sections	abrupt growth changes TRD growth injuries reaction wood	1795-2008	year
Corominas and Moya, 2010	Tordó torrent, Eastern Pyrenees (Spain)	flow	196 *Pinus sylvestris*	wedge-cuts, cross-sections, cores	year of germination growth injuries abrupt growth changes reaction wood	1949-2000	year
	Clot d'Esquers, Eastern Pyrenees (Spain)	landslide	49 *Pinus sylvestris*	? (cores)	reaction wood eccentricity year of germination	1932-1993	year
Corominas and Moya, 1999	basin of Llobregat r., Pyrenees (Spain)	landslide local flows	250 not specified	cores	eccentricity growth injuries reaction wood	1926-1995	year
Fantucci and Sorriso-Valvo, 1999	Greci, Calabria (Italy)	landslide local flows	24 *Quercus pubescens*	cores	abrupt growth changes bending of the stem	1820-1994	year
Gers *et al.*, 2001	NW Rheinhessen (Germany)	landslide	28 *Crataegus oxyacantha*	cores	abrupt growth change reaction wood	1970-1997	year
Grau *et al.*, 2003	Northwestern sub-tropical Argentina	landslide	22 *Alnus acuminata*	cores	abrupt growth change year of germination	landslide confirmed in 1983	year
Carrara and O'Neill, 2003	Bench road Gravelly range, Montana (USA)	landslide	11 *Pseudotsuga menziesii* (1 †)	7 cross-sections, 4 cores	abrupt growth changes reaction wood growth injuries	1855-1993(5)	year
	Cliff lake Gravelly range, Montana (USA)	landslide	10 *Pseudotsuga menziesii* (1 †)	9 cross-sections, 1 core			
	Freezeout lake Gravelly range, Montana (USA)	landslide	7 *Pseudotsuga menziesii* 2 *Pinus contorta* 1 *Abies lasiocarpa* 1 *Pinus flexilis*	9 cross-sections, 2 cores			
Stefanini, 2004	Secchio, Emilia-Romagna (Italy)	landslide	24 *Quercus cerris*	48 cores	abrupt growth changes	1920-2001	part of growing season
Paolini *et al.*, 2005	3 localities provinces Tucumán,Jujuy (Argentina)	landslide	*Alnus acuminata*	cores, cross-sections	year of germination abrupt growth changes	1935-2002	year
Wieczorek *et al.*, 2006	Meadow Run Virginia (USA)	landslide	3 *Sassafras albidum* 2 *Quercus rubra* 2 *Pinus virginiana* 1 *Quercus alba* 1 *Nyssa sylvatica* 1 *Kalmia latifolia*	cores, cross-sections	year of germination dating of adventitious sprouts abrupt growth changes eccentricity	1850-2002	year
Guida *et al.*, 2008	Monte Sirino Calabria (Italy)	landslide	54 { *Quercus cerris* *Alnus cordata* *Castanea sativa*[6] *Juglans regia* *Populus canadensis*[6] *Robinia pseudoacacia*	cores	abrupt growth changes eccentricity	1959-2004	year
Van Den Eeckhaut *et al.*, 2009	Koppenbrg, Flemish Ardennes (Belgium)	landslide	147 *Fagus sylvatica* (samples only from 19)	habit analysis 13 cross-sections, 32 cores	structure of habit eccentricity abrupt growth changes	1910-1999	year
Bégin and Filion, 2010	Poste-de-la-Baleine, Qubec (Canada)	landslide	363 *Picea glauca* (303 only for minimal age estimation)	cross-sections, cores (for minimal age estimation)	abrupt growth changes reaction wood year of germination	landslides confirmed in 1818, 1839 and 1846	part of growing season
Bollati *et al.*, 2012	Ombrone river basin (Italy)	landslide	45 *Pinus pinea*	cores, cross-sections	abrupt growth changes reaction wood	1990-2009	year
Lopez Saez *et al.*, 2012a	Bois Noir, Barcelonnette Basin (France)	landslide	79 *Pinus uncinata*	300 cores, 4 cross-sections	reaction wood abrupt growth change	1874-2009	part of growing season
Lopez Saez *et al.*, 2012b	Aiguettes landslide, Ubaye valley, southern French Alps (France)	landslide	223 *Pinus uncinata*	892 cores	age structure abrupt growth change reaction wood growth injuries	1890-2011	year part of growing season

[6] these species have been found useless for dendrogeomorphological purpouses and they were excluded out of the analysis; finally, samples only from 34 trees were evaluated

Lopez Saez *et al.*, 2012c	Pra Bellon landslide Ubaye valley, southern French Alps (France)	landslide	403 *Pinus uncinata*	1563 cores	year of germination abrupt growth change reaction wood growth injuries	1848-2011	year
Van der Burght *et al.*, 2012	Grossgufer canton Valais (Switzerland)	rockslide	269 *Larix decidua* (1792 budscale-counting) 45 *Picea abies* 39 *Betula pendula*	cross-sections counting budscale scars	year of germination	confirmed origin of talus in 1991	minimum age estimation
Stoffel *et al.*, 2006	Birchbach, canton Valais (Switzerland)	avalanche and flow	251 { *Larix decidua*, *Picea abies*	520 cores	TRD reaction wood abrupt growth changes growth injuries	1750-2002	part of growing season
Malik and Owczarek, 2009	Červená hora Hrubý Jeseník (Czech Republic)	avalanche and flow (not distinguished)	20 *Picea abies* 8 *Fagus sylvatica* 16 not specified †	cores, cross-sections	abrupt growth changes year of death	1912-2004	year
Szymczak *et al.*, 2010	Meretschibach, canton Valais (Switzerland)	avalanche and flow	57 *Picea abies* 12 *Alnus incana* 9 *Sorbus aucuparia* 4 *Betula pubescens* 2 *Larix decidua* 9 others[7]	171 cores, 34 wedge-cuts, 11 cross-sections	TRD abrupt growth changes reaction wood growth injuries	1930-2008	part of growing season
Kogelnik-Mayer *et al.*, 2011	Reiselehnrinne, Tyrol (Austria)	avalanche and flow	372 *Picea abies*	731 cores, 41 cross-sections	abrupt growth changes reaction wood TRD growth injuries	1821-2009	part of growing season

[7] 2 *Abies alba*, 2 *Acer pseudoplatanus*, *Laburnum alpinum*, *Corylus colurna*, *Ulmus glabra*, *Fraxinus excelsior*, *Buddleja daviddi*

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