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Dating past geomorphic processes with tangential rows of traumatic resin ducts

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Abstract

Past activity of geomorphic processes can be reconstructed on tree-ring series using the presence of injuries, reaction wood or abrupt changes in the annual increment. The analysis of these features provides valuable data on years with process activity. In contrast, an intra-annual dating has so far normally only been possible through the analysis of injuries. In this technical note, it is shown that, in tree-ring studies realized with conifers, resin ducts may have the potential for providing information on the intra-seasonal timing of past geomorphic processes as well. However, because ducts may occur as a result of influences other than geomorphic, detailed field investigations and the identification of processes present at the study site imperatively need to precede dendrogeomorphological investigations.

Data obtained from 1298 cross-sections indicate that the presence of resin ducts in *Picea abies* (L.) Karst. and *Larix decidua* Mill. can be considered to be the result of geomorphic activity if they form tangentially oriented rows with a compact and continuous arrangement of traumatic ducts. The presence of resin ducts may also help to improve the quality of reconstructions in studies using *Abies alba* Mill. as vertical resin ducts occur exclusively at or next to injuries. In contrast, resin ducts apparently cannot be used for dendrogeomorphological analyses of *Pinus* ssp.

Keywords: Resin ducts; Geomorphic processes; Dendrogeomorphology; Conifers

Introduction

Reconstructions of past geomorphic processes and events are generally based upon the inspection and dating of visible injuries (e.g., LePage and Bégin, 1996; Baumann and Kaiser, 1999; Hohl et al., 2002; Stoffel and Perret, 2006; Stoffel and Bollschweiler, 2008), the presence of reaction wood (e.g., Clague and Souther, 1982; Denneler and Schweingruber, 1993; Fantucci and Sorriso-Valvo, 1999; Stefanini, 2004) or on abrupt changes in the yearly increment of trees following an event (e.g., LaMarche, 1968; Strunk, 1997; Bachrach et al., 2004; Stoffel et al., 2005a, 2006). Also, the age of trees colonizing geomorphic forms can be assessed to determine the minimum ages of surfaces or deposits (e.g., Alestalo, 1971; Motyka, 2003, Harrison et al., 2006; Pierson, 2007).

Whilst all of these approaches provide valuable data on periods or years with geomorphic activity, a high-resolution, intra-annual dating has so far only normally been possible through the analysis of injuries. Reaction wood caused by tilting events, in contrast, has been shown to occur, at best, in the outer part of the growth

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ring of the year following tilting. In a similar way, "abrupt" changes in ring width (i.e. growth suppression or release) could not always be allocated within the growth ring either. For these reasons, several studies have begun to analyze tangential rows of traumatic resin ducts (TRD) over the last few years in order to improve the dating accuracy in dendrogeomorphological research (Lafortune et al., 1997; Stoffel et al., 2005b, c, 2006, 2008; Stoffel and Beniston, 2006), but these did not provide details on what TRD looked like and which criteria were used to consider this feature in the reconstructions.

In the present technical note, (i) examples are provided as to when and how TRD may be used for the dating of past geomorphic activity. In addition, the paper aims at (ii) documenting to what degree the inclusion of TRD may improve dating precision or the number of dated events, before (iii) limitations of the approach are highlighted.

Which tree species produce resin and what causes formation of traumatic resin duct?

Resin ducts are formed as a normal feature of development in tissues and organs, or their formation may be induced by external factors: Whilst pine trees produce copious amounts of resin terpenoids in the constitutive wood and developing secondary xylem (Phillips and Croteau, 1999), most other species limit the production of resin, under normal conditions, to the phloem in order to maintain an outer defense barrier (Martin et al., 2002). De novo formation of TRD in the developing secondary xylem is, by contrast, only observed after insect attack, fungal elicitation or any form of mechanical wounding (e.g., Fahn et al., 1979; Langenheim, 2003; McKay et al., 2003; Hudgins et al., 2004).

Mechanical wounding of the cambium and the formation of resin ducts may occur as the result of abrasion processes and wood-penetrating impacts caused by various geomorphic processes, including rockfall, rockslides, debris flows, flooding or snow avalanches. In addition, more superficial scars in juvenile trees may be the result of ungulate fraying and browsing. The presence of lateral tension in relation to the radial growth of the stem has also been reported as a trigger for resin-duct formation (Hug, 1979). Lastly, dendroecological studies have shown recently that extreme climatic conditions (droughts, water stress) can lead to the formation of resin ducts in certain conifer species as well (e.g., Wimmer and Grabner, 1997; Levanic, 1999; Rigling et al., 2002, 2003).

Jeffrey (1905) made a classification of conifers based on the anatomy of their secretory structures: In the stem of fir (*Abies* ssp.), cedar (*Cedrus* ssp.), hemlock (*Tsuga* ssp.), and golden larch (*Pseudolarix* ssp.), resin-producing cells form blisters, which are sac-like structures lined by epithelial cells. These cells are short-lived, and their walls become lignified during development (Nagy et al., 2000). Tube-like resin ducts represent a more complex structure and are found in the wood and bark of spruce (*Picea* ssp.), pine (*Pinus* ssp.), larch (*Larix* ssp.), and Douglas fir (*Pseudotsuga* ssp.). In these genera, resin is synthesized by thin-walled, long-lived secretory epithelial cells (Nagy et al., 2000).

But how much time does it take a tree to produce resin ducts after disturbance? Several experimental studies highlight that TRD are formed almost immediately after an event: Given any insect attack, fungal elicitation, or mechanical wounding occurred during the growth period of the tree, resin production starts only a few days after the event, and axial ducts emerge from the developing secondary xylem within less than 3 weeks after disturbance (see Ingemarsson and Bollmark, 1997; Ruel et al., 1998; Martin et al., 2002; McKay et al., 2003; Luchi et al., 2005).

When should traumatic resin ducts be considered to be the result of geomorphic processes?

It has been illustrated above that resin ducts may result from various disturbances. Consequently, detailed field studies, as well as the identification of processes present at the study site, imperatively need to precede dendrogeomorphological investigations. In addition, data from undisturbed reference trees must be sampled so as to separate years with widespread resin-duct formation caused by insect attacks or climatic events (i.e. droughts) from TRD induced by geomorphic processes. The appearance and nature of resin ducts then need to be analyzed in the area of wounding, abrasion or decapitation so as to define the characteristic features of "geomorphic resin-duct events". In this technical note, the identification of such features was based on 1298 cross-sections (949 scars) of different conifer species (i.e. *Abies alba* Mill., *Larix decidua* Mill., *Picea abies* (L.) Karst., *Pinus cembra* ssp. *sibirica* and *Pinus sylvestris* L.). The selected samples were taken from trees that have been scarred or abraded by past rockfall, debris flows or snow avalanches. An overview of the material analyzed is provided in Table 1. In a subsequent step, the characteristic features of tangential rows of TRD developed next to wounds were compared with those observed on 4336 increment cores of trees injured by rockfall, debris flow and snow-avalanche events (Table 2) so as to test the features and to identify "geomorphic resin-duct events" in these samples as well. As a rule, the first decade of juvenile growth rings has

Table 1. Material used for the determination of characteristic features of "geomorphic resin-duct events"

Geomorphic process	Study site	Species	Samples	Scars	Data source
Rockfall	Altdorf	Abies, Picea	193	86	Stoffel (2005, 2006)
Rockfall	Täschgufer	Larix	270	180	Stoffel et al. (2005b)
Rockfall	Schwarzenberg	Picea	100	68	Perret (2005)
Rockfall	Schwarzenberg	Picea	33	301	Perret et al. (2006)
Debris flow	Laggina	Larix	280	45	Bollschweiler et al. (2008)
Snow avalanche	Sitstafol	Larix	324	212	Stoffel et al. (2007)
Snow avalanche	Gadmen	Picea	98	57	This study
Total			1298	949	

Table 2. Material used for the identification of characteristic "resin-duct events" on increment cores (for details see text; GD = growth disturbances incl. compression wood, scars, TRD and abrupt growth changes)

Geomorphic process	Study site	Species	Samples	GD	Data source
Rockfall	Täschgufer	Larix	564	761	Stoffel et al. (2005c)
Debris flow	Bruchji	Larix, Picea	802	960	Bollschweiler et al. (2007)
Debris flow	Ritigraben	Larix, Picea, Pinus	2450	2263	Stoffel and Beniston (2006)
Snow avalanche	Birchbach	Larix, Picea	520	561	Stoffel et al. (2006)
Total			4336	4545	

not been included in the analysis, as tree rings in seedlings tend to produce more resin ducts per unit area in general (Larson, 1994), but only a few ducts around wounds located near the pith (Bannan, 1936).

Data obtained from the cross-sections indicate that the presence of resin ducts should only be considered to be the result of a geomorphic process if they form tangentially oriented rows with a compact and continuous arrangement of traumatic ducts. Characteristic examples of tangential rows of TRD are given in Fig. 1(a) and (b), with microsections from *L. decidua* and *P. abies*. It has also been observed that the formation of continuous TRD is restricted to strong geomorphic impacts with subsequent major damage caused to the tree (e.g., wood-penetrating impacts, abrasion); otherwise, *P. abies* and *L. decidua* did not necessarily form tangential rows but rather only a limited number of scattered ducts in the tree ring. As such a vague distribution of resin ducts may be caused by processes other than geomorphic (e.g., climate, insect attack, fungal elicitation), they should not be used for dendrogeomorphological purposes so as to exclude misinterpretation and faulty dating of past geomorphic events.

In *A. alba*, vertical resin ducts are absent from the secondary xylem, except at injuries where they occur in tangential series (Bannan, 1936). Given the process causing the scars identified in the field, the presence of resin ducts in *A. alba* can be declared to be undoubtedly the result of geomorphic activity. Fig. 1(c) provides a typical example of TRD in *A. alba*.

Further reliable indicators for the presence of cambium damage by past geomorphic activity are multiple series of TRD occurring in the immediate vicinity of the wound. Examples of multiple tangential series of TRD in the year of wounding and succeeding years are illustrated in Fig. 2. Franceschi et al. (2002) suggest that these multiple series of TRD are formed as a result of continuous production of signaling agents over several growing seasons, and that the TRD belong to the same initial event.

Based on our data, it seems to be impossible to identify "geomorphic resin-duct events" in *P. cembra* and *P. sylvestris*. These two subspecies produce abundant vertical resin ducts in their phloem and xylem, but, at the same time, do not produce characteristic TRD next to injuries as a reaction to mechanical wounding (Fig. 3). These observations are in agreement with Münch (1923) or Bannan (1936), who reported that ducts in *Pinus* ssp. are practically always scattered and that loose tangential series with widely separated ducts occur only very rarely.

What is the "added value" of TRD analysis in dendrogeomorphological studies?

Abrasion processes and wood-penetrating impacts not only cause injuries to trees, but also leave TRD next

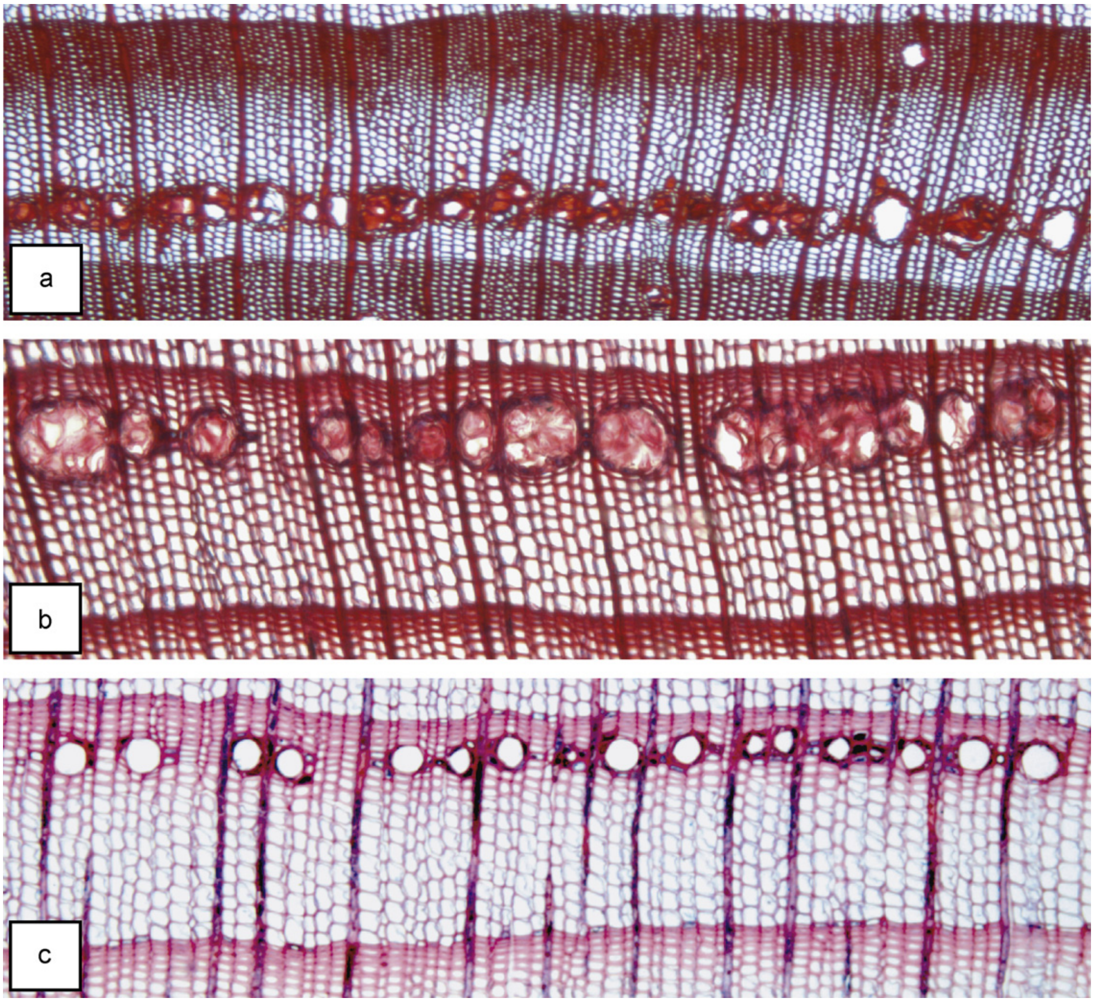

Fig. 1. Characteristic examples of tangential rows of traumatic resin ducts (TRD) bordering impact scars in (a) *Larix decidua* Mill., (b) *Picea abies* (L.) Karst. and (c) *Abies alba* Mill. (approximate magnification: 50 ×).

to the wound. Based on Bollschweiler et al. (2008), TRD can, on average, be identified in almost one-fifth of the total circumference remaining vital after the impact, and thus allow identification of events even if the cross-sections or increment cores are not taken directly at the location of the wound. This is especially helpful in the analysis of past events in *L. decidua* and *P. abies* where the thick bark and the sporadic peeling off of small bark pieces may totally conceal evidence of past events (Stoffel, 2005; Stoffel and Perret, 2006).

In addition, TRD develop in increasing numbers in the vertical and lateral extension of adult trees, even if the circumstances of the impact remain uniform (Thomson and Sifton, 1925; Bannan, 1936). This increase in the number of resin ducts apparently owes its origin to a greater sensitivity to wounding with age of species like *A. alba*, *L. decidua* and *P. abies*.

From our data, it also seems that TRD constitute the most commonly observed signature of a past growth anomaly on increment cores, and that some 44–86% of reconstructed growth disturbances would have remained undetected, had the presence of TRD not been taken into account (Table 3). The predominance of TRD is most obvious in the rockfall samples from 'Täschgufer', where century-old *L. decidua* trees were chosen for analysis. Data also shows that the large surfaces affected and the important volumes involved in debris flows and snow avalanches more commonly tilt trees and cause the subsequent formation of reaction wood than do individual rockfall fragments.

Fig. 4 illustrates that in the snow-avalanche samples gathered at 'Birchbach' and in the debris-flow trees selected at 'Bruchji', the loss of information would have been less important with 9% each. Disregarding TRD would have had, in contrast, drastic consequences for the analysis of past rockfall activity at 'Täschgufer' where 77% of all events would have been missed if we had taken into account the analysis of wounds, callus tissue, reaction wood, growth release and growth suppression alone.

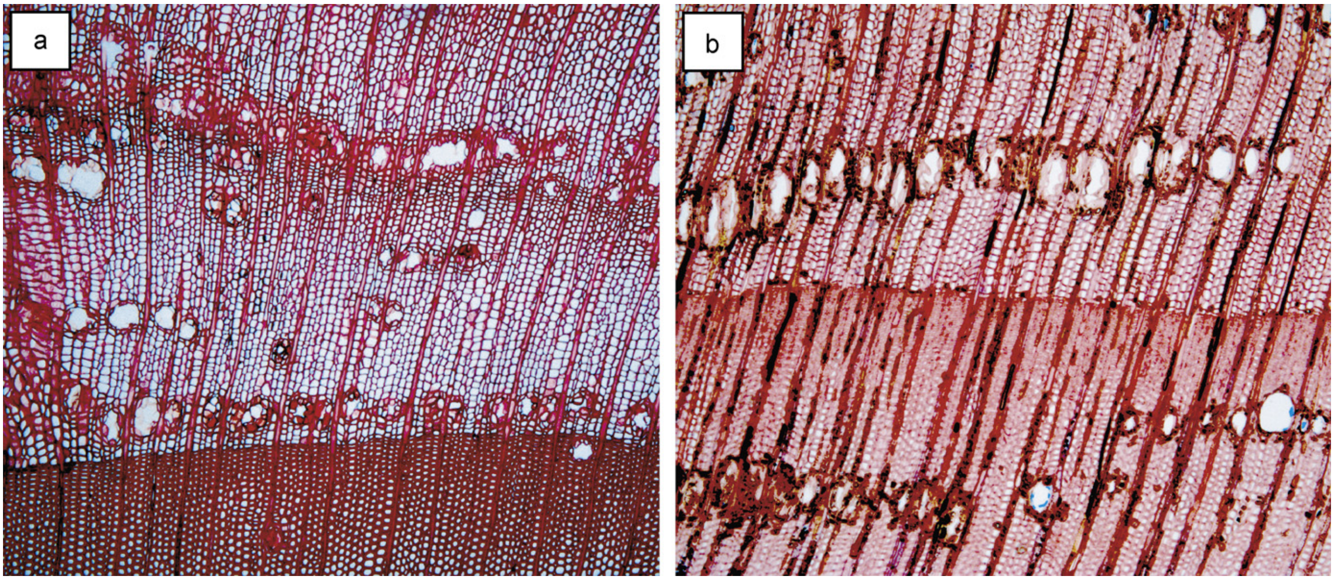

Fig. 2. After wounding, a tangential series is normally formed at the wound, but occasionally a number of later series may arise, either in the same or in succeeding rings. Multiple series of TRD in (a) *Larix decidua* Mill. and in (b) *Abies alba* Mill. (approximate magnification: 50 ×).

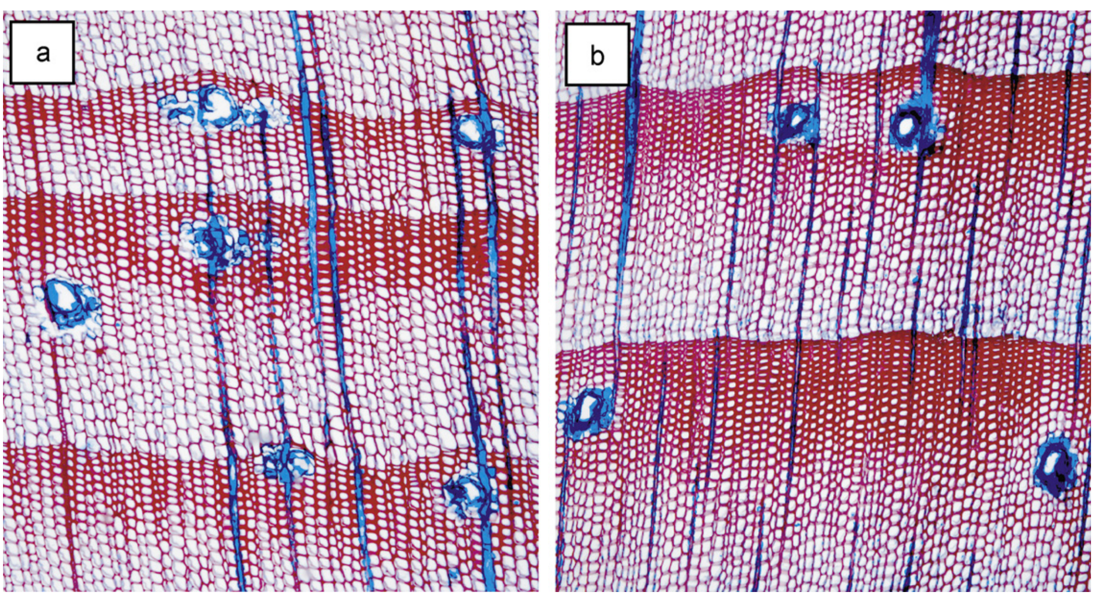

Fig. 3. (a) *Pinus sylvestris* L. and (b) *Pinus cembra* ssp. sibirica trees are not suitable for the dating of "geomorphic resin-duct events", as these species do not produce characteristic TRD as a reaction to wounding (approximate magnification: 50 ×).

Table 3. Relative importance of different tree-ring signatures used to date past geomorphic events

Signatures of past events (in %)	Rockfall Täschgufer	Debris flow Ritigraben	Debris flow Bruchji	Snow avalanche Birchbach
TRD	86	44	59	61
Wound/callus tissue	2	6	4	7
Reaction wood	3	32	15	22
Growth release	3	9	10	4
Growth suppression	6	9	12	6

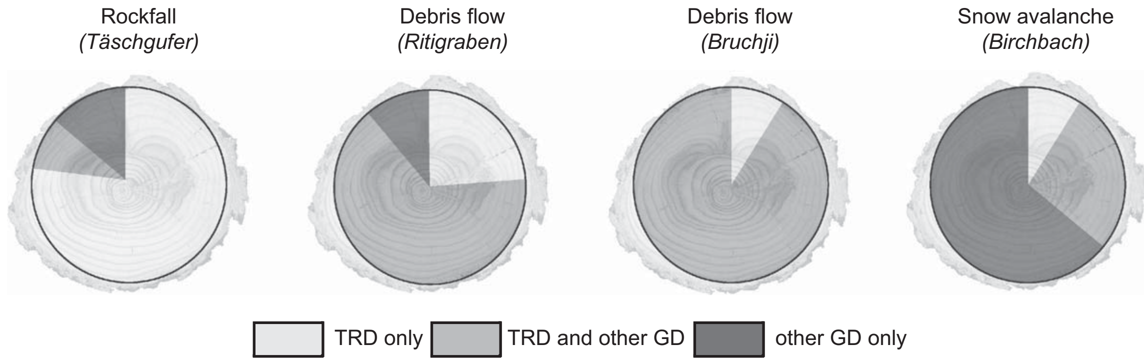

Fig. 4. Relative number of events dated via the presence of (a) TRD only, (b) TRD and other growth disturbances (GD; i.e. wounds, callus tissue, reaction wood, growth release, growth suppression) and (c) only growth disturbances (GD) other than TRD.

The importance of TRD analysis in geomorphic studies can be further emphasized by the results from the debris-flow study at 'Ritigraben': Here, a first detailed analysis focusing on all growth disturbances, except for TRD, yielded sufficient evidence for 53 events between AD 1605 and today (Stoffel et al., 2005a). A re-assessment of all growth disturbances, including TRD, allowed a densification of the frequency to 123 events as well as an extension of the reconstruction back to AD 1570 (Stoffel and Beniston, 2006; Stoffel et al., 2007, in press). Fig. 4 indicates that part of this increase was due to the identification of events that were only present on the tree-ring series via TRD (24%). On the other hand, events that have previously not been considered because of their weak confirmation in a few tree-ring series could now be dated with more confidence, as a large number of samples were showing TRD.

Where are the limitations of the TRD approach and what questions remain?

The consideration of tangential rows of TRD in dendrogeomorphological studies may help to improve and enlarge the reconstruction of past activity. Among the geomorphic processes analyzed in tree-ring research, debris flows, rockfall, rockslides, snow avalanche and flooding (carrying solid charge) appear to be particularly well suited for analysis. In addition, dating of windstorm events should be possible, and there is probably even a potential for earthquake studies. In contrast, the approach seems to be, at a first glance, of little help for landslide analyses, as this process preferably tilts trees and damages roots rather than causing injuries to stems.

Similarly, not all resin-producing species are equally well suited for the analysis of past geomorphic activity using TRD. *L. decidua* and *P. abies* have been shown to represent the two species with the largest potential, even more so as their thick bark regularly overgrows ('hides') evidence of past events. The approach can be used with *A. alba* to a limited degree as well, but because resin ducts are normally located very close to the injury, and as the later ones remain visible on the stem surface most of the time (Stoffel and Perret, 2006), the "added value" of TRD analysis can be considered to be of minimal value here. In contrast, resin ducts should not be considered for the analysis of past events when working with *P. sylvestris* or *P. cembra*, as they do not occur in tangential rows and are thus obviously produced by various kinds of external disturbances.

It is also known that if the injury has been severe, TRD may extend laterally and as far as several decimeters vertically from the wound with no, or only a small amount of, radial movement in the rings of *Larix* and *Picea* (Mayr, 1884; Bannan, 1936). As the thick bark and the sporadic peeling off of small bark pieces may totally hide evidence of past events in *L. decidua* and *P. abies*, it is often much easier to identify signatures of past events by the presence of TRD, rather than by scars on increment cores. But we still do not really know the maximal distance from the injury at which TRD can be identified in the tree-ring series and to what degree this distance would depend on the intensity of the impact. One of the few experimental studies existing suggests that decapitation of young *Pinus pinea* trees would result in resin ducts being formed in (at least) the first 10 cm below the wound (Lev-Yadun, 2002).

Finally, TRD may occur not only in the tree ring of the year of disturbance, but also in those rings formed in the years following an event. Although the tangential spread of TRD is usually most significant when it first occurs after an impact (Bollschweiler et al., 2008), important tangential extensions of TRD in the years following an event have been observed on a very limited number of samples as well. Consequently, analyses may run the risk of faulty dating if reconstructions are exclusively based on the presence of one single TRD occurring on one individual increment core.

Conclusions

This technical note has focused upon the potential of tangential rows of TRD in the analysis of past geomorphic processes in forested environments. Given that detailed analysis of resin ducts developed as a result of wounding or tree decapitation are performed and characteristic features for "geomorphic resin-duct events" assessed, TRD form a valuable tool for the identification of past rockfall, snow avalanche or debris-flow events in the tree-ring series of *L. decidua*, *P. abies* or *A. alba*. As conifers immediately produce resin ducts after mechanical wounding, the assessment of TRD within the tree ring may also improve dating precision and reduce the amount of misinterpreted dating caused by the potentially retarded onset of reaction wood or growth changes.

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