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Visual dating of rockfall scars in *Larix decidua* trees

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ABSTRACT

Dating past mass wasting with growth disturbances in trees is widely used in geochronology as the approach may yield dates of past process activity with up to subannual precision. Past work commonly focused on the extraction of increment cores, wedges, or stem cross sections. However, sampling has been shown to be constrained by sampling permissions, and the analysis of tree-ring samples requires considerable temporal efforts. To compensate for these shortcomings, we explore the potential of visual inspection of wound appearance for dating purposes. Based on a data set of 217 wood-penetrating wounds of known age inflicted to European larch (*Larix decidua* Mill.) by rockfall activity, we develop guidelines for the visual, noninvasive dating of wounds including (i) the counting of *bark rings*, (ii) a visual assessment of exposed wood and wound bark characteristics (such as the color and weathering status of wounds), and (iii) the relationship between wound age and tree diameter. A characterization of wounds based on photographs, randomly selected from the data set, reveals that young wounds typically can be dated with high precision, whereas dating errors gradually increase with increasing wound age. While visual dating does not reach the precision of dendrochronological dating, we clearly demonstrate that spatial patterns of and differences in rockfall activity can be reconstructed with both approaches. The introduction of visual dating approaches will facilitate fieldwork, especially in applied research, assist the conventional interpretation of tree-ring signals, and allow the reconstruction of geomorphic processes with considerably fewer temporal and financial efforts.

1. Introduction

In forested mountain environments, mass wasting processes frequently damage trees and leave wood-penetrating injuries or scratches on their bark (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014). As direct observations of geomorphic processes are rare and difficult to obtain over longer periods (Luckman, 1976), stem injuries and their dating with dendrogeomorphic techniques have been applied frequently in the past to reconstruct past process activity. In the case of processes involving high energies, such as rockfall, wounds represent by far the most common feature in stems affected by mass wasting activity (Stoffel et al., 2005a; Schneuwly and Stoffel, 2008; Moya et al., 2010). At the same time, wounds have also been considered key in dendrogeomorphic reconstructions of paleofloods (St. George, 2010; Ballesteros Cánovas et al., 2011), debris flows (Bollschweiler et al., 2007; Stoffel et al., 2008; Bollschweiler and Stoffel, 2010), or snow avalanches (Stoffel et al., 2006; Butler and Sawyer, 2008; Schläppy et al., 2014). Dendrogeomorphic techniques (Alestalo, 1971; Shroder, 1978; Stoffel and Corona, 2014) have been applied repeatedly to date growth reactions in trees affected by stem damage. Event dating focused mostly on scars or related proxy indicators, such as tangential rows of traumatic resin ducts (Bollschweiler et al., 2008; Stoffel, 2008; Schneuwly et al., 2009a,b). This well-established approach enables very accurate dating of historic events (Stoffel et al., 2005b,c, 2010; Corona et al., 2012) but is, at the same time, rather labor- and time-intensive (Trappmann and Stoffel, 2013). As a result, research has recently been directed toward the exploration of noninvasive, visual analysis of stem wounds to calibrate and validate rockfall simulations (Corona et al., 2013) or to estimate rockfall frequencies (Trappmann et al., 2014). Visual dating of wounds has not been used in the past, and the only assessment of visual wound inspection—using wound wood thickness as a wound age proxy—did not yield conclusive results (Fries, 2010).

Scars are defined here as 'the portion of the cambial zone where the cambium is killed by one injury' (Means, 1989, p. 1492), with scar infliction typically resulting in exposed wood. To protect itself against fungi and bacteria infestation, an injured tree will start to compartmentalize the affected wood (Shigo, 1986), form boundary zones within the bark (Biggs, 1985), and initiate the formation of anatomical changes within the xylem such as reduced tracheid or vessel lumina (Stoffel and Hitz, 2008; Arbellay et al., 2010, 2012, 2013) or the production of callus tissue (Neely, 1979, 1988; Delvaux et al., 2010)—a thin layer of undifferentiated cells as a response to injury that may help reestablish the vascular cambium after scarring (Smith and Sutherland, 2001). In the case of

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deep wounds, which are a common feature in trees injured by high-energy, geomorphic impacts (e.g., Dorren and Berger, 2006; Schneuwly-Bollschweiler and Schneuwly, 2012), trees will typically start to form callus as an extension of the undisturbed vascular cambium along the wound edges. Enhanced cell division leads to the new differentiated wound cambium (Oven and Torelli, 1999) that is responsible for the slow, centripetal overgrowth of wound wood and wound periderm with well-differentiated cells (Smith and Sutherland, 2001; Grünwald et al., 2002; Stobbe et al., 2002). The ongoing cell division also leads to the disruption of wound periderm and thus results in a constantly growing layer of dead tissues, hereinafter referred to as *wound bark*. While large scars on old trees may never become closed (Pallardy, 2010), small wounds in rapidly growing trees may completely heal over within only a few years through the fusion of tissues developing from the wound margins (Stoffel and Perret, 2006; Vasaitis et al., 2012). After fusion, annual growth rings are again produced normally (Neely, 1979).

Wound closure rates can be highly variable between species and individual trees. Factors influencing growth rates include, amongst others, initial scar size, tissues affected, tree vigor, season of wounding or scar position on the stem (Neely, 1979; Dujesiefken et al., 2005; Romero et al., 2009). Schneuwly-Bollschweiler and Schneuwly (2012) studied wound closure rates in *Larix decidua* Mill. trees affected by rockfall impacts and report wound closure rates averaging 6 mm y^{-1}. In their study, wound closure was found to be considerably increased in the first two years after scarring, and young trees with small stem diameters overgrew wounds more efficiently than older and larger trees.

While tree reactions to wounding are well understood in principle, no work currently exists on the development of wound bark and/or wound characteristics during and after wound closure. As a consequence, no attempts have been undertaken to date to use visible wound characteristics for dating purposes.

However, if analysis was based solely on visual dating, temporal efforts could be reduced by 50–60% as several steps involved in a classical dendrogeomorphic study (i.e., sample extraction and laboratory analysis) could be skipped. In view of this considerable reduction in temporal efforts, this paper therefore aims at developing a guideline for the dating of wounds in *L. decidua* trees that is based on externally visible wound characteristics. The key objectives were to (i) determine and characterize all age-dependent characteristics of wounds; (ii) develop a user-friendly dating concept using a limited number of key variables; (iii) explore the validity of visual dating in applied research; and (iv) verify the applicability of the dating concept through a series of tests performed with trained persons.

2. Material and methods

2.1. The data set

The data set used for the development of the visual dating approach consists of 217 rockfall wounds in *L. decidua* trees. Samples were selected from three sites in the Swiss Alps located between 1470 and 2240 m asl (Table 1). At the sites Saas Almagell (SA; Morel et al., 2015), Täschgufer (TG; Stoffel et al., 2005a), and Saas Balen (SB; Schneuwly and Stoffel, 2008), rockfall is the only process inflicting wounds to trees, and individual rockfall fragments typically do not trespass 1–2 m^3. Injuries were analyzed on stem cross sections ($N = 68$) at TG and SB and indirectly on increment cores at SA ($N = 149$). In the case of increment cores, a detailed photograph of each wound was also taken. Only trees showing single and strong signals (Kogelnig-Mayer et al., 2011; Stoffel and Corona, 2014) in their tree-ring series were included in the database. Trees showing several scars located close to each other on the trunk or ambiguous signals in the tree-ring record were discarded from further analysis so as to avoid false attribution of wound ages. Samples were processed following standard dendrochronological techniques (Bräker, 2002; Stoffel and Bollschweiler, 2008). Scar age was defined as the number of tree rings formed after wounding.

2.2. Characterization of wounds

Recent wounds typically exhibit nonweathered wood and bast fibers but lack overgrowing wound wood (Fig. 1). With increasing wound age, injuries will be closed successively from the wound margin toward the wound center. The outer margin of the bark overgrowing the wound is oldest and therefore may provide hints about injury age. Here, we classify wounds on the basis of seven variables which are assessed at the outer wound margin (Fig. 4), namely, *wound closure*, *bark ring count*, *color*, *resin*, *surface roughness*, *weathering,* and *transition wound–bark*.

We distinguish two categories of *wound closure*, namely *open* wound in cases where wood is (still) visible or *closed* wound in cases where the scar is completely overgrown. A *bark ring count* is *possible* if growth zones can be identified along the wound perimeter (Fig. 2) or *impossible* if bark rings cannot be observed.

The *color* of the outer wound margin (Fig. 3) typically is *purple*, similar to an intense reddish color, in rather fresh wounds in which the overgrowing wound wood is still rather thin. The color of wound margins will typically turn *brown* with time; a color that can also be described as reddish, yellowish, or slightly greyish. *Brown* wound colors typically are observed on thick overgrowing wound wood. *Black* is used to describe very dark wound surfaces, whereas the class *grey or bark color* is used in cases where the color of wound surfaces is similar to that of the surrounding, unaffected bark.

Resin typically is *glossy* for as long as it is (still) liquid and transparent; it turns *mat* as soon as the resin dries and thus becomes bright but nontransparent, or eventually even disappears. We recommend not including yellow to dark brown resin or dried resin burls. With respect to *surface roughness,* we distinguish between *smooth*, *rough,* or *bark-like* surface structures. While a smooth surface has almost no fissures or scales, a rough surface may contain shallow discontinuities and small scales. A *bark like* surface is characterized by fissures (mainly parallel to the stem axis) that can eventually lead to the formation of scale structures similar to those appearing in the unaffected surrounding bark; these wound surfaces will also tend to exhibit faint traces of old bark rings. The *weathering* of exposed wood and bast fibers starts as soon as wood is exposed to atmospheric conditions. *Fresh* wounds are characterized by intense wood and bast colors and/or spiky fibers sticking out of the exposed wood. *Weathered* wounds, by contrast, typically exhibit greyish and dried wood and bast structures. The *transition wound–bark* is defined here as *sharp* in cases where a pronounced cut of uninjured bark is visible at the wound margin. It is defined as *rounded* as soon as well-developed wound wood forms a less-pronounced cut but where the wound surface is still at a lower level as compared to the uninjured bark. The transition is defined as *flat* if wound healing has created an almost seamless transition from uninjured bark to wound bark.

Table 1
Characteristics of the three sites where wound samples were analyzed.

Site	Process	No. of samples	Location	Altitude	Source
Saas Almagell	rockfall	149	46°06′ N / 7°57′ E	1700–2240 m asl	Morel et al., 2015
Täschgufer	rockfall	35	46°04′ N / 7°47′ E	1780–1900 m asl	Stoffel et al., 2005a
Saas Balen	rockfall	33	46°09′ N / 7°55′ E	1470–1610 m asl	Schneuwly and Stoffel, 2008

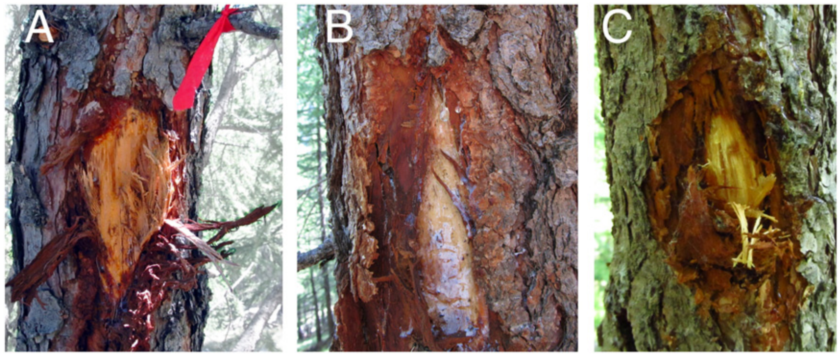

Fig. 1. *Recent* and *open* wounds with *fresh* exposed wood; wood and bast fibers are sticking out of the wound (A, C), which can also be covered by *glossy* resin (B); overgrowing wound wood has not yet developed on these samples.

2.3. Reduction of classification variables

The visual dating approach presented in this study is intended to be a user-friendly, easy-to-apply, and fast approach for nonscientists working on natural hazards and/or persons interested in information about the temporal frequency of geomorphic events at a specific site. As such, the approach has to be based on a small number of variables that, however, need to be accurate, easily obtained, and even more so powerful predictors of wound age.

One possibility to assess the reliability of variables is the evaluation of repeatability of classifications by test persons. We used a total of six test persons, all working in the field of dendrogeomorphology. After a briefing of <2 h, they classified wound variables on 20 photographs of wounds randomly selected from a data set of 150 wound pictures. The outcome is presented in Table 2 and illustrates the ranked reliability of all classification variables used in the assessment with an intraclass correlation coefficient (ICC). The ICC is a measure of reproducibility of classification and was used here to assess the level of agreement between the authors of the study and the test persons for all variables attributed to wounds on the photographs. To select the most suitable parameters, we ranked variables according to their reliability and predictive power. Reliability was assessed according to ICC values and frequency of occurrence in wounds. Predictive power was evaluated as a combination of (i) the number of distinguishable features per variable, (ii) the standard deviation (SD) of the features, and (iii) the range of values obtained per feature.

A Principal Component Analysis (PCA) was performed to identify the most relevant variables and to reduce the number of variables to be used for the visual dating procedure. Based on the component plot, grouping could be observed for several (ordinal transformed) variables (Fig. 5). Within each group, only the best criteria in terms of reproducibility and predictive power have been used to define a final set of visual dating parameters.

Based on the PCA, *transition wound–bark*, *color*, *surface roughness,* and *resin* appear as correlated variables, with wound *color* being the key variable within this group, well reproducible (ICC = 0.772) and an accurate estimator of scar age (four different categories with clearly distinct mean age values and a low SD). *Weathering* provides additional

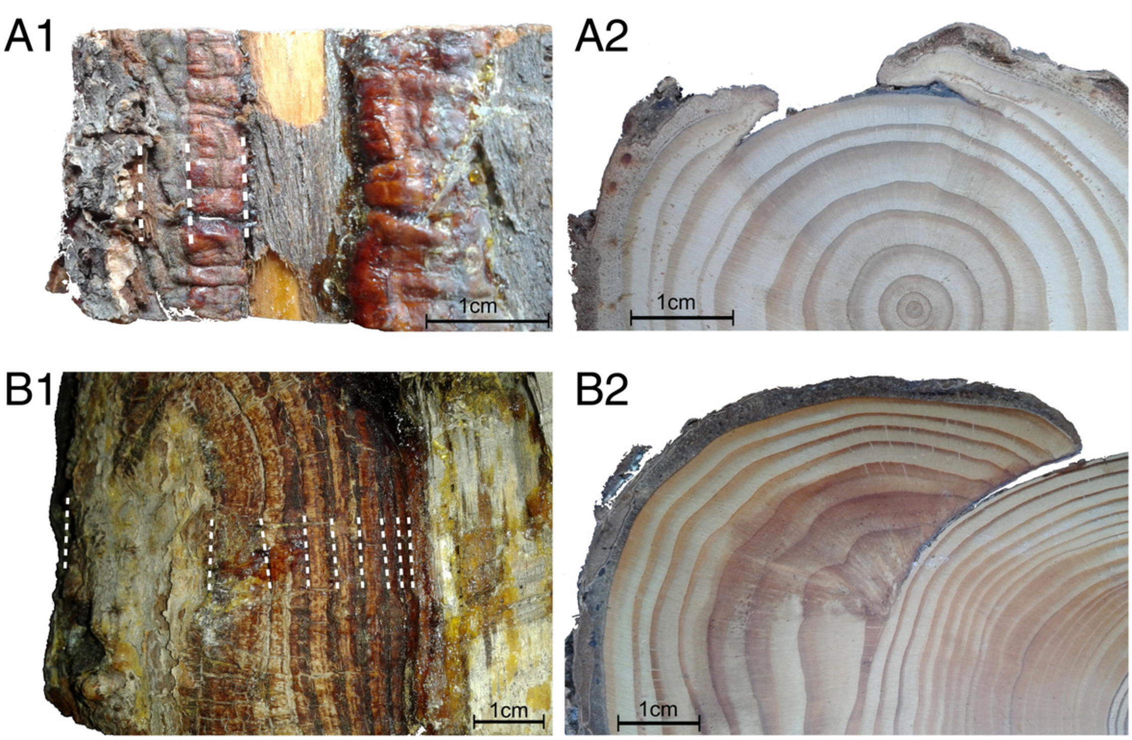

Fig. 2. Annual bark rings in the overgrowing wound bark and corresponding cross sections (bark ring borders are highlighted by white dotted lines); wound ages A1/A2 = 2 y, B1/B2 = 8 y.

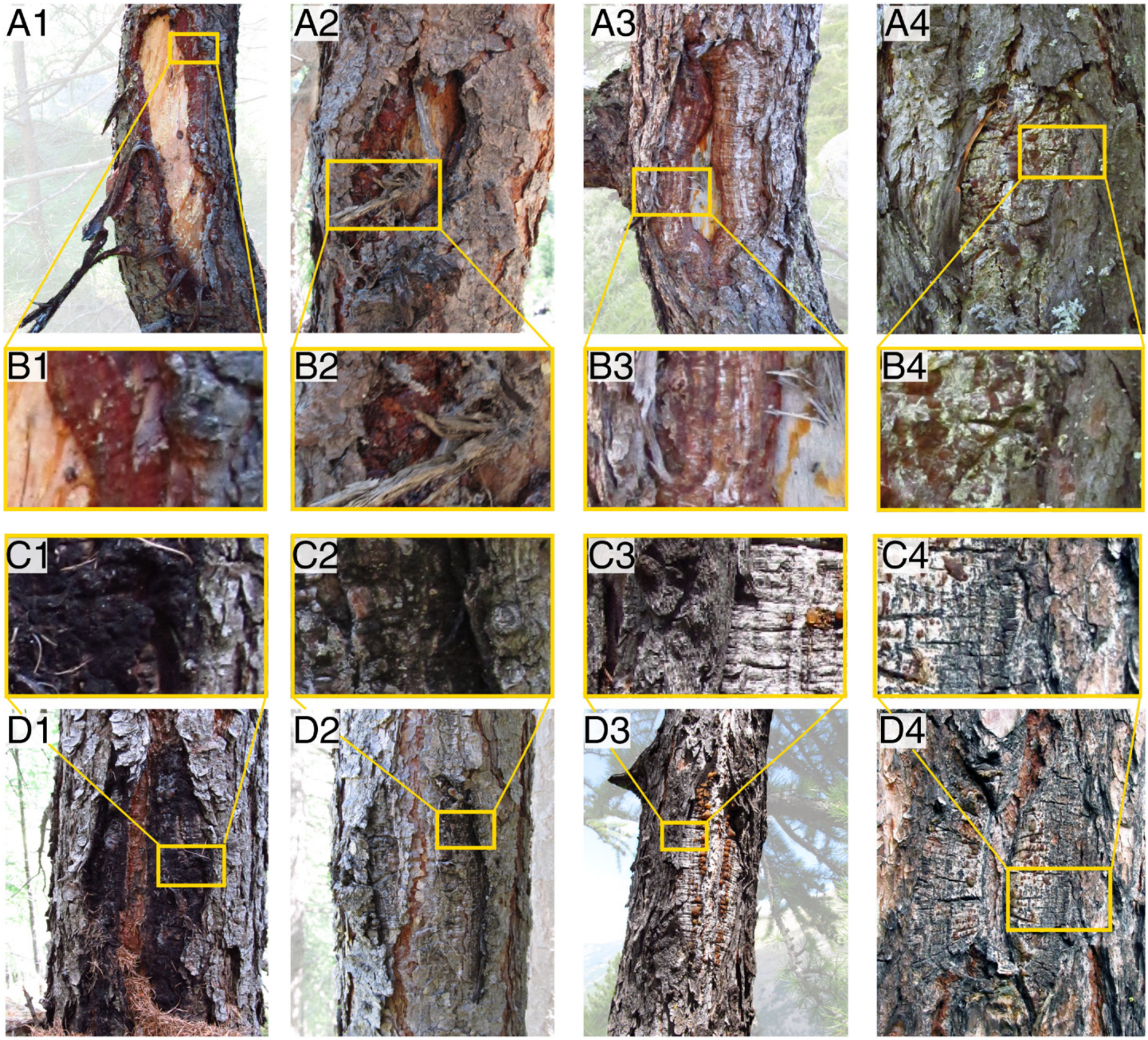

Fig. 3. Selection of wounds illustrating different *colors* at the outer wound margin: (A1/B1) *purple* wound margin, *fresh* weathering status, *open* injury; (A2/B2) *purple* wound margin, *weathered* wood fibers sticking out of the wound; (A3/B3) *brown* wound margin; (A4/B4) *brown* wound margin blurred by *mat* resin, *closed* wound; (C1/D1) and (C2/D2) *black* wound margin; (C3/D3) and (C4/D4) *old* injuries with *grey or bark-colored* wound margins and stretched wound bark.

and even more crucial information that cannot be provided by any other variable.

2.4. Relationship between tree diameter and wound age

While younger wounds can typically be defined with the variables illustrated above, visual characteristics alone have limited predictive power for older wounds, which are typically characterized by their grey (or bark like) wound bark color and laterally extended wound geometry resulting from secondary thickening of the stem axis. This lateral extension of wound bark on the stem surface can be described as a sequence of circular arcs with increasing radii and a constant central angle. Assuming constant radial tree-ring increment, the relative annual increase in arc length (i.e., arc length year x / arc length year x−1) will be greater for smaller radii, as will the degree of lateral stretching. For this reason, wounds in young trees are more likely blurred, older in appearance, and laterally extended. By contrast, wounds inflicted to older trees with smaller DBH increase are more likely to be conserved on the stem surface.

To develop an age estimator for old wounds, grey- or bark-colored wounds were extracted from the data set ($N = 53$). For these wounds, a statistically significant correlation was found between DBH and wound age (Fig. 6; linear regression through origin, $R^2 = 0.6$, $p < 0.001$). The standard error of estimate is 19 years. For *old* wounds, Eq. (1) can be used to estimate wound age:

$$A = 1.5 * DBH \tag{1}$$

where A is the wound age in years and DBH is the stem diameter at breast height measured in cm.

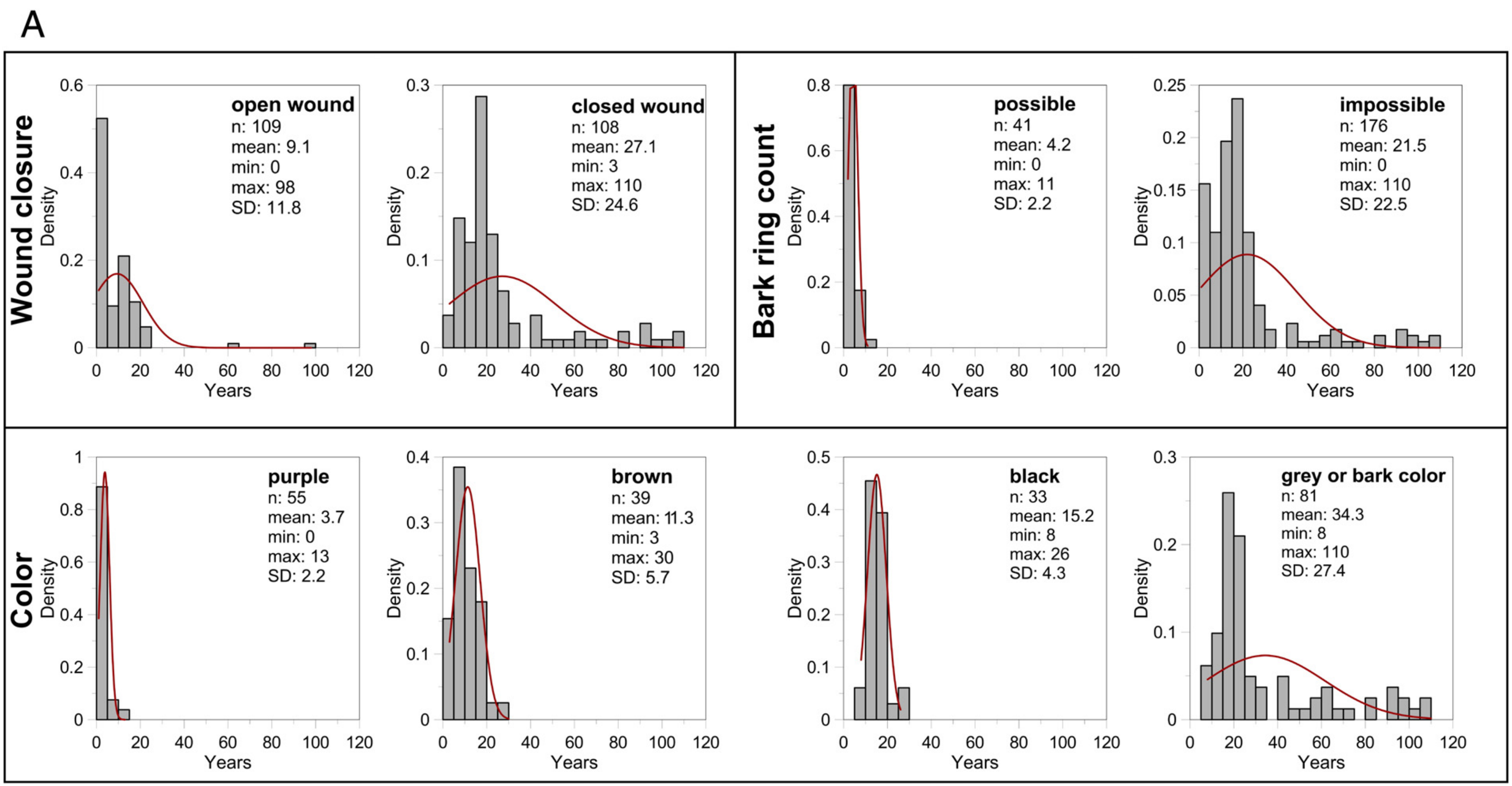

Fig. 4. (A) Features of analyzed wounds presented as histograms. (B) Features of analyzed wounds presented as histograms.

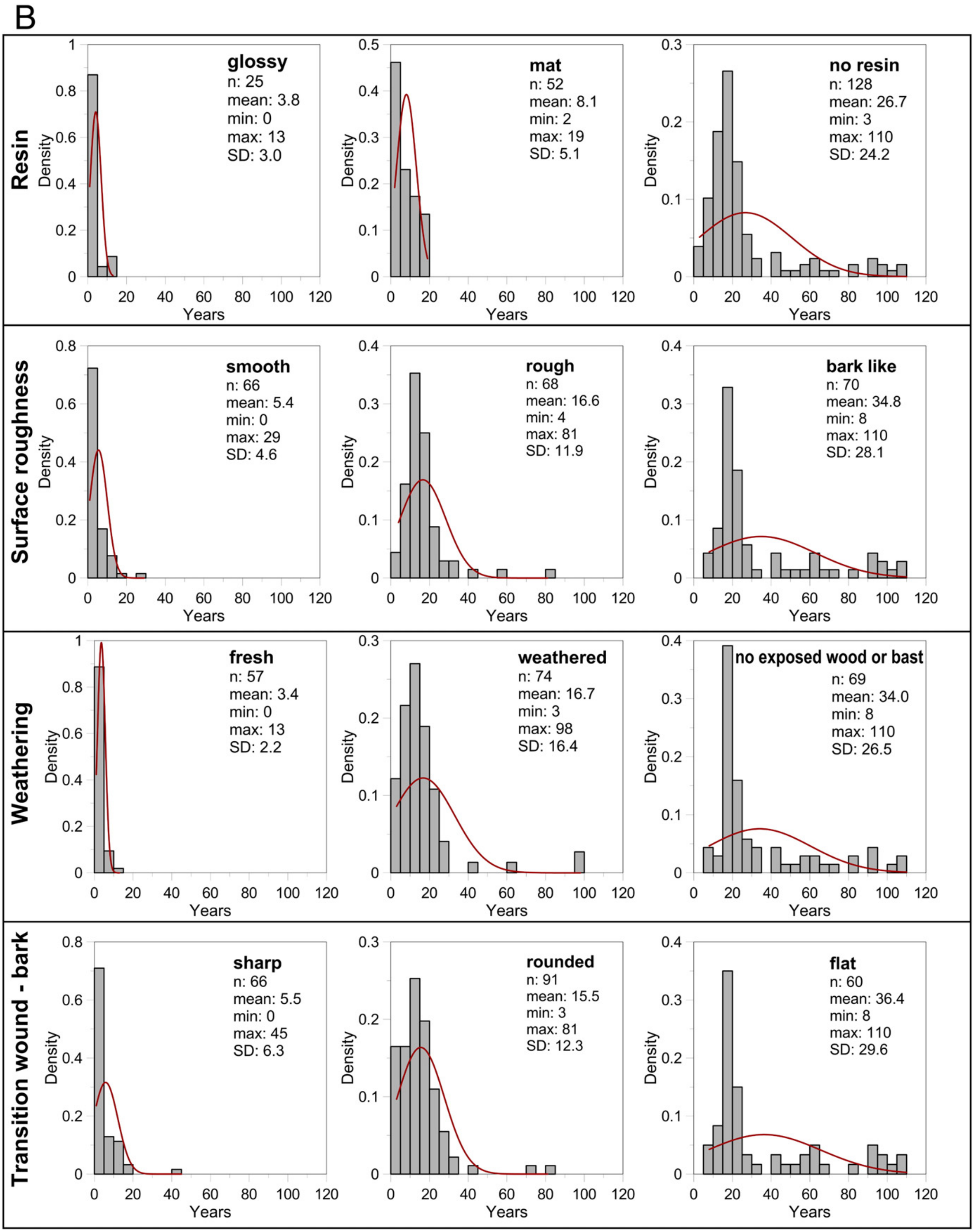

Fig. 4 (*continued*).

Table 2
Ranked reliability of characterization variables according to intraclass correlation coefficient (ICC, two-way random single measures); number of cases showing absolute agreement on variables between the authors and the test persons.

Classification variable	ICC	No. samples	Absolute agreement	(%)
Wound closure	0.909	113	108	96
Surface roughness	0.777	98	68	69
Color	0.772	107	76	71
Resin	0.734	104	78	75
Weathering	0.701	112	82	73
Transition wound–bark	0.463	112	58	52

3. Results

3.1. Suggested visual dating procedure

The suggested visual dating procedure and resulting wound ages are presented in Fig. 7. Suggested ages are mean ages from the data set, excluding those wounds for which bark rings can be counted and the wound age thus dated precisely. *Recent* wounds could be dated easily through the absence of wound wood, which could not yet develop (Fig. 1) and through the presence of *fresh* wood or bast fibers (Fig. 7A). In cases where bark rings can be distinguished at the wound margin, bark ring counts are by far the preferred option and clearly yield the highest precision (Fig. 7B), in particular for wounds inflicted up to ~10 years prior to sampling. Bark rings can be identified as homogeneous zones (in terms of color and roughness) growing in parallel bands next to the wound margin and are often delimited from each other by a thin dark band. Usually, the first two bark rings are larger than subsequent rings. However, we observe that secondary thickening may lead to the disruption of the newly built periderm, especially in younger conifers with high increment rates, which may in turn lead to the formation of bright linear features, which do not, however, represent bark ring borders. As a consequence, bark ring counts should be realized at several positions around the wound as mat resin may sometimes blur bark rings. Noteworthy, bark rings in closed wounds or open but not actively overgrowing wounds can be used for age estimates as well but will only provide a minimum age of injury occurrence.

In the case of *old* wounds, characterized by their grey or bark-like color and stretched geometry, Eq. (1) provides the most accurate wound age data (Fig. 7C).

In cases where the strategies described above are not yielding any results, the age estimation of wounds should be based on classification variables (Fig. 7D). Wound *color* is the key variable in this case. Younger injuries with *purple* wound surfaces can be further classified via the state of wood and bast fibers (*fresh* or *weathered*), with the latter pointing to slightly older wound ages.

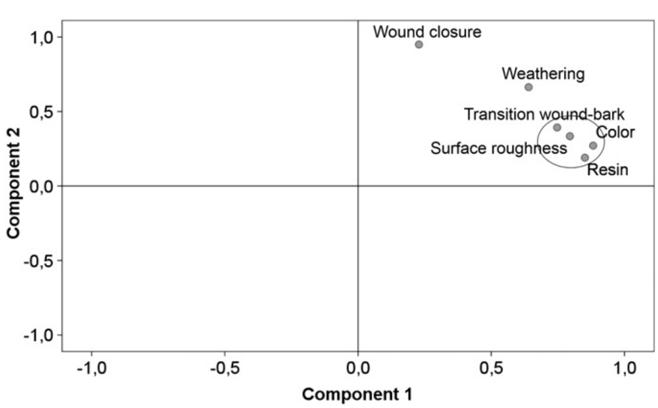

Fig. 5. Component plot resulting from the Principal Component Analysis showing correlations between classification variables. Groups of variables with similar principal components are highlighted with an ellipse.

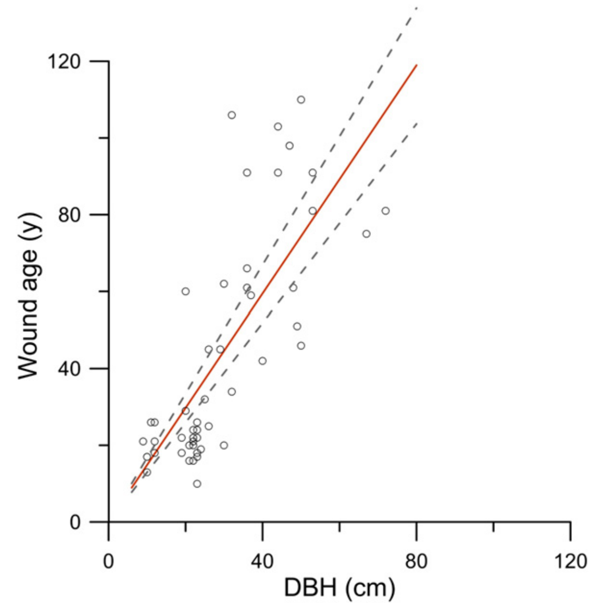

Fig. 6. Scatter plot and trend line (linear regression through origin; 95% confidence intervals) showing significant correlation ($R^2 = 0.6$, $p < 0.001$) between wound age and tree diameter for *old* wounds.

The standard deviation (SD) presented in Fig. 4 provides the range of possible wound ages as a function of available wound variables; it allows for certain corrections of wound ages. By way of example, the presence of glossy resin at the outer margin of a brownish wound would indicate a younger wound age than suggested in Fig. 7. The presence of thick layers of fallen needles deposited inside the wound, massive wound wood, or the occurrence of moss and lichen on the wound will, by contrast, indicate older wound ages than suggested by the approach.

3.2. Spatio-temporal patterns of rockfall activity as derived from visual dating

Visual dating was then used to date wounds on a rockfall slope located next to Saas Almagell (SA) and for which a dendrogeomorphic reconstruction of rockfall activity has previously been performed. Fig. 8 shows a comparison of both approaches and illustrates quite clearly that visual and dendrogeomorphic approaches can yield almost identical patterns of spatiotemporal rockfall activity, at least at the slope scale. Larger zones of enhanced, recent rockfall activity in the upper and southern parts of the slope can be distinguished clearly from zones with older rockfalls in the lower and northern parts of the slope. Larger, absolute dating errors are observed in zones with older wounds, whereas younger wounds could be dated with high precision in most cases.

3.3. Comparison of visual with dendrogeomorphic dating

The visual dating approach introduced here was tested by four tree-ring experts analyzing each of 30 photographs of wounds randomly selected from a database of 150 pictures. Fig. 9 gives a comparison of results obtained with classic dendrogeomorphic dating approaches with those derived by the experts using the visual dating technique. The resulting mean absolute dating errors are given in Fig. 10 and remain within 1.9 years for young wounds (age class 0–4 years). Dating errors become gradually larger with increasing wound age and are in the order of 3.7, 6.2, 8.8, and 19 years for wounds with real age comprised between 5–10, 11–20, 21–30, and 31–110 years, respectively.

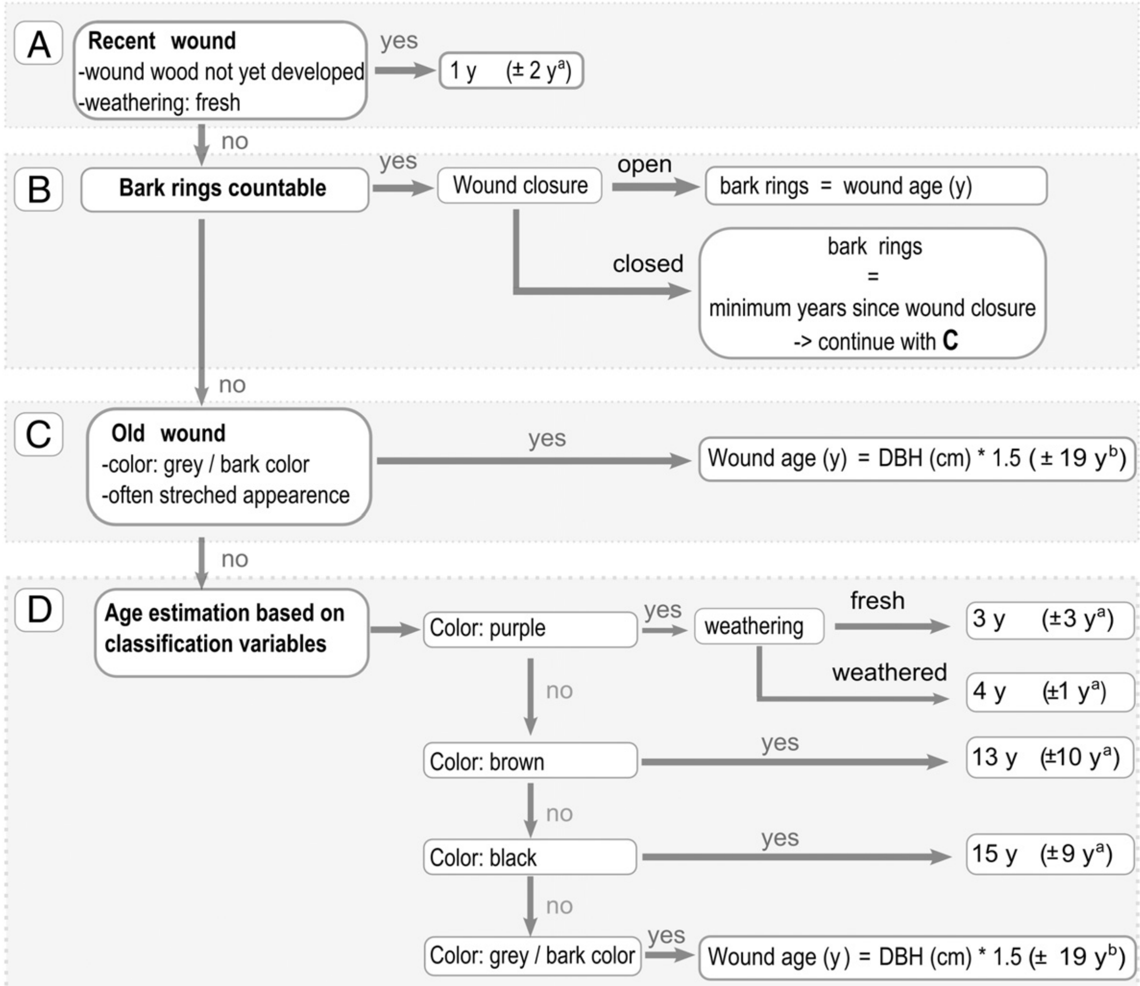

Fig. 7. Visual dating approach with estimates for wound age of *L. decidua* trees. ([a]Dating error given as two standard deviations; [b]standard error of estimates.)

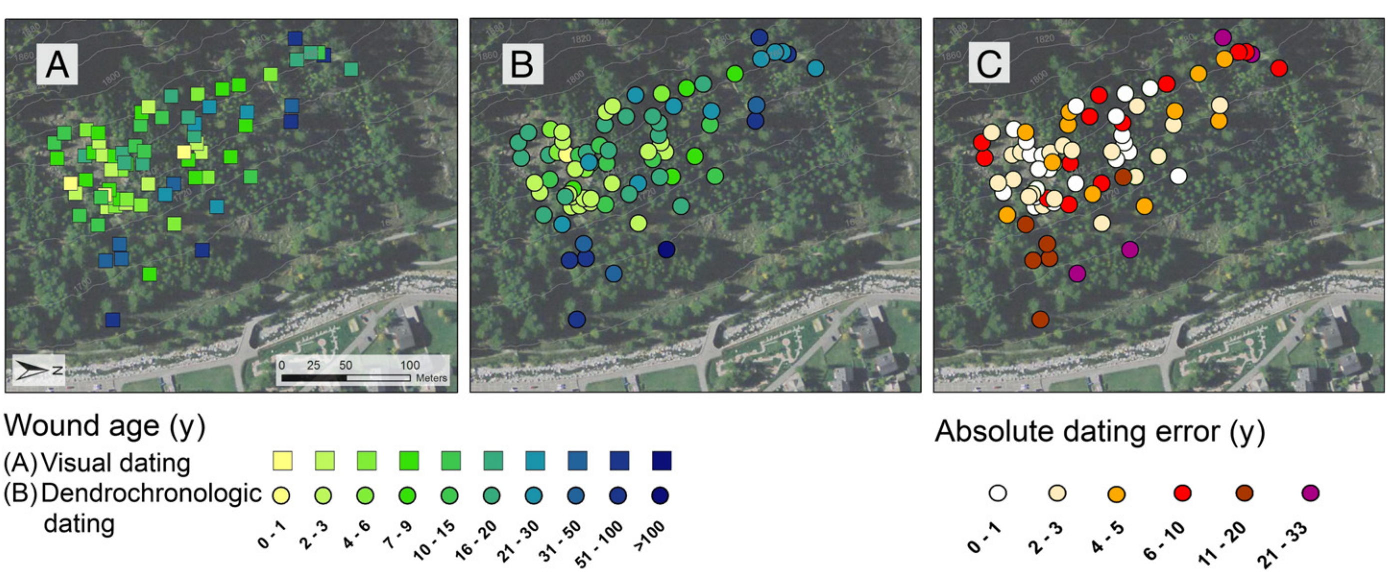

Fig. 8. Reconstruction of rockfall activity based on wounds analyzed with (A) the visual dating approach (photographs) and (B) dendrogeomorphic techniques. Results are very similar with respect to spatiotemporal patterns of rockfall activity and if considered at the slope scale; (C) absolute differences between the approaches.

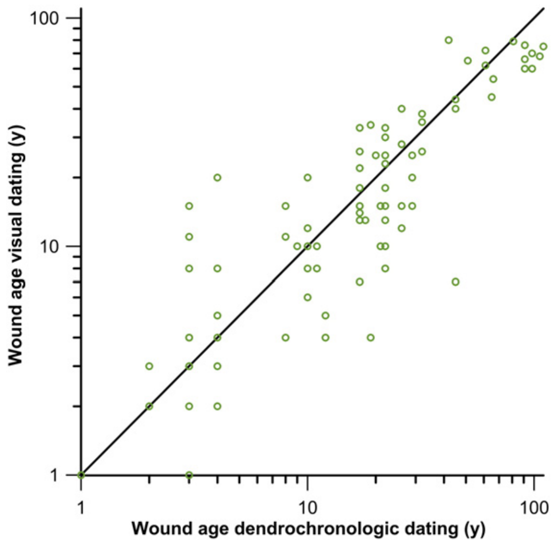

Fig. 9. Dating errors of trained test persons who followed the visual dating approach as specified in Fig. 7 and on wounds seen on photographs.

4. Discussion

This study focuses on the visual analysis of external characteristics of wounds inflicted to *L. decidua* by geomorphic processes. The idea of considering visible disturbance in trees in dendrogeomorphic research is not completely new in the sense that tree selection and the definition and optimization of sampling procedures (Schneuwly-Bollschweiler et al., 2013; Corona et al., 2014) typically have focused on the presence of trees with visible growth defects. As such, severely affected trees have preferentially been selected on landslide bodies (Lopez Saez et al., 2012, 2013), avalanche paths (Muntán et al., 2009; Corona et al., 2012), or for the assessment of hydrological processes (Bollschweiler and Stoffel, 2010; Ballesteros Cánovas et al., 2011). In the case of rockfalls, Stoffel et al. (2005a, b) selected heavily affected trees, whereas Schneuwly and Stoffel (2008) or Moya et al. (2010) even limited sampling to trees with clearly visible wounds. Šilhán et al. (2011) suggested sampling heights as a function of average wound height on the stem. The only published work taking visible scars as such into account are those of Perret et al. (2006), who developed a methodology to monitor the spatial distribution of rockfalls, and Trappmann and Stoffel (2013) who used a simple scar count approach to distinguish areas of differing rockfall frequencies. In contrast to the studies described above, the visual dating approach developed in this contribution is different in as such as it enables the assessment of the temporal distribution (i.e., dating) of rockfall activity based on an outer inspection of wounds without any extraction and analysis of wood samples.

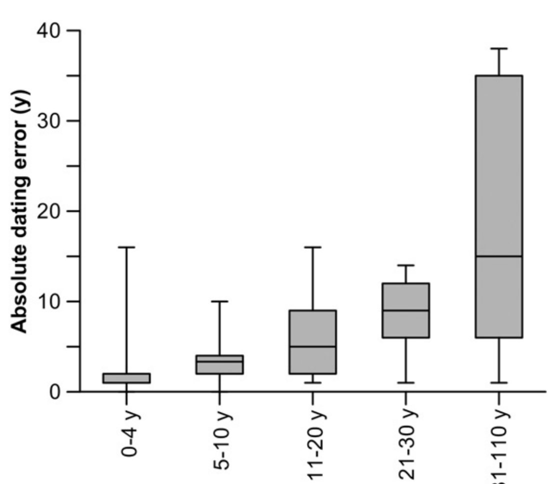

Fig. 10. Boxplot with absolute dating errors of test persons for different age classes.

The validation of the visual dating approach shows that characterization variables that are easy to obtain, such as *wound closure* (*open* or *closed*), could be reproduced almost perfectly (96%) by the test persons. For the variables *color* and *weathering*, the test persons could replicate the authors' classification in 71% and 73% of the cases, respectively. Younger wounds were generally dated with high accuracy by the test persons, whereas larger dating errors typically occurred in the case of older scars. Nevertheless, and as shown in Fig. 8, our study also points to the fact that rockfall inventories based on visual dating can indeed yield very valuable (and rather reliable) spatiotemporal patterns of rockfall activity at the slope scale. Based on the performance of the test persons, we also realize that the recognition of wound features and the *correct* classification will depend on the experience of the investigator. A profound training therefore seems crucial to guarantee an adequate dating performance and sufficient precision. We believe that training longer than that conducted in our case (roughly 1.5 h per test person), also in the field, could minimize the frequency and magnitude of discrepancies in wound dates between dendrogeomorphic and visual dating approaches.

In the case of this study, we analyzed wounds in *L. decidua*, but other species can be expected to have a significant potential for visual dating as well. Several conifer species (e.g., *Pseudotsuga menziesii* (Mirbel) Franco) and broadleaves have been described in the past to produce bark rings (Schweingruber, 1996) but were not used so far for dating purposes. Identical cambial responses to wounding have been reported for *Abies alba* Mill., *Picea abies* (L.) Karst., and *Pinus sylvestris* L. (Oven and Torelli, 1999). Although wound closure has been described to be less efficient in *P. abies* (Bangerter, 1984; Schneuwly-Bollschweiler and Schneuwly, 2012) and wound surfaces have been shown to be frequently covered by thick patches of exuded resin (Metzler et al., 2012), which possibly might impact dating accuracy, testing the potential of visual dating in these species would certainly be worthwhile. Visual dating using tree species other than *L. decidua*, however, will require adaptation of the characteristics used. The requirement for calibration of suggested age values using *L. decidua* should be verified in case that site conditions are essentially different from those at our study sites and expected to significantly influence wound appearance. When the approach is transferred to *L. decidua* growing in sites with significantly differing environmental conditions from our study sites, the suggested age values might need calibration.

The timespan that can be covered by the visual dating approach is clearly limited to the time that wounds remain visible on the stem surface. The oldest visible wounds found by Moya et al. (2010) on oak trees had an age of 40 years and large wounds had remained open for 24 years, whereas small injuries were closed within only 1 year. The oldest wound in our study, still visible as a faint feature on the bark, was 110 years old, and one exceptionally, clearly visible open wound had an age of 98 years. On broadleaved trees, especially on species with smooth bark, Stoffel (2005) and Trappmann and Stoffel (2013) expected traces of wounds to remain visible for decades or even the entire lifespan of the tree. In young *L. decidua*, however, the effective masking of scars has been described as a well-known limitation for dendrogeomorphic (and hence visual) dating (Stoffel and Perret, 2006). Our study agrees with the findings presented above, unless wounding occurred in older conifers where wound blurring tends to be more limited. This observation is probably reflecting the less important secondary thickening of the stem axis, which in turn will reduce the lateral extension and hence the blurring of wounds. This observation also suggests that older trees could be more suitable to assess rockfall activity with visual dating. However, this is only valid where impact energies are sufficiently high to produce wounds rather than being buffered by the increasingly thicker bark of older trees (Favillier et al., 2015). The age-dependent ability of trees to record rockfalls is also critical for classical dendrogeomorphic research. Šilhán et al. (2013), for instance, demonstrated that the sensitivity of *Pinus nigra subsp. pallasiana* (Lamb.) Holmboe to rockfall increased in the first decades of their growth, peaked at ages of 80 to 90 years, and then gradually decreased. Besides changing bark thickness, this might be explained by differences in reactions to rock impacts between younger and older trees. Older trees will produce decreasing ring widths as they have to allocate their resources to a continuously growing mass of trunk and branches that, in turn, limits their potential to produce anomalous growth features in the tree-ring record (Stoffel and Corona, 2014). In summary, consensus exists in dendrogeomorphic rockfall literature that a balanced sampling of young and old trees will yield the most reliable reconstructions. This is expected to be equally true for visual dating, as impacts will in general remain visible for longer timespans if the tree was already older at the time of impact, whereas younger trees can be expected to be more sensitive because less energy is needed to create a scar.

Although visual dating will only rarely provide annually resolved event dates and thus cannot replace dendrogeomorphic approaches, it has the advantage of being noninvasive, which can be a significant advantage for studies in protected areas where coring or cutting permissions are difficult or impossible to obtain. The visual dating approach also has the advantage of requiring comparably little time and limited financial efforts. An estimated 50–60% of the time required for classical dendrogeomorphic studies can be saved, as sample extraction and laboratory analysis can be omitted. Visual dating thus seems to represent a suitable alternative for studies focusing on larger surfaces. The approach can also be employed to support dendrogeomorphic surveys in case that the xylem is rotten, wounds are located at positions that cannot be reached during sampling, or in cases where the tree's ability to record rockfall impacts in the growth-ring series is expected to be limited. In addition, it can provide a first estimate of wound ages and the spatial distribution of rockfall activity directly in the field and thereby facilitate sampling design (Morel et al., 2015) and serve as a supplementary criterion for dendrogeomorphic dating.

5. Conclusion

We conclude that the external appearance of *L. decidua* wounds can be used to approximately date the impact of geomorphic processes, but that dating precision will not be annual in most cases. Thus, the approach presented here does in no way aim at replacing established dendrogeomorphic techniques nor does it pretend to be a highly accurate dating tool. Nevertheless, depending on the goal of the study, visual dating can indeed represent a valuable alternative to classic dendrogeomorphic surveys, especially in cases where large surfaces are investigated and provided that the focus is on return periods and spatial patterns rather than on the precise dating of individual events. Our study also shows that generally dating errors will be lower for trees with young wounds and that the error tends to increase gradually with increasing wound age. Provided that the persons using the approach receive detailed training (see supplementary material), we conclude that visual dating will doubtlessly meet the needs of practitioners and can provide an overview of rockfall activity at the slope scale with comparably low temporal and financial efforts.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2015.04.030.

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