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Tree-age control on reconstructed debris-flow frequencies: examples from a regional dendrogeomorphic reconstruction in the Crimean Mountains

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ABSTRACT: The Crimean Mountains (Ukraine) are renowned for the highest occurrence of debris flows along the northern coast of the Black Sea, but information on their origin, frequency and triggers is widely lacking. This study reconstructs a regional time series of debris flows in eight catchments located on the slopes above Yalta. Dendrogeomorphic analyses were performed on 1122 increment cores selected from 566 black pines (*Pinus nigra* ssp. *pallasiana*) with clear signs of external damage induced by past debris-flow activity. The trees sampled were divided into old and young trees. The sample contains 361 young trees with post-1930 innermost rings and 205 old trees with pre-1930 germination dates. The two groups of trees were analyzed separately to identify possible age effects in the reconstructed debris-flow series and to assess the ability of *P. nigra* to record geomorphic disturbances over time. We date a total of 215 debris flows back to AD 1701 and observe a mean decadal frequency of 6.9 events, with a peak in activity during the 1940s (20 events). The young trees record an increase in debris-flow activity over the last 70 years, whereas the frequency of events remained fairly constant in the old trees for the same period. By contrast, the formation of reaction wood became increasingly scarce with increasing tree age whereas the occurrence of abrupt growth suppression increased. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: debris flows; dendrogeomorphology; growth disturbances; age effects; Crimean Mountains

Introduction

Debris flow (DF) represents one of the more common and widespread geohazards and an effective geomorphic process of sediment transfer in mountain environments (Rickenmann, 1999). Their sudden occurrence, high energies and related damage potential call for tools that allow their prediction, which is, in turn, ideally based on data and chronologies of past events (Rickenmann, 1999; Cardinali *et al.*, 2002; VanDine and Bovis, 2002). Optimal datasets on DF also contain information on triggering factors (Soldati *et al.*, 2004; Stoffel *et al.*, 2011; Schneuwly-Bollschweiler and Stoffel, 2012) or magnitude–frequency relations of DF (Jakob and Friele, 2010; Stoffel, 2010). Data on the magnitude and meteorological conditions controlling DF activity are even more important in densely populated regions (Pasuto and Soldati, 2004), such as the southern slopes of the Crimean Mountains (Ukraine) where DF and other types of mass movements occur frequently (Pánek *et al.*, 2009b; Šilhán *et al.*, 2012). The steep slopes above Yalta accommodate several DF torrents which could, under unfavorable conditions, impact the city, but data to assess the frequency of such DFs or their triggering conditions have not been studied in detail so far.

Previous dendrogeomorphic work was primarily based on the reconstruction of DF histories in single catchments, mostly in the European Alps (e.g. Bollschweiler *et al.*, 2007, 2008; Stoffel *et al.*, 2008). Recent work by Procter *et al.* (2011), however, clearly demonstrated that regional, dendrogeomorphic time series of DF might be more suitable to assess the probability of DF occurrence in single catchments and to obtain more reliable and robust results at larger scales. Regional studies are still scarce and only exist for comparably small regions of the Swiss (Bollschweiler and Stoffel, 2010a) and Italian Alps (Pelfini and Santilli, 2008) as well as for the Western Carpathians (Šilhán and Pánek, 2010; Šilhán, 2014), but not for south-eastern Europe.

Despite recent progress in dendrogeomorphic research on DF (Stoffel and Wilford, 2012), concern emerged about the suitability and capability of trees of different age to record geomorphic disturbance with equal confidence (Bekker, 2004;

Bollschweiler and Stoffel, 2010b; Šilhán *et al.*, 2012, 2013; Stoffel *et al.*, 2013; Trappmann *et al.*, 2013). The question here is whether trees will indeed respond differently and with different growth reactions to the same DF impact at different age (with age also being a surrogate of tree size and bark thickness to some extent).

The main objectives of this work are thus to (1) reconstruct spatio-temporal patterns of DF activity on the southern slopes of the Crimean Mountains (Ukraine); and to (2) analyze the influence of tree age on dendrogeomorphic results, in particular on the ability to record damage in trees of different age and with respect to the nature of growth responses.

Study Area

The Crimean Mountains (Ukraine) are a part of the Caucasus–Crimean fold-and-thrust belt that forms the northern fringe of the Black Sea basin (Figure 1) (Pánek *et al.*, 2009a). The highest ridges of the Crimean Mountains are > 1200 m above sea level (a.s.l.) and asymmetrically shifted to the Black Sea coast, thereby forming very steep southern slopes. As a result of this contact of physically different lithologies, the very pronounced local relief, active seismicity, relatively high annual precipitation (>1000 mm) and coastal abrasion, the southern slopes of the Crimean Mountains must be considered extremely prone to various types of mass movements (Pánek *et al.*, 2008, 2009b; Šilhán *et al.*, 2012). The area under investigation is situated in the steepest and highest portions of the coastal slopes of the Crimean Mountains, approximately 4 km west of the densely populated settlement of Yalta (44° 28.7′ N / 34° 04.5′ E; Figure 1). The study area is dominated by eight adjacent torrential catchments draining the eastern slopes of Ai Petri Mountain (1234 m a.s.l.); the main characteristics of the individual torrents are presented in Table I. Lithology is characterized by thin-bedded, strongly fractured Upper Jurassic limestones, highly susceptible to weathering and mass movements (Derenyuk *et al.*, 1984; Šilhán *et al.*, 2012). The piedmont areas of the torrents are gently inclined (<20°) and show terraced slopes with several generations of DF cones, talus and/or landslide lobes (Figure 1). Within this study area, dendrogeomorphic work focused on the most active parts of the torrents with recent (±200 years) DF levees and lobate deposits showing signs of DF external damage in trees.

Methods

Dendrogeomorphic field methods

Geomorphic mapping was conducted at a scale of 1:5000 and focused on erosional (gullies, debris flow channels) and depositional (lateral levees, lobes) landforms related exclusively to DF activity. Positions of sampled trees were also mapped using a global positioning system (GPS) and aerial photographs.

Tree-ring analysis focused on black pines (*Pinus nigra* ssp. *pallasiana*) with visible growth defects and assumed growth disturbances (GDs) in the tree-ring record related to past DF activity (e.g. stem burial, tilting and wounding; Bollschweiler *et al.*, 2007, 2008; Bollschweiler and Stoffel, 2010b). Table II provides details of visible growth defects observed in the field. We sampled trees of all sizes (ages) following the latest recommendations for tree selection and tree-ring sampling (Stoffel *et al.*, 2013; Stoffel and Corona, 2014). All sampled trees grew at locations with visible evidence of past DF activity (gullies, lateral levees or accumulation lobes) and the absence of other geomorphic processes, so that the signals recorded in the tree-ring series can be related to past DF events with high confidence (Bollschweiler and Stoffel, 2010b). Trees with visible damage at heights > 1 m (scars, decapitation or branches breakage) were disregarded to avoid the inclusion of reactions other than DF (such as falling trees, thunderstruck, etc.). Moreover, scars on tree stems, typical for other processes such as rockfalls (Schneuwly *et al.*, 2009a, 2009b), represented only 7.6% of all visible stem damages (Table II). Each tree was sampled with two increment cores; one core was taken downslope and another one in the flow direction of DF. Sampling height was as low as possible in the case of buried trees, in the area of maximum bending in tilted trees and at injury height in trees with visible scars.

In addition to the disturbed trees growing on the DF cones and along torrents, we also sampled 40 old but undisturbed *Pinus nigra* individuals growing beyond the areas affected by DF or other geomorphic processes. These trees were used for the construction of a regional reference chronology to identify signs of significant climatic anomalies and/or insect outbreaks. The growth anomalies recorded in the reference chronology are therefore related to non-geomorphic disturbances and were excluded for further analyses in the disturbed trees.

Dendrogeomorphic laboratory methods

All samples were processed following the standard dendrogeomorphic procedures described by Stoffel and Bollschweiler (2008). Individual working steps included sample drying, sanding, tree-ring counting and ring-width measurements with a VIAS timetable and PAST4 software (VIAS, 2005). Tree-ring series of disturbed trees were then compared with the reference chronology to identify and correct false and/or missing rings. All identified missing rings were added to the series and false rings were corrected. Dating of DF was based on the identification of anomalies in the increment curves and by visual inspection of the increment cores. Within this study, dendrogeomorphic analysis was restricted to (i) abrupt growth suppression resulting from stem burial, (ii) abrupt growth release following elimination of neighboring trees or insignificant stem burial and related tree fertilizing by nutrient-rich, fine grained limestone material (Strunk, 1997; Mayer *et al.*, 2010), (iii) the presence of callus tissue forming the wound-healing callus pad, and (iv) reaction wood after tree tilting due to the pressure of DF material. Tangential rows of traumatic resin ducts could not be used in the present case as *Pinus nigra* is known to form abundant resin even in the absence of any external disturbance (Stoffel, 2008). Only severe growth suppression (70% reduction with respect to previous growth) and strong growth releases (200% increase) lasting for at least four consecutive years were taken into account (Schweingruber *et al.*, 1990; Stoffel and Corona, 2014).

Dating of DF events was based on a semi-quantitative approach (Bollschweiler *et al.*, 2007; Bollschweiler and Stoffel, 2010b; Schneuwly-Bollschweiler *et al.*, 2013), where ≥ 2 trees have to be located in a logical spatial position (e.g. in the same flow line on the same cone, or within the same deposit of a DF) and where the same ≥ 2 trees have to exhibit GD which can unequivocally be attributed to DF activity. Only those years with at least one DF in any of the catchments were considered for further analyses. We also computed decadal frequencies so as to demonstrate possible temporal trends in DF activity (Stoffel and Beniston, 2006; Stoffel *et al.*, 2008; Bollschweiler and Stoffel, 2010a). As a result of the decreasing number of available trees with age, lower boundaries of time series for individual torrents were limited to periods where ≥ 25% of all

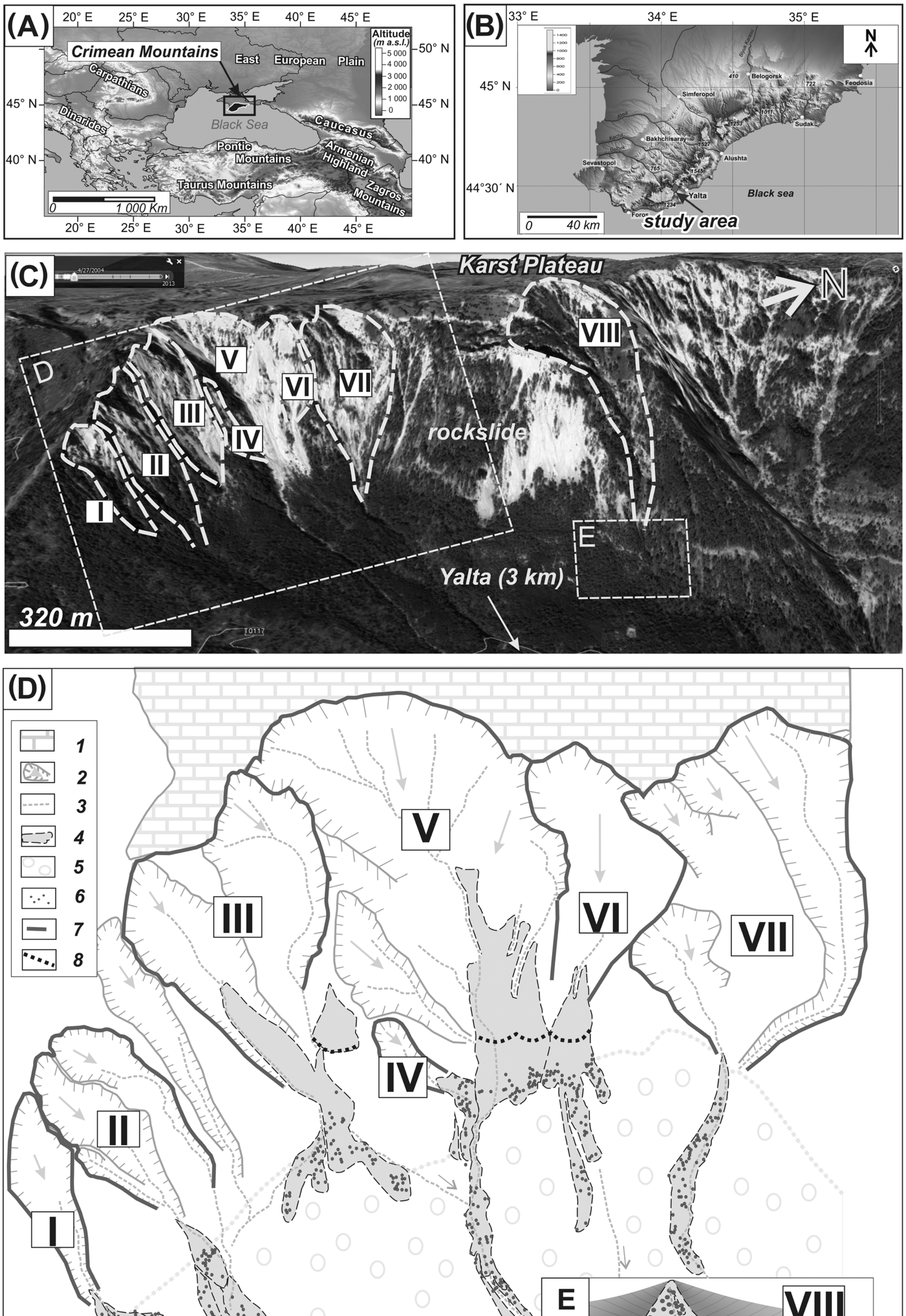

Figure 1. (A) Location of the Crimean Mountains. (B) Location of the study area. (C) Oblique Google Earth image of the study sites. (D) Geomorphic sketch of catchments I–VIII (1 – karst plateau, 2 – hydrological divides, 3 – torrential channel, 4 – active debris-flow accumulation, 5 – old debris-flow and talus deposits, 6 – sampled trees, 7 – boundaries of debris-flow catchments, 8 – outer border of zones potentially affected by rare rockfalls). (E) Geomorphic sketch of catchment VIII.

Table I. Basic morphometric parameters of individual catchments

	I	II	III	IV	V	VI	VII	VIII
Orientation	Northeast (NE)	NE	NE	NE	East (E)	E	E	Southeast (SE)
Area (m^2)	18 490	35 176	65 409	38180	100 507	12 615	102 394	260 720
Maximum elevation (m a.s.l.)	960	1038	1125	975	1145	1077	1145	1215
Minimum elevation (m a.s.l.)	800	770	815	805	780	850	790	690

Table II. Types of visible growth defects in sampled trees

	Catchments								
Visible growth defect (%)	I	II	III	IV	V	VI	VII	VIII	Total
Stem tilting	47 (42.3)	49 (44.5)	56 (38.6)	24 (41.4)	92 (40.0)	46 (36.2)	57 (40.7)	42 (43.8)	413 (40.6)
Stem burial	57 (51.4)	56 (50.9)	77 (53.1)	31 (53.4)	119 (51.7)	69 (54.3)	67 (47.9)	51 (53.1)	527 (51.8)
Injuries (scars)	7 (6.3)	5 (4.6)	12 (8.3)	3 (5.2)	19 (8.3)	12 (9.5)	16 (11.4)	3 (3.1)	77 (7.6)
Total	111	110	145	58	230	127	140	96	1017

trees sampled per torrent were available for analysis (see Table III). Event years were considered local events if DF activity was restricted to < 50% of all torrents in a given year and regional events as soon as DF occurred in ≥ 50% of all torrents.

Results

Number and age of sampled trees, growth disturbances (GDs)

A total of 1122 increment cores were sampled from 566 disturbed *Pinus nigra* trees in eight active DF torrents (mean: 71 trees per torrential catchment; maximum: 136 trees in catchment V, minimum 38 trees in catchment IV; see Figure 1 for details). Mean age of trees at sampling height is 102.1 years (standard deviation [SD] 83.2 years), with oldest trees being found in catchments VIII (mean 166.8 years) and II (146.9 years), and the youngest population being present in catchment VII (69.4 years). Noteworthy, all stands reveal a sudden increase in tree numbers after the 1930s (see later). The tree-ring sample was therefore separated in pre- and post-1930 trees, hereafter referred to as 'young trees' ($n = 361$; mean 68.1; SD 8.8 years) and 'old trees' ($n = 205$; mean 217.2 years; SD 69.4 years). We analyzed the two subsets of trees separately so as to decipher the ability of trees of different age to record the same DF events. We used tree age as a surrogate of stem size with the associated changing physical parameters such as the elasticity of the trunk (in stems of flexible bending during DF impact) or bark thickness (as a layer protecting the trunk from abrasion and wound-penetrating impacts). The mean stem diameter of 'young trees' was 11.4 cm (SD = 2.4 cm; maximal diameter = 16.3 cm; minimal diameter = 6.3 cm). The mean stem diameter of 'old trees' was 40.3 cm (SD = 13.5 cm; maximal diameter = 71.4 cm; minimal diameter = 17.6). In the same line of thoughts, we analyzed the contribution of both subsets of trees to the reconstructed DF frequency since the 1930s. Detailed information including the number and age of trees sampled for each of the torrential catchments is provided in Table III.

Dendrogeomorphic analyses of all *Pinus nigra* trees yielded information on 1271 GD related to DF activity. Abrupt growth suppression (37.6%) and compression wood (36.4%) were observed most frequently in the full sample, followed by abrupt growth release (14.9%) and the presence of callus tissue (11.1%). However, as shown in Figure 2, the contribution of individual types of GD differed significantly between individual torrents, in particular in catchments VIII (31.8% of callus tissue of all GD in this catchment), II (57.6% of growth suppression, only 1.4% of callus tissue) and IV (55.1% of compression wood). Pronounced differences in the type and expression of reactions to disturbance are also evident between the 'young' and 'old' trees for the period 1939–2010, as shown in Figure 3. Note that the first DF event recorded by the 'young' trees is dated to 1939.

Two-thirds of all GD (828; 65.1%) used in this study occurred during the period 1939–2010, i.e. period when 'young trees' contributed to the DF reconstruction, so that differences in the nature of reactions and the number of identified events can be analyzed in detail (Figure 3). Interestingly, 44% of all disturbances are in the form of compression wood in the 'young' trees, whereas in the 'old' trees, compression wood represents only 5% of all GD. 'Young' trees do not reveal any signs of growth release, whereas this feature contributed to 10% of all reactions in the 'old' trees. In a similar way, growth suppression can be observed much more frequently in the 'old' (20%) than in the 'young' trees (8%). Wounds and related callus tissue, in contrast are more abundant in 'young' trees (10%) and almost absent in 'old' trees (2%).

Frequency of debris flows (DFs)

A total of 215 DFs have been identified in 105 individual event years in the eight torrents, with the oldest event dating back to AD 1701 (Figure 4). The largest number of events has been reconstructed in catchment V (44 events), the smallest in catchment IV (11 events), resulting in the highest (1.9) and lowest (0.7) decadal frequencies at the catchment scale. At the regional level, decadal DF frequency is 6.9 events with a recurrence interval of 1.4 years. Total numbers, decadal frequencies and recurrence intervals of DF in particular catchments are provided in Table IV.

For the time period covered by the 'young' and 'old' subsets of trees (1939–2010), we observe 108 DF events from which 34 (31.5%) are recorded exclusively in the growth series of 'young' trees, but not recorded in the 'old' trees. Analysis of the 'young' trees allows reconstruction of 97 DF events

Table III. Number and age of sampled trees

	I	II	III	IV	V	VI	VII	VIII	Total	Reference chronology
Sampled trees (number)	57	58	79	38	136	73	71	54	566	40
Minimum age (years)	44	35	16	23	18	22	34	46	16	197
Maximum age (years)	348	352	342	306	321	331	208	299	352	362
Mean age (years)	129.1	146.9	95.5	85.8	77.0	91.4	69.4	166.9	102.1	284.1
Standard deviation (years)	79.4	89.6	69.2	82.5	78.1	88.5	29.4	92.8	83.2	40.5
Period covered	1746–2010	1701–2010	1865–2010	1865–2010	1764–2010	1719–2010	1842–2010	1774–2009	1701–2010	1669–2010
50% of all trees present since	1903	1898	1946	1968	1968	1966	1948	1832	1947	1736
25% of all trees present since	1746	1701	1865	1865	1764	1719	1842	1774	1701	1686

Note: The length of chronologies (i.e. the period covered by the reconstruction) was limited to the period for which ≥ 25% of all trees sampled were available for analysis. The period covered by reference chronology was limited to the period for which at least five trees were living (Stoffel and Bollschweiler, 2008).

(89.8%), whereas only 11 DF events (10.2%) would have been recorded had sampling and analysis been based exclusively on the 'old' trees at the study sites (i.e. without taking account of the 'young' trees present at the sites). Catchment VI shows the largest contribution of 'young' trees to the dating of DF events (53.8%), the lowest contribution of 'young' trees is recorded in catchment VIII (7.1%). The relative contribution of the subsets to the overall number of reconstructed DF events is shown in Figure 5.

Figure 6 shows that on a temporal scale, DF activity remained at a comparable level between the 1840s and 1930s, with the exception of the 1880s and 1890s for which activity was significantly reduced. DF activity was at its peak in the 1940s during which 20 events have been reconstructed (recurrence interval: 0.5 years). A gradual increase in activity can be observed since the 1950s, and up to the 1990s, whereas the last decade (2000s) is again characterized by less marked activity (Figure 6).

Spatial patterns of debris flows (DFs)

Sixteen event years (out of 105; 15.2%) are considered here as regional events, as they have been recorded in four or more torrents in the same year. The remaining 89 event years (84.8%) are considered more localized phenomena, since they have triggered DFs in one to three catchments. Regional and local events are presented by 75 and 140 DFs, respectively. The highest number of catchments producing DF events during regional events occurred in 1865 and 1944, when six out of eight torrents were active. The contribution of individual catchments to regional events is given in Table IV; it was highest in catchment IV (81.8%) and lowest in catchment VIII (23.3%). The average contribution of individual catchments to regional events is 38.9%.

Discussion

In this study we analyzed spatio-temporal patterns of DF events affecting the steep coastal slopes of the Crimean Mountains above the city of Yalta. Based on tree-ring analysis of 566 individuals of *Pinus nigra*, 215 DF events could be reconstructed in eight steep torrential catchments since AD 1701.

The nature of GD in trees will ultimately be driven by the nature of the process itself, with rockfalls causing primarily scars and apex losses (Shroder, 1978; Schneuwly *et al*., 2009a, 2009b; Stoffel *et al*., 2013; Trappmann *et al*., 2013). The nature of GD will also depend on the tree species analyzed (Stoffel and Perret, 2006; Stoffel, 2008; Stoffel and Corona, 2014). In our case, signs of past DF activity were mostly visible in the form of abrupt growth suppression reflecting stem burial and/or root plate damage. In contrast, abrupt growth releases were scarce in our case and thus point to the negligible role of tree fertilizing processes during minor burial events or the lack of major events that thinned out the surrounding canopy. The proportional representation of compression wood is comparable to that of growth suppression, but was much more represented in younger trees (with more flexible stems) and may therefore appear more important as compared to other DF sites. Similarly we do not consider the abundance of compression wood in our dataset as a sign of high magnitude DF, particularly given the scarcity of callus tissue which suggests that the impact forces of individual DF are not very strong (which in turn can be explained with small grain sizes and limited DF volumes). Catchment VIII – the largest one analyzed in this study – is somewhat exceptional in this respect

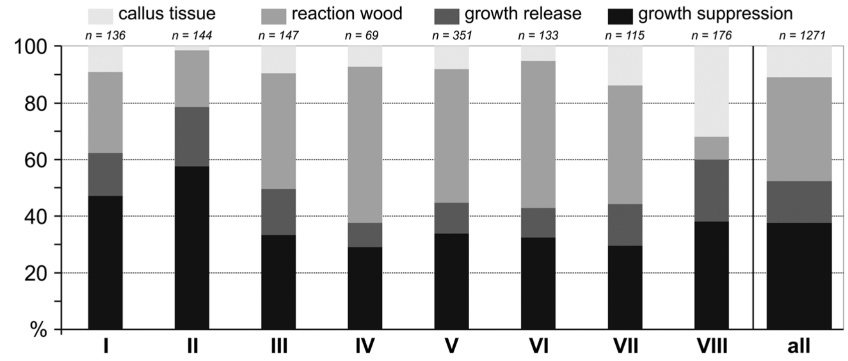

Figure 2. Ratio of growth disturbances from all trees in individual catchments for the entire reconstructed period.

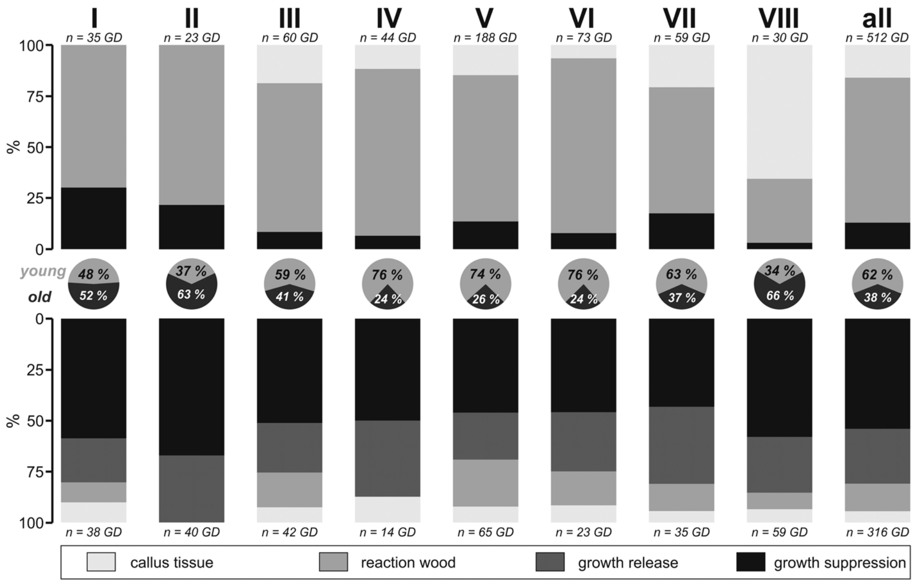

Figure 3. Ratio of growth disturbances (GDs) between 'young' and 'old' trees in individual catchments for the period 1939–2010 (i.e. period for which GDs are recorded in both age groups). Proportions of GDs recorded with 'young' and 'old' trees in individual catchments are illustrated in the pie charts.

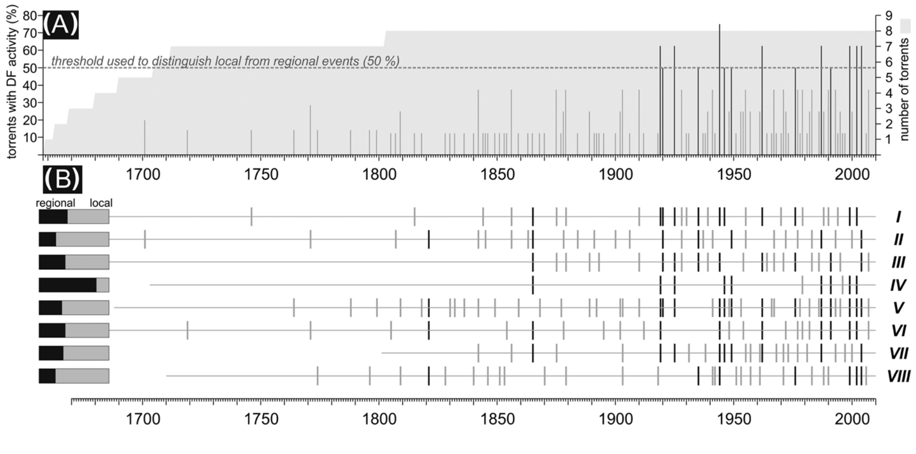

Figure 4. Debris-flow (DF) occurrence at the study sites. (A) Percentage of torrents with DF event. (B) Ratio of regional (events in ≥ 50% of torrents) versus local (events in < ≥ 50% torrents) events in individual catchments (horizontal lines – age of the oldest tree; short vertical black line – regional event; short vertical gray line – local event).

as the nature of disturbances in the tree-ring records (31.8% of callus tissue) indicates the presence of more massive impacts and presumably higher magnitude DF with more devastating effects.

The tree sample used in this study was separated into a 'young' and an 'old' subset with the aim to analyze (i) the effects of DF to tree disturbance with different age and (ii) the ability of trees to record impacts with increasing age. In the Crimean Mountains, a large number of trees germinated in the 1930s. The massive (re-)colonization of the investigated slopes might be the consequence of the 1927 earthquakes ($M = 6$ and 6.8) which might have been responsible for massive rockfalls leading to the elimination of the previously existing forest stands (Nikonov and Sergejev, 1996; Šilhán *et al.*, 2012).

Table IV. Events (including percentage of single catchments), decadal frequency and recurrence of debris flows

	Catchments								
	I	II	III	IV	V	VI	VII	VIII	Total
Debris-flow events	27 (12.6)	29 (13.5)	24 (11.2)	11 (5.1)	44 (20.5)	24 (11.2)	26 (12.1)	30 (14.0)	215
Decadal frequency	1	0.9	1.6	0.7	1.9	0.8	1.5	1.3	6.9
Recurrence (years)	10	10.7	6.3	13.6	5.2	12.5	6.5	8.0	1.4
Length of record (years)	264	309	145	145	246	291	168	235	309

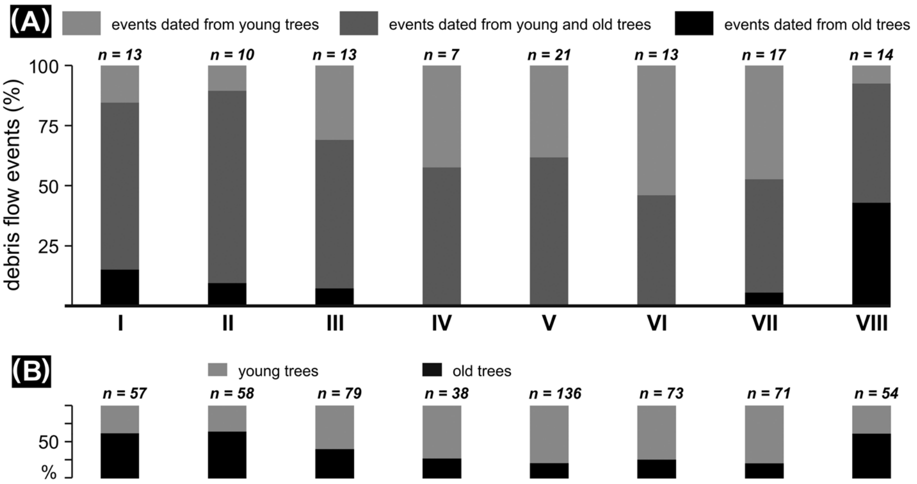

Figure 5. Influence of tree age ('young' versus 'old' trees) on the reconstruction of debris flow (DF) in particular catchments between the 1930s and today (i.e. the period when dating of DF was also based on 'young' trees): (A) percentage proportion of DF events dated with 'young' and 'old' trees; (B) percentage of 'young' and 'old' trees.

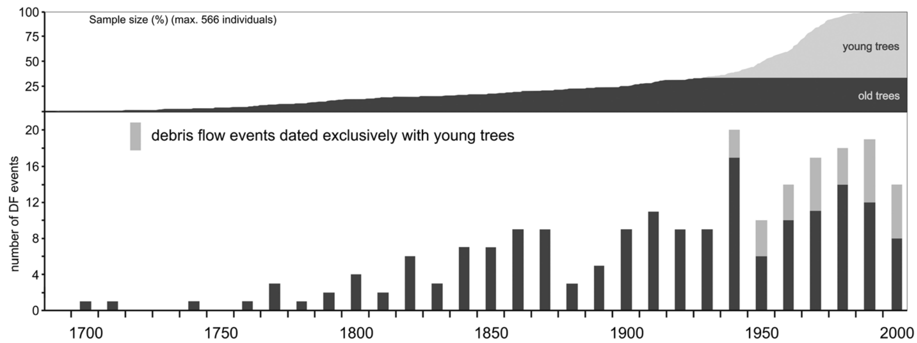

Figure 6. Decadal frequency of debris flows (DFs) with sample size (DF dated exclusively in 'young' trees are given with grey columns).

Data analyzed in this study demonstrate quite clearly that the reaction of trees to DF impacts will be different depending on their age. Young trees are more elastic and have thinner barks (Hengst and Dawson, 1994; Pinard and Huffman, 1997), which may favor the occurrence of tree tilting and the formation of compression wood. In a similar way, stem damage might be inflicted more easily so that even low-magnitude DFs have shown to be capable of influencing growth of such trees in a significant way. On the contrary, the older *Pinus nigra* trees studied here have more massive stems and thicker bark structures and have thus been considered to be less prone to DF damage (Lopez Saez *et al.*, 2011). Whereas scars and tilted stems (with related reaction wood) are indeed scarce in the 'old' subset of *P. nigra* trees, we still observe periods of abrupt growth suppression and/or release in these samples, as shown in Figure 3. The *P. nigra* trees sampled in this study do not only show different reactions to DF with increasing age, but older trees also clearly record fewer DF events. We also realize that the proportion of 'young' trees sampled in the individual catchments correlates significantly ($r = 0.94$) with the number of DF events which were reconstructed exclusively with 'young' trees (Figure 5). On a temporal scale, the inclusion of young trees will lead to an apparent increase in the decadal frequencies of DFs (Figure 6). The ability of the 'young' trees to record DFs still persists after 70 years (as documented in this study), but it remains uncertain at what age *P. nigra* trees will become less sensitive to certain magnitudes of DFs and thus become less sensitive recorders of hydrogeomorphic disturbances. If looking at the 'old' subset of trees, one does not recognize a significant reduction in their ability to record DFs for the period covered by both datasets. The number of DFs recorded exclusively by the 'old' subset of trees even increased between the 1950s and 1980s (Figure 6), although at a slightly lower level and with different types of reactions as compared to the 'young' subset of trees. As a result of their thick bark and less flexible stems, the 'old' trees will become insensitive to smaller DFs (i.e. to those DF which cannot injure the wood behind the thick bark and/or tilt the massive tree trunks of older, mature trees) and will only record the higher magnitude events. The 'younger' trees will also record evidence of smaller DFs and thus cause an 'inflation' of DF events in the frequency. In a spruce–beech forest affected by rockfalls, Trappmann and Stoffel (2013) reported that bark thickness affects the time-series of rockfalls, and thus confirm the findings of this study to some extent. It therefore seems that the nature of GD changes with increasing age, stem diameter and bark thickness of *P. nigra*, and that the overall number of events recorded might be smaller in 'old' as compared to 'young' trees, especially if the first are impacted by small(er) DF events. In this sense, we conclude that the increase in DF activity since the 1940s clearly reflects the contribution of the 'young' trees to the time series and should not thus be seen as evidence of change in DF activity in the catchments itself (Figure 6).

At the same time, however, the position of trees sampled with respect to the channel or the cone seems as essential for the recording of DF events as their age, and we cannot exclude that the massive rockfalls triggered by the 1927 earthquake (Šilhán *et al.*, 2013) might have altered the flow paths of subsequent DFs.

The drivers of debris generation seem to be slightly different in our case as compared to the high-mountain environments in Switzerland, where increased frequency of DF is often predisposed by higher temperatures influencing permafrost degradation and dynamics of rock glaciers (Kääb *et al.*, 2005; Lugon and Stoffel, 2010) in addition to rainfall inputs (Schneuwly-Bollschweiler and Stoffel, 2012).

The abundance of regional and local DF events in a given catchment is controlled primarily by its area and its position with respect to other catchments and by the intensity and duration of the generating storm. The largest number of regional events can be found in catchment IV which is a narrow system of limited area, where triggering precipitation events are unlikely to be limited to its territory and likely to activate DF in adjacent catchments as well. On the contrary, catchment VIII is somewhat isolated with respect to the other catchments and thus has the largest amount of local events (Figure 4). This evidence suggests highly site-specific effects of downpours or intense precipitation which is more localized, thereby resulting in these very specific patterns which are somewhat characteristic for mountainous regions (Bollschweiler and Stoffel, 2010a; Schneuwly-Bollschweiler and Stoffel, 2012).

Conclusion

Dendrogeomorphic investigation of eight DF tracks situated on the southern slopes of the Crimean Mountains and next to the coast of the Black Sea enabled dating of 215 DFs by means of tree-ring analysis of 1122 increment cores sampled from 566 *Pinus nigra* trees. We reconstruct a mean decadal DF frequency of 6.9 events for the study region (eight torrents) and for the period 1701–2010. The trees sampled belong to two subsets with distinct differences in age; analysis of 'young' and 'old' trees was performed separately to decipher the ability of trees of different age to record DF events. Results show quite clearly that older trees record impacts of DF less easily and that different reactions prevail between the age classes. As a result of these differences in recording events in *P. nigra*, we call for (i) more balanced sampling where both younger and older trees are included for analysis, (ii) further work on the role of age on the ability of trees to record impacts, possibly through experiments and an expansion of analyses to other species; as well as for (iii) more work in the Black Sea region which has been neglected considerably in the past as far as dendrogeomorphic work is concerned.

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