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Seasonal timing of rockfall activity on a forested slope at Täschgufer (Swiss Alps) – a dendrochronological approach

by

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with 8 figures and 2 tables

Summary. Dendrochronology was used to study 25 years of rockfall activity on a forested slope at Täschgufer, Täsch (Swiss Alps). We introduce a new approach by evaluating the initiation of callous tissue and resin duct formation after rockfall occurrence to determine the seasonal timing of events. Results from 270 stem discs of 18 *Larix decidua* Mill. trees show distinct seasonal differences in rockfall activity and indicate that, except for the years with anthropogenic activity on the slope, the occurrence of rockfall proves to be mostly restricted to the dormancy and is rather uncommon during the vegetation period. Only 12 % of the injuries occur within the vegetation period, which locally lasts from early June through mid October. In contrast, some 88 % of the scars occur in the dormant season between mid October and end of May. Direct observations on the slope confirm these findings, indicating that rockfall activity is highest in April and May, when global insolation on the west-facing Täschgufer slope gradually rises and ice lenses formed from meltwater slowly disappear in the joints and fissures of the rockfall source areas. According to nearby meteorological data, rockfall at Täschgufer seems to be neither influenced by thunderstorms in summer nor abundant rainfall in autumn.

The approach used for this investigation proves to be a useful tool for analyzing differences in intra-annual rockfall activity on forested slopes. In the case of data available on the different growth phases within the vegetation period of the selected tree species at the study site, results on the seasonal timing of rockfall activity can even be given with almost monthly resolution. However, for rockfall occurring within the dormant season, tree-ring analysis needs to be completed with direct observations on the site.

Zusammenfassung. *Saisonale Steinschlagverteilung auf einem bewaldeten Hang im Täschgufer (Schweizer Alpen) – ein dendrochronologischer Ansatz.* – Mit Hilfe dendrochronologischer Methoden wurde auf einem bewaldeten Hang im Täschgufer, Täsch (Schweizer Alpen) die Steinschlagaktivität während der letzten 25 Jahre untersucht. Um die saisonale Verteilung des Steinschlags zu bestimmen, wurde ein neuer Ansatz gewählt, welcher das Einsetzen von Kallusgewebe und Harzkanälen im geschädigten Holz untersucht. Die Ergebnisse von 270 Stammscheiben von 18 Lärchen (*Larix decidua* Mill.) zeigen deutliche saisonale Unterschiede bezüglich der Steinschlagaktivität. Mit Ausnahme der Jahre, in denen am Hang bauliche Maßnahmen vorgenommen wurden, trat Steinschlag im Untersuchungsgebiet praktisch ausschließlich während der winterlichen Wachstumspause zwischen Mitte Oktober und Ende Mai

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auf (88 %) – Verletzungen während der Vegetationsperiode bildeten die Ausnahme (12 %). Direkte Beobachtungen am Hang bestätigen diese Resultate und deuten überdies darauf hin, dass die Aktivität im April und Mai am ausgeprägtesten sein dürfte. Während dieser Periode nimmt die globale Sonneneinstrahlung am westexponierten Hang des Täschgufer kontinuierlich zu und vermag so die Eislinsen aufzutauen, die durch das Gefrieren von Schmelzwasser in den Spalten und Rissen der Anrisszonen gebildet werden konnten. Im Gegensatz dazu zeigt ein Vergleich mit Daten einer nahegelegenen Wetterstation, dass die Steinschlagaktivität im Täschgufer weder durch Sommergewitter noch durch anhaltende Niederschläge im Herbst beeinflusst wird.

Der im Rahmen dieser Untersuchung verwendete Ansatz erwies sich als geeignetes Werkzeug für die Analyse intra-annueller Variationen in der Steinschlagaktivität. Unter Einbezug der Wachstumsdaten der Baumart am untersuchten Standort lassen sich Steinschlagereignisse innerhalb der Vegetationsperiode mit nahezu monatsgenauer Auflösung wiedergeben. Jedoch werden für die Analyse von Steinschlagereignissen während der Wachstumspause zusätzliche Informationen aus direkten Beobachtungen benötigt.

Résumé. *Répartition temporelle des chutes de pierre sur un versant boisé du Täschgufer (Alpes suisses) – une approche dendrochronologique.* – La dendrochronologie a été utilisée pour étudier 25 ans d'activités de chutes de pierres sur le versant boisé de Täschgufer, à Täsch (Alpes suisses). Une nouvelle approche, basée sur l'apparition de tissu calleux et de canaux résinifères résultant d'impacts dus à des chutes de pierres, permet de déterminer la saison des événements. Les résultats issus de l'analyse de 270 échantillons prélevés sur les troncs de 18 mélèzes (*Larix decidua* Mill.) montrent des différences saisonnières dans l'activité des chutes de pierres. A l'exception des années influencées par l'activité humaine sur le versant, la majorité des événements sont survenus durant la période de dormance et peu durant la période de végétation. Seuls 12 % des blessures sont produits durant la période de végétation (début juin à mi-octobre), alors que 88 % sont déterminés durant la période de dormance (mi-octobre à fin mai). Les observations directes sur le versant confirment ces résultats, indiquant que l'activité de chutes de pierres est plus importante en avril et en mai. À ce moment, l'ensoleillement global sur ce versant orienté vers l'Ouest augmente graduellement, alors que les lentilles de glace formées par l'eau de fonte disparaissent lentement des joints et fissures des roches situées dans les zones de départ des chutes de pierres. Selon les données météorologiques régionales, les chutes de pierres ne semblent ni influencées par les orages d'été, ni par les abondantes précipitations d'automne.

L'approche utilisée dans cette étude prouve qu'elle est un outil utile pour analyser les différences intra-annuelles de chutes de pierres sur un versant boisé. Si l'espèce sélectionnée sur le terrain d'étude (*Larix decidua* Mill.) montre bien les différentes phases de croissance durant la période de végétation, les résultats de l'analyse peuvent indiquer l'occurrence des chutes de pierres quasi au mois près. En revanche, pour celles survenues durant la période de dormance, l'analyse des cernes de croissance doit être complétée par des observations directes sur le site.

1. *Introduction*

Rockfall is a widespread phenomenon in mountain environments (e. g., Whalley 1984, Selby 1993, Erismann & Abele 2001). It consists of free falling, bouncing or rolling stones of different size, with volumes of single components smaller than 5 m^3 (Berger et al. 2002). As rockfall frequently endangers inhabited areas or traffic routes in mountainous regions (Bloetzer & Stoffel 1998), it became one of the most intensely studied geomorphic processes of the cliff zone (Luckman & Fiske 1995).

Previous studies have addressed the initiation and kinetics of the process (Fahey & Lefebure 1988) as well as the rates of cliff retreat (Rapp 1960, André 1986, 1997). Recent advances focus on rockwall instability (Košťák et al. 1998), the time prediction of rockfall (Glawe et al. 1993) or interacting rockfall triggers (André 2003). Perennial monitoring of rockfall activity, the measurement of near-surface rock temperatures and moisture content further allowed evaluation of freeze-thaw cycles in rockfall triggering (Hall 1997, Matsuoka & Sakai 1999). Studies on past rockfall frequency are mainly based on short-term observations in the field (Luckman 1976, Douglas 1980, Gardner 1983). Historical approaches concentrate on lichenometry, allowing evaluation of long-term changes in rockfall accretion rates as well as spatial and temporal patterns of rockfall activity (Luckman & Fiske 1995, McCarroll et al. 1998).

In mountain forest stands, geomorphic processes injure trees by tilting, scaring, or breaking their stems (Alestalo 1971). Affected coniferous trees react upon such impacts with reaction wood, callous tissue or resin ducts (Schweingruber 1996), allowing one to precisely date geomorphic disturbances. So far, dendrogeomorphology has mainly been applied to the analysis of mass movements (Shroder 1980, Strunk 1992, Wiles et al. 1996, Baumann & Kaiser 1999, Fantucci & Sorriso-Valvo 1999, Solomina 2002, Stoffel et al. 2004). In rockfall research, tree-ring analyses concentrated on the determination of sedimentation rates and the dynamics of forest edges on scree slopes (Lafortune et al. 1997, Hétu & Gray 2000). Studies on forest – rockfall interactions dealt with the analysis of rockfall scars in individual trees (Gsteiger 1993), biogeomorphology of visible scars (Perret et al. subm.) or the effectiveness of mountain forests as a protection against rockfall (Bebi et al. 2001, Dorren et al. 2004).

However, the previously mentioned studies on rockfall in mountain forests did not explore the precise information that tree-rings may furnish on intra- and inter-annual fluctuations of rockfall activity. It is therefore the purpose of the present study to analyze the frequency and the seasonal timing of rockfall using dendrochronological methods. We report on results obtained from 270 stem discs of 18 heavily injured European larch trees (*Larix decidua* Mill.). Based on methods used in fire scar analyses (Brown & Swetnam 1994, Ortloff et al. 1995), we introduce a new approach evaluating the initiation of callous tissue and resin ducts to analyze the seasonal timing of rockfall. Results show distinct seasonal differences in rockfall activity and indicate that, except for the years with anthropogenic activity on the slope, the occurrence of rockfall is restricted to the dormancy of trees and rather uncommon during the vegetation period. The discussion is focused on the seasonal timing and the driving factors of rockfall triggering.

2 *Study area*

The analysis is conducted on the west-facing Täschgufer slope descending from the Leiterspitzen summit (46°4′N, 7°47′E, 3,214 m a. s. l.) in the Siviez-Mischabel Range (Valais), southern Swiss Alps (fig. 1). As illustrated in figures 1b and 2, rockfall frequently occurs on the slope, originating from the heavily disintegrated gneissic rockwalls underneath the Leiterspitzen summit. The figures also show that the main rockfall source areas are located between 2,300 and 2,600 m a. s. l. (Rockfall Source

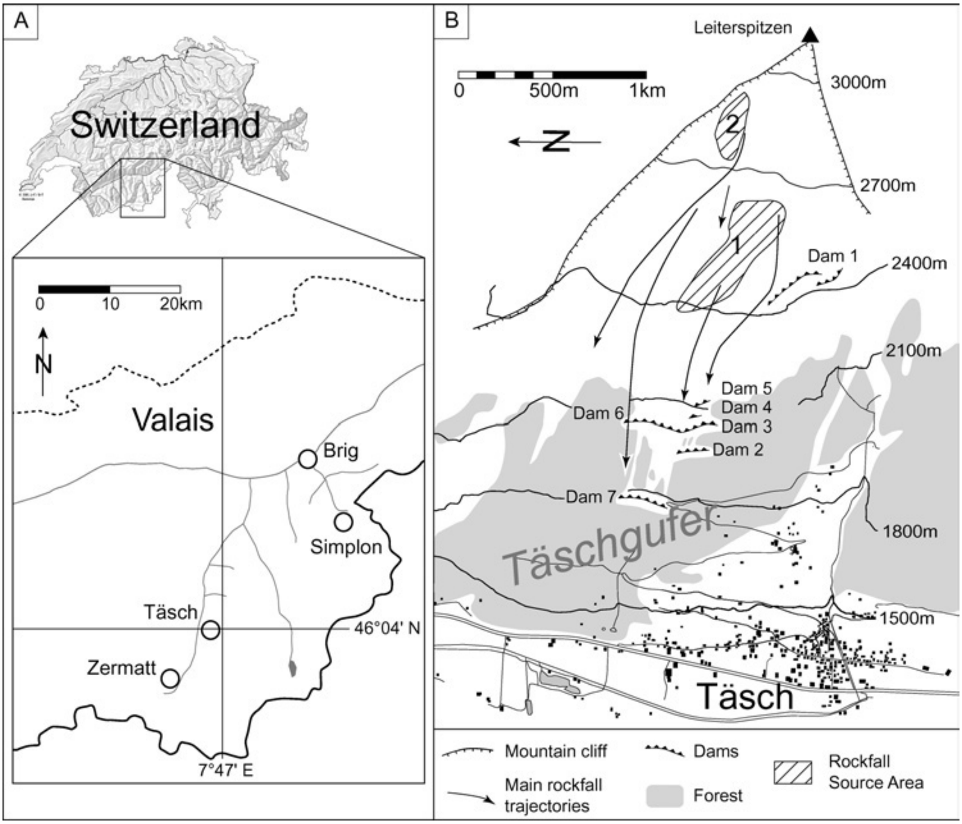

Fig. 1. a) The Täschgufer slope is located in the southern Swiss Alps north-east of Täsch. b) Sketch map of the rockfall slope with the main Rockfall Source Areas, the main trajectories and the dams built after 1988.

Area 1) and above 2,700 m a. s. l. (Rockfall Source Area 2) as well as the main rockfall trajectories. Remobilization of rocks is common from the steep slopes of loose rockfall debris located above 2,100 m a. s. l. Here mean slope gradients locally rise up to 48°. Below, slope gradients gradually decrease to reach 20° next to the valley floor. Maximum sizes of single rocks at Täschgufer do normally not trespass 1–2 m^3.

Besides frequent rockfall activity, one major rockslide on the Täschgufer slope is noted in local chronicles (Zurbriggen 1952). Its age was estimated with lichenometry to at least 600 years BP (Joris 1995). Furthermore, small debris flows occur on the Täschgufer slope. Single surges generally count a few cubic meters and pass the slope in well-defined channels. Avalanches have not been witnessed on the slope. Next to the rockfall slope, the local timberline is formed by European larch (*Larix decidua* Mill.) at about 2,300 m a. s. l. In the part heavily affected by rockfall, the surface is sparsely wooded with small individual trees and large areas remaining free of vegetation.

Mean annual air temperatures at Täschgufer are derived from meteorological data at Zermatt (SMI 2003). Using a local temperature lapse of 5.1 °C km^{-1} (KING 1996), mean annual air temperature reaches + 4.5 °C at Täsch and −4.5 °C at the Leiterspitzen summit. Precipitation most frequently occurs between August and November, including persistent rain from low-pressure masses located in the Mediterranean Sea (GREBNER 1994). On the sparsely wooded surfaces around 1,800 m a. s. l., annual average precipitation is estimated to 660 mm. Here, snow usually covers the slope in early winter, reaching a maximum depth of around 70 cm in early March (SMI 2000). Snowmelt generally starts in mid March. In contrast, snow accumulation is modest around the Rockfall Source Areas 1 and 2 and surfaces remain largely snow-free during the winter months.

The Rockfall Source Areas at Täschgufer are situated on the borderline between seasonal frost and permafrost environments, as suggested by a locally calibrated permafrost distribution model (GRUBER & HOELZLE 2001). As illustrated in fig. 2, the presence of permafrost is namely proofed at the southern edge of the slope between 2,400 m and 2,500 m a. s. l., where massive ground ice was encountered during construction works (HAEBERLI 1992).

In the mid-1980s and again after 1993 (LAUBER 1995), rockfall activity apparently increased on the slope and rocks repeatedly caused damage to infrastructure (roads, hiking trails) on the valley floor. On October 6, 1985, single blocks damaged an agricultural building in Täsch. As a consequence, in 1988 an unhitched road for construction traffic and an earth-fill deflection dam (Dam 1; see fig. 1b) initiated the realization of major protection measures on the slope. Further earth fill deflection dams were built in the succeeding year (Dams 2 to 5). Finally, two large protection dams were erected north of the existing constructions in 1996/97 (Dam 6, 400 m in length) and 1998 (Dam 7, 260 m in length).

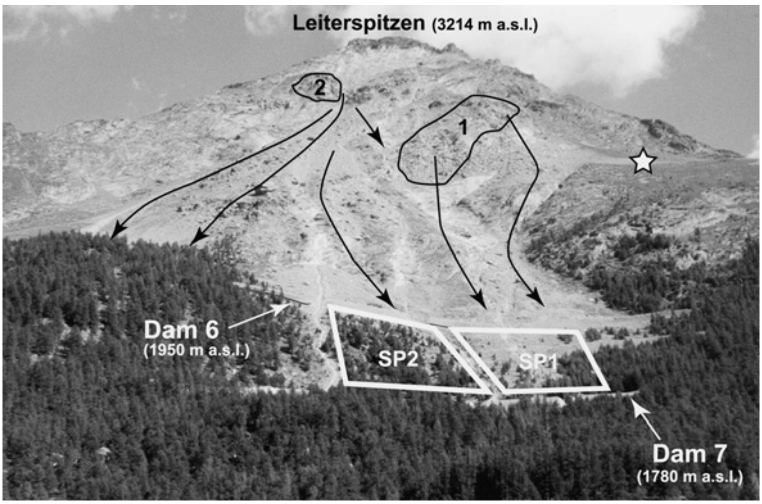

Fig. 2. View of the Täschgufer slope and the Leiterspitzen summit (3,214 m a. s. l.): Note the main Rockfall Source Areas (1, 2), the main rockfall trajectories (arrows) and the zone where massive ground ice was encountered (star) during construction works (Photo: D. Schneuwly).

For the investigation described in this paper, two study plots (SP1, SP2) are selected in the heavily injured forest stand between Dams 6 and 7 (1,780 to 1,900 m a. s. l.). Figure 3 shows the two neighboring plots which cover a surface of 0.06 km^2. At SP1, the slope surface is vegetation-free and alpine pioneer formations exceptionally occur in the southern part. European larch trees (≤ 50 yrs) have recolonized the plot, forming relatively dense forest patches. At SP2, the slope surface is mostly covered with alpine pioneer formations. Trees are generally older than 50 yrs and the recolonization rate is weak. While rockfall at SP1 widely originates from Rockfall Source Area 1, rockfall activity in SP2 is influenced by both zones, but predominantly by blocks provided from Rockfall Source Area 2.

3 *Material and methods*

The investigations on the frequency and the seasonal timing of rockfall activity at Täschgufer are based on a dendrochronological analysis of scars and resin ducts in stem discs of European larch trees. The position of callous tissue and scars within the tree-ring is used to determine the moment of the impact.

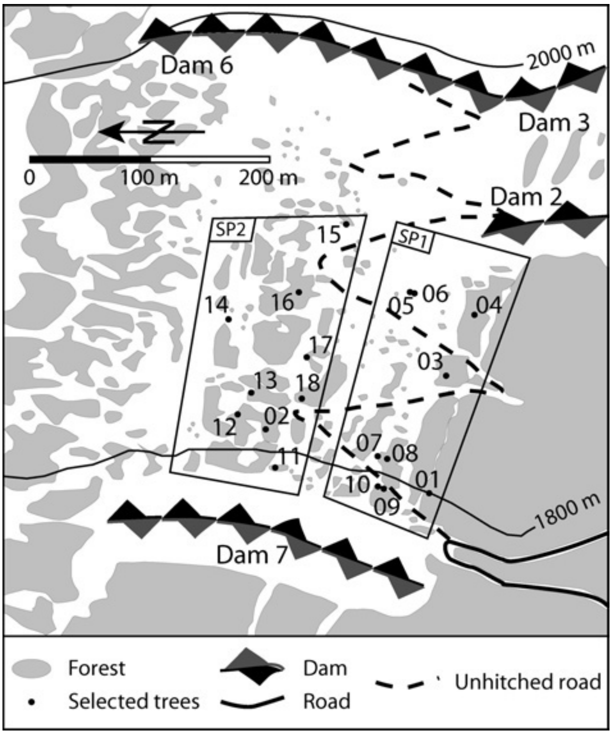

Fig. 3. Location of the study site and the investigated study plots (SP1, SP2). For this study, nine *Larix decidua* trees have been selected in each plot (trees 1 to 18).

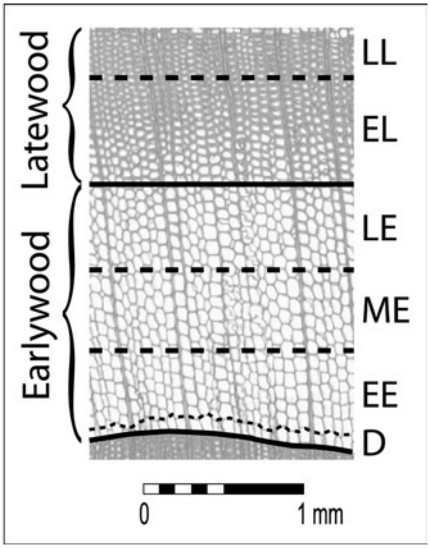

Fig. 4. Tree-rings are subdivided into thin-walled earlywood (E) and thick-walled latewood (L) cell layers. At the end of the vegetation period, cell formation ceases and the dormancy (D) occurs. E is furthermore subdivided into early (EE), middle (ME) and late (LE) earlywood, L into early (EL) and late (LL) latewood.

3.1 *Dendrochronological analysis of rockfall activity*

For the analysis of intra-annual rockfall activity at Täschgufer, 18 European larch trees (*Larix decidua* Mill.) were selected on the slope and felled at ground level. Criteria for the selection of trees included a high number of visual injuries and a diameter at breast height (DBH) ranging from 15 to 25 cm. The locations of the selected trees (trees 1, 3–10 in SP1; trees 2, 11–18 in SP2) are given in fig. 3. From the sampled trees, 270 stem discs were sawn and polished. Ring-widths were measured and data processed following the procedure described in Bräker (2002). Yearly increments were then crossdated with undisturbed trees growing next to the rockfall slope and disturbed samples age-corrected, where applicable.

Rockfall injuries (scars) were used to date past events. After the destruction of dividing cambium cell layers by the impact, tree-ring formation fails to appear in the injured area (Schweingruber 1996). At the lateral edges of the injury, cambium cells start to continuously overgrow the wound producing callous tissue (Sachs 1991, Larson 1994). For this investigation, the position of the first layer of callous tissue within the tree-ring was used to determine the seasonal timing of rockfall activity. Traumatic rows of resin ducts (Larson 1994, Schweingruber 1996, 2001) occurring next to the injury were used as a further indicator to analyze the distribution of intra-annual rockfall activity (Stoffel 2002).

3.2 *Seasonal timing of rockfall*

In temperate climates, coniferous trees are characterized by a vegetation period in summer and a dormant season (dormancy) in winter. As illustrated in fig. 4, cambium starts to produce thin-walled earlywood cells (E) at the beginning of the growth period. In summer, cell formation gradually merges to thick-walled latewood cells (L), before cell growth slowly ceases in fall. As callous tissue and resin ducts appear

Table 1 Onset of the different growth phases (GrPh) in coniferous trees (*Larix decidua, Pinus montana* and *Pinus uncinata*) at sites comparable to the Täschgufer slope. Data at Simplon (1, 2) represent the situation in 1976 (MÜLLER 1980), those at Sahún (3) the situation in 1993/94 (CAMARERO et al. 1998). Based on these data, an approximate date for the onset of growth phases is derived for the study site (4).

GrPh	*Larix decidua* (1) Simplon, 1800 m	*Pinus montana* (2) Simplon, 1800 m	*Pinus uncinata* (3) Sahún (E), 1790 m	*Larix decidua* (4) Täschgufer, 1800 m
E	May, 29	May, 29	June, 10	end of May – early June
L	July, 17	July, 17	July, 18	mid July
D	October, 9	October, 9	October, 11	early October

at once after mechanical impact (BAUMANN & KAISER 1999), injuries can be attributed to these different segments of the vegetation period. In the case of rockfall injuries occurring outside the preceding or within the first days of the vegetation period, callous tissue and resin ducts instantaneously substitute earlywood cells at the beginning of the new growth period. In both cases, rockfall is attributed to the dormant season (D). Growth reactions within earlywood cells are furthermore subdivided into early (EE), middle (ME) and late (LE) earlywood, those in latewood into early (EL) and late (LL) latewood. Knowing the species' growth data at the study site, the intra-annual distribution of rockfall activity can be dated, as demonstrated by forest fire and fire scar analyses (BROWN & SWETNAM 1994, ORTLOFF et al. 1995).

In the Valais region, growth data exists for several conifer stands *(Larix decidua, Picea abies, Pinus montana)* with different slope orientations at Simplon (1,800 m a. s. l.). Table 1 provides details on the timing of radial growth for the conifer stands at Simplon. According to MÜLLER (1980), who studied the stands in 1976, radial growth (earlywood cells) is initiated in late May. Formation of latewood cells starts by mid July and cell formation ceases in early October. The table further shows that this growth data perfectly coincide with the results of CAMARERO et al. (1998), who analyzed a *Pinus uncinata* stand at Sahún (1,790 m a. s. l.), Spanish Pyrenees, in 1993/94. By virtue of the similarity of the results, growth data of *Larix decidua* trees at Simplon (MÜLLER 1980) are used to correlate the intra-annual position of injuries within the tree-ring with calendar data at Täschgufer.

4 *Results*

Dendrochronological analysis of the 18 *Larix decidua* trees allowed identification of 180 rockfall scars between 1977–2001, representing a mean of more than 7 hits yr^{-1}. From fig. 5 it can be seen that rockfall activity at Täschgufer both varied between single years as well as within the growth period.

As for the inter-annual variations in rockfall activity, fig. 5 shows an increased number of rockfall scars in 1990 and from 1994 to 1997. While in 1990 and 1995, 26 and 29 scars occurred respectively in the selected trees, none of the trees were scarred in 1978, 1979, 1981 and 1986. As the selected trees only record rockfall signals at 18 specific points within the study site, these results represent a rough tendency of rockfall activity on the slope by showing a minimum frequency of events for the last 25 yrs.

Concerning the intra-annual distribution of rockfall activity, scars attributed to the dormant season (D) largely predominate: about 79 % of all scars were generated outside the vegetation period or immediately at its beginning. In both cases, growth reactions occurred within the first layer of earlywood cells and are hence attributed to the dormant season (D). In contrast, only 6 % of the scars belong to the earlywood cell layers, whereas 15 % of the injuries are located in the latewood. Over the last 25 years, abundant rockfall activity during latewood formation was mostly restricted to the years 1985, 1989, 1996 and 1997. Figure 6 displays characteristic examples (microsections) of callous tissue and resin ducts in dormancy, earlywood and latewood.

4.1 *Rockfall activity and construction works*

Distinct differences in the number of scars and the seasonal timing of rockfall exist both between the years with construction activity on the slope (Dams 1 to 6) and the years without anthropogenic interventions. As indicated in table 2, the above-average number of injuries in 1990, 1996 and 1997 coincide with major anthropogenic interventions on the slope. In total, 65 scars were supposedly related to the construction of dams.

During the construction works of Dams 2 to 5, 30 injuries are noted in the latewood cell layers (EL) of 1989 and the succeeding dormant season (D 1990). The spatial distribution of injuries attributed to the construction of these dams is represented in fig. 7a. While rocks released during construction works caused injuries to all trees in SP1, several individuals remained unaffected in SP2. Repeatedly affected trees are restricted to SP1 (trees 4, 5, 8 and 10) and located close to the construction sites of Dams 2 to 5. Within the period of construction works, the first scars are noted in EL 1989, when injuries were restricted to Tree 5. Rockfall activity apparently increased

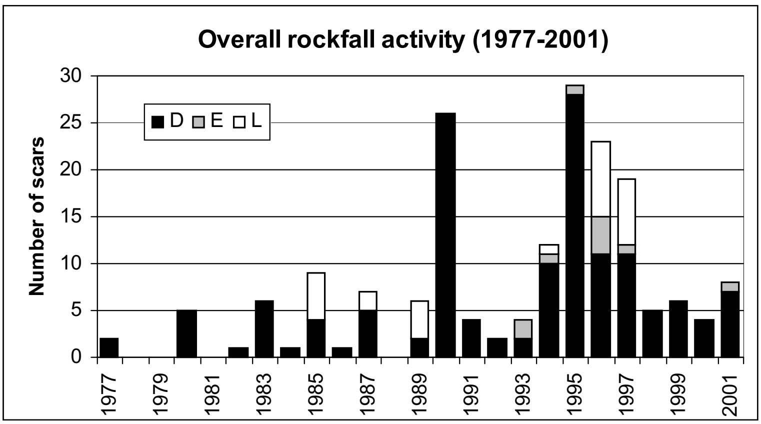

Fig. 5. Reconstructed minimum frequency of rockfall activity on the Täschgufer slope (1977–2001; D = dormancy, E = earlywood, L = latewood).

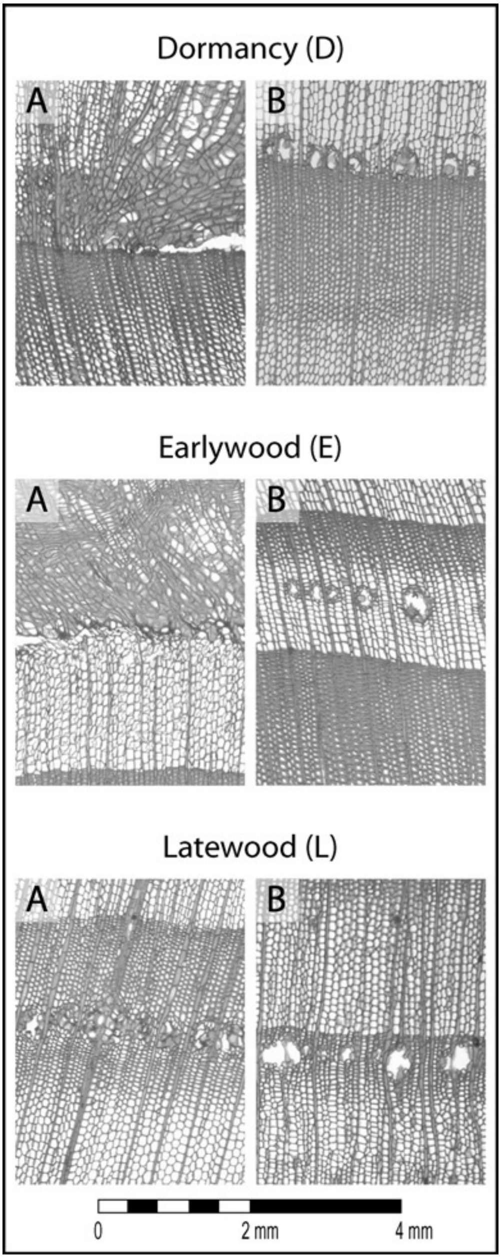

Fig. 6. Microsections of characteristic callous tissue (A) and traumatic rows of resin ducts (B) as a result of rockfall activity in the dormant season (D), earlywood (E) or latewood (L).

during the dormancy of 1990 (26 scars). During this time, rocks were most probably released by final aggradations in late fall 1989. Moreover, some rocks may have been mobilized during the thawing in spring 1990 as a result of the destabilization by the preceding building activities.

Table 2 Seasonal timing of rockfall activity on the slope between 1977 and 2001. Gray surfaces represent the periods of construction works influencing the study plots (i. e. Dams 2 to 6). Accordingly, numbers in italics designate rockfall scars which have most probably been caused by anthropogenic interventions on the slope.

Year	Dormancy (D)	Earlywood cells (E)			Latewood cells (L)		Total
		EE	*ME*	*LE*	*EL*	*LL*	
1977	2						2
1978							0
1979							0
1980	5						5
1981							0
1982	1						1
1983	6						6
1984	1						1
1985	4				5		9
1986	1						1
1987	5				1	1	7
1988							0
1989	2				*4*		6
1990	*26*						26
1991	4						4
1992	2						2
1993	2		2				4
1994	10			1	1		12
1995	28		1				29
1996	11			*4*	*3*	*5*	23
1997	*11*		1		*7*		19
1998	*5*						5
1999	6						6
2000	4						4
2001	7	1					8
Total:	**143**	**0**	**5**	**5**	**21**	**6**	**180**

Trees with scars occurring during the constitution of Dam 6 (1996/97) are displayed in fig. 7b. In this period, 35 injuries were recorded in all 18 trees. In contrast to the relatively homogenous spatial distribution of scars in 1989 and 1990 (Dams 2 to 5), injuries caused by the constitution of Dam 6 are dispersed throughout the study plots. While anthropogenic rockfall apparently caused major damage in SP1, scars are again missing in several trees of SP2. While the first scars occur in Tree 7 within the last layers of earlywood cell layers (LE) in 1996, most injuries occur within the latewood cell layers (EL and LL) of 1996 (8 scars). In the succeeding dormant season (1997), 11 scars are counted in the samples. Similarly to the scars attributed to the dormancy (D) of 1990, rockfall activity in D 1997 is supposedly linked to construction works in late fall 1996 or the release of formerly destabilized rocks

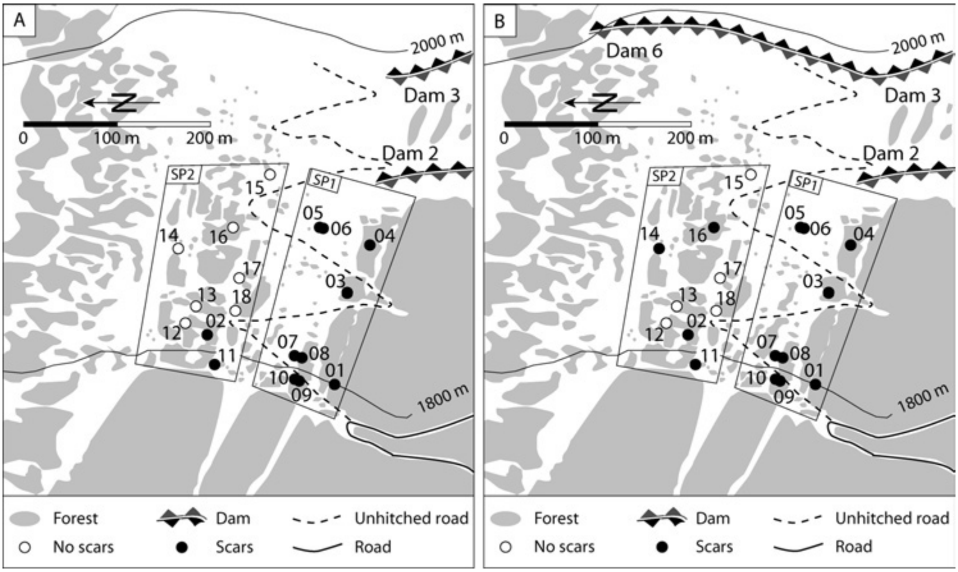

Fig. 7. Spatial distribution of rockfall activity (a) during the construction of the deflection dams (Dams 2 to 5) and (b) the first protection dam (Dam 6).

in spring 1997. In the second year of construction works, anthropogenic interventions caused 7 injuries within the latewood cell layers (EL) and in the dormant season of 1998 (5 injuries). Again, these scars are assessed the result of final aggradations of Dam 6 in fall 1997.

Contrary to expectations, the 18 selected trees obviously remained unaffected during the first year of construction works on the slope in 1988, when the unhitched road for construction traffic and Dam 1 were built. As the construction site of Dam 7 was located below the study plots, trees also remained unaffected during these anthropogenic interventions on the slope.

As for the intra-annual distribution of rockfall activity during construction works on the slope, it can be seen from table 2 that rockfall injuries outside the dormant season are mostly restricted to the periods with anthropogenic interventions on the slope. In this sense, 19 out of 27 injuries attributed to the latewood cell layers between 1977 and 2001 were most likely released by construction works. Similarly, four out of five scars attributed to the last layers of earlywood cells are supposedly linked to construction works on the slope.

4.2 *Natural rockfall activity*

By excluding the rockfall activity attributed to construction works, the number of scars observed in the 18 trees over the past 25 years is reduced from 180 to 115, which means that naturally driven rockfall activity accounts for almost 5 hits yr^{-1} on an average. Figure 8 shows the variations of rockfall activity between individual years and within the different growth periods.

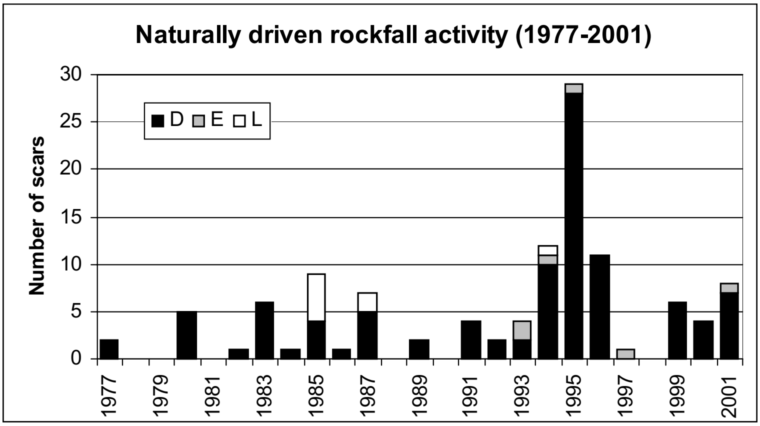

Fig. 8. Reconstructed minimum frequency of naturally driven rockfall on the Täschgufer slope (1977–2001; D = dormancy, E = earlywood, L = latewood). Rockfall triggered by anthropogenic activity on the slope is disregarded.

Again, rockfall activity greatly varies between the individual years. While no scars can be discerned in 1978, 1979, 1981 and 1988, above-average numbers of scars are recorded in 1985, 1994, 1995, 1999 and 2001. In this sense, reconstructed rockfall activity appears to coincide with direct observations on the Täschgufer slope, indicating increased rockfall activity in 1985 and after 1993 (see section 2). Above-average numbers of scars are mainly recorded after 1993. During the dormant season of 1994, rockfall activity caused 10 scars. A comparable number of injuries can be discerned in the dormancy of 1996 (11 scars). Massive rockfall in the dormant season of 1995 caused important damage to the selected trees, leaving 28 injuries. During the dormant season of 2001, rockfall activity caused 7 scars.

As for the intra-annual distribution of rockfall scars, events attributed to the dormant season are even more predominant (88 %). It can clearly be seen from fig. 8 that scars rarely occur in earlywood (E = 5 %). Similarly, injuries are uncommon in latewood, where only 8 scars (L = 7 %) can be discerned. A considerable number of scars was linked with abundant rockfall activity in the dormant season.

The spatial distribution of trees injured within the dormant season keenly varies between the individual years: Between 1977 and 1990, scars occurring during dormancy exclusively belong to trees located in SP2. Not a single injury can be discerned in SP1. Starting in 1991, scars repeatedly occurred at SP1, indicating an activation of rockfall originating from Rockfall Source Area 2. In 1993, scars were exclusively restricted to SP1, while SP2 apparently remained unaffected. During the dormant season of 1995, naturally driven rockfall caused injuries to trees in both study plots, but predominantly to those in SP2. In total, 38 injuries attributed to the dormant season are recorded in SP1 between 1991 and 2001. Simultaneously, naturally driven rockfall activity in SP2 accounted for 35 scars, 22 of which occurred during the increased rockfall activity in 1995 and 1996. During the only above-average activity outside the dormant season in EL 1985, rockfall affected trees in SP1 (trees 8, 9 and 10).

5. *Discussion*

In the study we have reported here, the use of stem discs procured a reasonable chart of rockfall activity and the seasonal timing of rockfall events on the Täschgufer slope. Similar to investigations on past fire regimes (Brown & Swetnam 1994, Ortloff et al. 1995), we introduced a microscopic approach to rockfall research which allowed determination of the seasonal timing of rockfall events by analyzing the position of the scars within the tree-rings.

Results on the rockfall frequency show that years with many scars in the selected trees consistently coincide with findings of geological mandatory opinions reporting on the observed rockfall activity on the slope (e. g., Lauber 1995). Over the last 25 years, naturally driven rockfall activity caused 115 scars in all 18 trees investigated.

Microscopic analyses indicate that rockfall scars were predominantly caused by rockfall events during the dormant season (88 %), which locally lasts from mid October through end of May (see table 1). Direct observations on the slope confirm these results, indicating that abundant rockfall tends to be highest in April and May. The size of rockfall components (up to 2 m^3), the sporadic occurrence of larger events as well as the seasonal timing indicate that rockfall triggering at Täschgufer most likely depends on seasonal rather than on diurnal freeze-thaw cycles. At the beginning of snowmelt in mid March, meltwater easily penetrates the heavily jointed and fissured bedrock in the Rockfall Source Areas. The water would then fill the rock joints which are still at a subfreezing temperature, as described by Matsuoka (2001) and Matsuoka et al. (2003). As a consequence, meltwater would refreeze causing permanent opening of the joints. In April and May, direct insolation gradually rises (Hufty & Theriault 1983), favoring the thawing of ice and activating rockfall on the west-facing slope.

Comparisons of meteorological data (SMI 2003) further indicate that periods with increased rockfall activity do not depend on short-term meteorological events. In agreement with the findings of Matsuoka & Sakai (1999), rockfall at Täschgufer seems to be neither influenced by thunderstorms in summer nor abundant rainfall in autumn. Even so, there seems to be no (direct) correlation between the only important rockfall event outside dormancy in latewood 1985 and the October 6, 1985 event mentioned in section 2. As the reactions in the injured trees were initiated within the first layers of latewood cells, we suppose that the reconstructed rockfall event occurred between mid July and August 1985 and not in late fall.

Spatial distribution of injuries further show that naturally driven rockfall activity strongly varied over the last 25 years. Between 1977 and 1990, selected trees in study plot 1 (SP1) remained unaffected by rockfall activity linked with thawing processes in spring. Therefore it seems that spring events triggered at Rockfall Source Area 1 only occurred after 1990. In contrast, results indicate that thawing processes in spring regularly triggered rocks from Rockfall Source Area 2.

Dam construction works on the slope in 1989 and again in 1996 and 1997 left 65 rockfall scars in the 18 selected trees. Within these periods, rockfall activity almost caused 22 hits yr^{-1}. Astonishingly, scars are missing during the first year of construction works in 1988, when Dam 1 and the unhitched road for construction traffic were built. While the absence of injuries during the realization of Dam 1 may be explained by the position of the construction site, it may not be accountable for the absence of scars during the construction of the unhitched road, repeatedly crisscrossing study plot 1 (SP1).

This study has taken a step in the direction of investigating the seasonal timing of rockfall activity using a microscopic approach of tree-rings. Due to the small number of trees we used for testing this new approach, the reconstructed event frequency can only give a rough review of rockfall activity over the last 25 years: Firstly, data only reflects punctual rockfall activity in 18 trees. Distances between the selected trees are generally large, allowing rocks to pass without causing damage. Secondly, the minimum height of selected trees proves to be critical for trees 7 and 8, which only trespassed mean impact heights by 1987. Thirdly, broken-off primary crowns and the formation of vertical sprouts growing from former branches ("candelabra form" trees) may furthermore influence the height of trees and therefore reduce the probability of a tree being hit. Tree 15 has, for instance, been decapitated at least four times by rockfall activity since 1977.

As for the intra-annual distribution of scars, microscopic analysis furnishes concise data on the seasonal timing of rockfall occurrence within the vegetation period, i. e. from early June through mid October. In contrast, reactions to injuries caused during dormancy (i. e. mid October to end of May) only occur at the beginning of the succeeding vegetation period and can hence not be analyzed in more detail. Combining permanent observations of rockfall rates in the field, measurement of rock temperatures and the circulation of water with tree-ring analysis would further help to understand rockfall activity and releasing processes during the dormant season. Finally, future research will need to integrate a larger number of tree samples to draw even more conclusive results on past rockfall activity.

6 *Conclusion*

The approach outlined in this study proves to be a useful tool for analyzing differences in intra-annual rockfall activity on forested slopes. In the case of data available on the different growth phases within the vegetation period of the selected tree species at the study site, results on the seasonal timing of rockfall activity can even be given with almost monthly resolution. In this sense, this method allows one to compare periods with apparently increased rockfall activity reconstructed from dendrochronological analysis with meteorological data. However, for rockfalls occurring within the dormant season, tree-ring analysis may not furnish detailed information on the timing and growth reactions because the formation of callous tissue or resin ducts is only initiated within the first layer produced in the succeeding vegetation period. Therefore, dendrochronological analysis need to be completed with direct observations on the site.

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