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# 1 **Tree-ring reconstruction of snow avalanche activity: Does avalanche path selection** 2 **matter?**

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19

## 20 **Abstract**

21 In the current context of anthropogenic global warming, one of the purposes of dendrogeomorphic analyses is to  
22 provide long and continuous chronologies of mass movements, so as to detect potential trends or shift related to  
23 increasing temperatures. However, on documented slopes, the comparison between historical archives and tree-  
24 ring records suggests that dendrogeomorphic reconstructions systematically underestimate the natural activity of  
25 the process under investigation. In the specific case of snow avalanches, underestimation generally amounts to  
26 50% and the main causes generally given for this difference are related to the magnitude of past events. In this  
27 study, we hypothesize that the morphometric characteristics of avalanche paths and their forest cover could have  
28 significant impacts on the length and reliability of tree-ring reconstructions. In order to test this hypothesis, we  
29 selected four adjacent, albeit differently structured, avalanche paths from the Queyras massif (French Alps), with  
30 the aim to compare their potential for a continuous reconstruction of past avalanche activity. On the most active  
31 avalanche paths characterized by high-altitude release areas (covered only by shrubby vegetation), tree-ring  
32 reconstructions do not exceed one century in length, with recurrence intervals of high magnitude events > 25  
33 years. By contrast, on forested couloirs where lower slopes and forest coverage up to the release areas limits the  
34 intensity of events, the frequency of reconstructed snow avalanches is 2.5 times higher, the reconstructions span

35 longer periods and the convergence rate with historical archives attest to the reliability of the dendrogeomorphic  
36 approach. These results suggest that a careful selection of couloirs is essential and that priority should be given  
37 to forested sites as (i) they allow for exhaustive and (ii) reliable reconstructions over (iii) long periods of time.

38 **Keywords: dendrogeomorphology, snow avalanche, forest cover, reliable reconstruction, French Alps,**  
39 **tree-rings.**

## 40 **1. Introduction**

41 Avalanches are one of the major natural hazards in mountain regions. Every year, they damage urban  
42 infrastructures, transportation networks and endanger human lives (Bründl et al., 2004). During the 2017-2018  
43 winter season, 64 avalanche-related accidents were recorded in France, including 26 fatal accidents (ANENA,  
44 2018). In recent decades, the expansion of urbanization in mountainous massifs, increasing mobility, and the  
45 diversification of winter recreation have led to an increase in avalanche risk (Einhorn et al., 2015; Nöthiger and  
46 Elsasser, 2004; Techel et al., 2016). In France, observations of avalanche events are documented in the *Enquête*  
47 *Permanente sur les Avalanches* (EPA; or permanent avalanche survey), a database that contains ~100,000  
48 avalanche events for ~4000 recognized paths in the French Alps and the Pyrenees since the beginning of the 20<sup>th</sup>  
49 century (Bourova et al., 2016; Mougin, 1922). Data on avalanches are gathered by forest rangers, who also  
50 record various quantitative (e.g., runout altitudes, deposit volumes) and qualitative (e.g., flow regime, snow  
51 quality) data (Jamard et al., 2002). Despite its uniqueness, the quality of EPA records locally depends to a large  
52 extent on the rangers' careful data recording, a fact that makes certain local series of limited use (Eckert et al.,  
53 2007; 2010a). In addition, Teich et al. (2012) stated that in forested terrain, avalanches are sometimes poorly  
54 documented as they are not of key importance compared to large destructive events threatening settlements,  
55 infrastructure, and human lives in open terrain.

56 On wooded avalanche paths, forest stands act as protective barriers, or snow bridges in release areas (Bebi et  
57 al., 2009). Based on dendrogeomorphic approaches (Alestalo, 1971; Stoffel and Corona, 2014), focused on the  
58 identification and dating of growth disturbances in ring width series, trees can also be used to reconstruct past  
59 avalanche activity with annual resolution and for periods covering past decades to centuries (Butler and Sawyer,  
60 2008) and to fill certain gaps in incomplete historical chronicles (Stoffel et al., 2010). Since the pioneer works in  
61 dendrogeomorphology (Burrows and Burrows, 1976; Butler, 1979; Carrara, 1979; Mears, 1975; Potter, 1969;  
62 Shroder, 1980, 1978), an increasing number of studies has focused on snow avalanches by using tree-ring  
63 analysis to reconstruct years of avalanche activity (Boucher et al., 2003; Casteller et al., 2007; Corona et al.,  
64 2013, 2012, 2010; Favillier et al., 2018, 2017; Garavaglia and Pelfini, 2011; Laxton and Smith, 2009; Muntán et  
65 al., 2004; Stoffel et al., 2006), to calibrate avalanche flow models (Casteller et al., 2008; Schläppy et al., 2014), to  
66 analyze the impact of ecological and anthropogenic disturbances on snow avalanche regimes (Germain et al.,

67 2005) or to identify the synoptic situations responsible for the triggering of regional snow avalanche activity  
68 (Casteller et al., 2011; Dubé et al., 2004; Germain et al., 2009; Muntán et al., 2009). In the current context of  
69 global warming (Gobiet et al., 2014), tree-ring reconstructions are also expected to provide insights into longer-  
70 term (multi-centennial) fluctuations of avalanche activity (Ballesteros-Cánovas et al., 2018; Corona et al., 2013;  
71 Heffernan, 2018; Schläppy et al., 2016; Stoffel and Corona, 2018).

72 However, on documented paths, comparison between observations listed in the EPA and tree-ring records  
73 suggests that the dendrogeomorphic reconstructions systematically underestimate years with natural avalanche  
74 activity (Corona et al., 2013, 2012, 2010; Schläppy et al., 2014). The main causes that are typically given for this  
75 difference are related to the magnitude of past events. Avalanches have to be of sufficient magnitude to create  
76 impacts on trees (Bartelt and Stöckli, 2001; Bebi et al., 2009). Conversely, major avalanches may remove or blur  
77 the evidence of previous or subsequent events in case large parts of the forest are destroyed (Bryant et al., 1989;  
78 Carrara, 1979), or disturb tree growth in such a way that younger events cannot be identified in the tree-ring  
79 record (Kogelnig-Mayer et al., 2011). In that regard, the morphometric characteristics of the avalanche path–  
80 through their influence on the frequency and/or magnitude of events and the long-term viability of the forest stand  
81 – are susceptible to have a significant impact on the completeness of the ensuing tree-ring reconstruction. We  
82 therefore hypothesize that, in the absence of anthropogenic interventions, the potential for a complete and  
83 continuous avalanche reconstruction could vary strongly amongst adjacent paths.

84 In order to test this hypothesis, (1) a dendrogeomorphic approach has been deployed on a slope of the upper Guil  
85 valley (Ristolas municipality, French Alps) in the Queyras massif. This slope was selected as it is composed of  
86 four avalanche paths characterized by comparably low anthropogenic interventions (i.e. very limited grazing or  
87 forest harvesting in the past) but marked differences in terms of morphology (starting zone altitudes and path  
88 lengths), avalanche dynamics (frequency and magnitude of events), and forest cover (i.e. forested paths and  
89 corridors characterized by a marked transverse zonation), thus enabling the comparison between reconstructions.  
90 In order to enhance the detection of snow avalanche years and to disentangle the potential effects of snow  
91 avalanches from disturbance pulses caused by climatic or exogenous factors, such as cold/dry years or larch  
92 budmoth outbreaks, the four-step procedure developed by Favillier et al. (2017) has been used. (2) The multi-  
93 centennial reconstructions are validated through comparison with historical chronicles, old maps, and aerial  
94 photographs. (3) Their comparison enables discussion of the dendrogeomorphic potential of each of the analyzed  
95 paths. This subsequently provides criteria that can, in the future, help to select the best sites for as complete as  
96 possible and continuous avalanche reconstructions, that are crucial for the detection of potential trends in  
97 avalanche activity related to climatic and other environmental changes.

## 98 **2. Study site**



99 The site under investigation is located on the western slope of the Upper Guil Valley, upstream from the Echalp  
100 hamlet, at the locality Ravin de la Salce (44°44'47" N, 6°59'42 E; Fig. 1). The talus slope covers an area of 1.47  
101 km<sup>2</sup> and extends from the Guil thalweg (1740 m asl) to the Crête des Baysses (2700 m asl). The mean slopes in  
102 the upper part of the talus range between 35 and 40°, while the distal segment appears geometrically concave  
103 with mean slope angles comprised between 20 and 25°. The site is dominated by the Crête des Baysses, a 400-  
104 m schisto-calcareous rockwall cut by several subvertical faults oriented S-N and SW-NE (Lemoine and Tricart,  
105 1986).

106 Climate is characterized by a mixed montane-Mediterranean to continental character (Touflan et al., 2010).  
107 According to the data from the nearby meteorological station of Saint-Véran (2125 m asl), located 12 km south-  
108 west from the slope, annual temperature is -1.5 °C for the period 1981–2010 and average annual precipitation  
109 amounts to 710 mm. During winter, mean air temperature (DJF) is -5.3 °C while precipitation amounts to 127 mm.  
110 Precipitation falls primarily as snow from November to April. Average annual snowfall reached 320 cm (±183 cm)  
111 for the period 1928–2007. The forest cover is dominated by European larch (*Larix decidua* Mill.) between 1750 m  
112 and 2300 m asl. The understorey is dominated by herbaceous species and shrubs, namely *Rhododendron*  
113 *ferrugineum* L. (rhododendron), *Juniperus comunis* (common juniper) and *Vaccinium myrtillus* L. (bilberry).

### 114 **3. Material and methods**

#### 115 *3.1. Archival data on past events*

116 First, we compiled a historical database of past snow avalanches at Ravin de la Salce using the EPA covering the  
117 period 1930-2013. Then, with the aim to complement the archival database, topographic maps and 19 aerial flight  
118 campaigns available from the French National Geographic Institute (IGN, at a scale of ca. 1:25,000) were used to  
119 detect evidence of damaging avalanche events since 1945.

#### 120 *3.2. Delineation of avalanche paths*

121 The delineation of the avalanche paths at Ravin de la Salce is complex due to (i) multiple release areas and  
122 avalanche tracks in the eastern part of the slope, (ii) the absence of preferential flow paths, and (iii) the dense  
123 forest cover, which is effectively masking geomorphic evidence of past avalanche events in the western part of  
124 the study site. To precisely delineate the spatial extent of each path, we used the CLPA avalanche map (*Carte de*  
125 *Localisation des Phénomènes Avalancheux*) that complements the EPA and localizes the maximum lateral extent  
126 and runout elevations of avalanche paths as retrieved from historical testimonies and the analysis of aerial  
127 photographs (Bonnetoy et al., 2010). In addition, the numerical avalanche dynamics model RAMMS (Rapid Mass  
128 Movement System; Christen et al., 2010; Gruber and Bartelt, 2007; Rudolf-Miklau et al., 2015) – has been  
129 employed to estimate the spatial pattern of high magnitude avalanche events. RAMMS predicts avalanche runout

130 distances, flow velocities and impact pressures on three-dimensional digital terrain models based on a Voellmy-  
131 fluid friction model.

132 RAMMS simulations were based on a 5-m Digital Elevation Model (DEM) extracted from the IGN RGE ALTI@  
133 database. Slopes with angles ranging from 30 and 45° were considered as potential release areas (Salm, 1982;  
134 Schweizer, 2003). In order to refine the detection, these thresholds were adjusted to account for the potential bias  
135 induced by the DEM resolution (ARPA and CEMAGREF, 2008) according to the following formula:

$$136 \quad \alpha_r = \alpha \times \text{RES}^{-0.075} \quad (1)$$

137 Where  $\alpha_r$  is the corrected angle value,  $\alpha$  is the angle value (30-45) and RES is the resolution of the DEM (here  
138 RES=5 m).

139 For each delineated release area, one single simulation was performed with the objective of delineating the area  
140 exposed to extreme avalanche events. To this aim, typical friction parameter values were used following the  
141 recommendations of Gruber and Bartelt (2007). Snow depth in the release areas were set to 2 m, which,  
142 according to Gaume et al. (2013), corresponds to a return period of more than 100 years in terms of three-day  
143 snowfall events at the site.

### 144 *3.3. Sampling strategy, identification, dating, and classification of growth disturbances*

145 To reconstruct past avalanche activity based on dendrogeomorphic techniques, trees were sampled along three  
146 longitudinal transects. The upper transect (T1, 2200-m asl) is located in the release area of the two westernmost  
147 paths delineated according to the procedure detailed above, and at timberline for the easternmost paths. The  
148 intermediate transect (T2, 2000-2100 m asl) is located in the median part of each path. Finally, T3 (1880-1950-m  
149 asl) is situated in the distal and concave segment of the couloirs.

150 In summer 2017, 342 increment cores (52, 127, 77, 86 on E1, E2, C1, and C2, respectively) from 306 European  
151 larch (*Larix decidua* Mill.) trees were collected using a Pressler increment borer. The position of each tree was  
152 recorded with a 1-m precision GPS device and measurements were taken for the tree (diameter at breast height)  
153 and the disturbed feature (type, height). In this study, several kinds of growth disturbances (GD) to trees most  
154 commonly attributed to snow avalanches such as abrupt growth suppressions (Butler and Malanson, 1985;  
155 Corona et al., 2012; Kogelnig-Mayer et al., 2013; Stoffel et al., 2013), impact scars (Corona et al., 2014; Stoffel  
156 and Perret, 2006; Trappmann et al., 2013), callus tissue (CT; Schneuwly et al., 2009b; Stoffel et al., 2010),  
157 tangential rows of traumatic resin ducts (TRD; Bollschweiler et al., 2008b; Schneuwly et al., 2009a; Stoffel and  
158 Hitz, 2008) as well as the initiation of compression wood (Butler et al., 2010; Timell, 1986) were retained in the  
159 analysis.

160 Following recent recommendations by Stoffel and Corona (2014), Tichavský and Šilhán (2016) and Šilhán and  
161 Stoffel (2015), old and young trees were considered in our sampling procedure in order to ensure the  
162 completeness of avalanche chronologies.

163 Sampling positions were optimized based on recommendations given by Stoffel et al. (2013). Sample preparation  
164 and analysis followed the procedures described in Stoffel and Bollschweiler (2008) and Stoffel et al. (2013). GD  
165 were visually identified in the tree-ring series and cross-dated against the Echalp (1338-2010) and Souliers (1448-  
166 2009) local reference chronologies computed from undisturbed trees (Corona et al., 2013; Saulnier et al., 2017).  
167 In a subsequent step, intensities were assigned to GDs in order to emphasize features that are clearly associated  
168 with avalanche activity and to discriminate these from disturbances possibly induced by other factors (Corona et  
169 al., 2012; Stoffel et al., 2013). GDs were classified based on the visual quality of the evidence of reactions within  
170 each sample according to the intensity scale presented in Kogelnig-Mayer et al. (2011): weak (intensity class 1),  
171 medium (intensity class 2), and strong (intensity class 3) reactions and clear evidence of injuries (intensity class  
172 4) were thus distinguished.

173 The age structure of the stand was approximated by counting the number of tree rings of sampled trees.  
174 However, since the innermost rings of some trees were rotten and trees were not sampled at their stem base, the  
175 age structure might be strongly underestimated (Bollschweiler et al., 2008a). Nonetheless, as *L. decidua* has  
176 been shown repeatedly to recolonize surfaces cleared by snow avalanches or other mass-movement processes  
177 and established dominance within a few decades, we believe that our age distribution could help the  
178 documentation of destructive events at our study site (Stoffel et al., 2006; Van der Burght et al., 2012). As a  
179 consequence, in order to detect potential forest recolonization dynamics, individual tree ages were spatially  
180 interpolated using an inverse distance weighted interpolation algorithm using ArcGIS (IDW; ESRI, 2013; Kennedy,  
181 2013).

#### 182 3.4. Detection of past avalanche events in growth disturbance series

183 To detect past snow avalanche years – during which at least one snow avalanche is reconstructed in the selected  
184 paths – in the GD series, we adopted the four-step procedure (Fig. 2) developed by Favillier et al. (2017) (Please  
185 refer to it for more details). This approach addresses the necessity to disentangle the potential effects of snow  
186 avalanches from disturbance pulses caused by climatic or exogenous factors, such as cold/dry years or larch  
187 budmoth outbreaks. Based on this procedure, the minimum population threshold was set to 15 trees alive the  $t$   
188 year. GD and index  $I$  (Shroder, 1978, Eq. 2) – used to discriminate potential avalanche and non-avalanche events  
189 – were defined according to the sample size following the recommendations of Butler and Sawyer (2008) and  
190 Corona et al. (2012).

$$191 \quad I_t = ((\sum_{i=1}^n R_t) / (\sum_{i=1}^n A_t)) * 100 \quad (2)$$

192 where  $\Sigma R$  is the number of trees responding to an event in year  $t$ , and  $\Sigma A$  represents the number of trees alive in  
193 year  $t$  at the path scale, where the extension of each individual path is delineated according to Sect 3.1. In other  
194 words, the detection of avalanche events is made in each path independently, and with a definition of each path  
195 corresponding to avalanche flow physics.

196 In addition to the procedure described in Favillier et al. (2017), lowered thresholds were adopted to maximize the  
 197 number of detected events without including exogenous noise. Additional events were only added if they  
 198 exceeded the I threshold and if the number of GD was less than 1 under the GD threshold. According to the  
 199 second step of the procedure (Fig. 2), climatic and ecological signals interfering with the dendrogeomorphic signal  
 200 were identified. In total, 17 larch budmoth (LBM, *Zeiraphera diniana* Gn.; cf. Baltensweiler et al., 1977, and Kress  
 201 et al., 2009) outbreak years (see Table 1) have been reconstructed and 34 characteristic narrow rings have been  
 202 identified in the Southern/Intermediate French Alps since 1720 CE according to Saulnier et al. (2017). Similarly,  
 203 20 years with negative May-September anomalies of temperature and precipitation (with values exceeding 1.5 SD  
 204 below the average) have been considered as extreme dry/cold years (Table 1) during the period 1720–2003 and  
 205 according to the gridded HISTALP point temperature information (Efthymiadis et al., 2006) closest to the study  
 206 site. Potential avalanche events detected in step 1 coinciding with LBM outbreak episodes or extremely cold/dry  
 207 years were examined in more detail to avoid misclassification. According to the procedure, we systematically  
 208 excluded growth suppressions from the account of GDs. Avalanche and non-avalanche years were discriminated  
 209 at the path scale based on a threshold of 3 GDs (Fig. 2).

210 In the third step, levels of confidence – very high (vHLC,  $W_{it} > 0.3$ ), high (HLC,  $0.3 > W_{it} > 0.2$ ) and medium  
 211 (MLC,  $W_{it} < 0.2$ ) –were distinguished for each detected event based on a weighted index factor ( $W_{it}$ , Eq. 3)  
 212 accounting for the type and intensity of GDs (Favillier et al., 2017).

$$213 \quad W_{it} = \frac{[(\sum_{i=1}^n T_i * 7) + (\sum_{i=1}^n T_s * 5) + (\sum_{i=1}^n T_m * 3) + (\sum_{i=1}^n T_w * 1)]}{\sum_{i=1}^n A_t} \quad (3)$$

214 where, for each year  $t$ ,  $T_i$  is the sum of trees with injuries;  $T_s$  is the sum of trees with strong GDs;  $T_m$  is the sum of  
 215 trees with medium-intensity GDs;  $T_w$  represents the sum of trees with weak-intensity GDs, and where  $A$  gives the  
 216 total number of trees alive in year  $t$ . Despite the precautions taken at each previous step, each additional event  
 217 detected during step 1 and events coinciding with an ecological or a climatic year at step 2 were only rated with a  
 218 low level of confidence (LLC) (Fig. 2).

219 In the last step, avalanche events and corresponding GDs were mapped using the ArcGis 10.2.1 Time Slider  
 220 (ESRI, 2013; Kennedy, 2013). On the basis of the sampling transects, avalanche reaching the upper,  
 221 intermediate, and lower transects were rated as eXtra-Large (XL), Large (L), Medium, (M) or Small (S),  
 222 respectively. At the path scale, the annual probability for an avalanche event was computed by dividing the  
 223 number of reconstructed events by the period covered by the reconstruction.

## 224 4. Results

### 225 4.1. Delineation of avalanche paths at Ravin de la Salce

226 At Ravin de la Salce, precise geomorphic mapping including field observations, interpretation of aerial  
 227 photographs (CLPA), extent of past avalanche events derived from the EPA and flow extensions simulated with

228 the RAMMS numerical snow avalanche simulations revealed a minimum of four distinct avalanche paths, namely  
229 (from west to east): E1 (19.7 ha, 1075 m long, 240 m wide, release area 2110-2180 m asl), E2 (25.3 ha, 1130 m  
230 long, 255 m wide, 2140-2340 m asl), C1 (42 ha, 1515m long, 300 m wide, 2290-2520 m asl), and C2 (55 ha, 1725  
231 m long, 366 m wide, 2430-2620 m asl) (Fig. 1b, 3; see Table 2). According to the performed RAMMS simulations,  
232 the maximum velocities and pressures are significantly lower on E1/E2 ( $<10 \text{ m.s}^{-1}$  and 100 kPa) than on C1/C2  
233 ( $>30 \text{ m.s}^{-1}$ ,  $>300 \text{ kPa}$ ). E1 and E2 are covered by a dense larch forest from the top of the slope to the runout  
234 zones. A characteristic transverse vegetation pattern can be observed across C1 and C2: the inner zone is  
235 colonized by herbaceous and shrubby (*R. ferrugineum*, *J. communis*) formations, whereas *L. decidua* is dominant  
236 in the outer zone.

#### 237 4.2. Snow avalanches recorded in historical archives

238 Archival data on past events at Ravin de la Salce go back to 1930. The EPA inventoried 10 events on avalanche  
239 paths E1 and E2, namely in 1930, 1947, 1951, 1959, 1961, 1973, 1977, 1986, 2003, and 2009. According to the  
240 EPA database in which E1 and E2 paths were grouped in a unique couloir, the longest events would have  
241 occurred on 25 February 1947, 24 February 1951, and 1959 (undated), reaching an altitude of  $< 1550 \text{ m asl}$ .  
242 Damage to the forest stands are reported for the snow avalanches that occurred in 1977 (undated) and on 16  
243 December 2008. For the period 1930-2008, the mean recurrence intervals between two consecutive events is 8  
244 years based on EPA records. The absence of avalanche events between 1930 and 1947 is probably due to the  
245 absence of systematic observations during the interwar period and World War II. Similarly, due to the absence of  
246 elements at risk, avalanche paths C1 and C2 do not contain any records of past events in the EPA. However, one  
247 event was retrieved from the CLPA datasheet, pointing to an avalanche that would have occurred on 16  
248 December 2008 in at least one of these couloirs. In addition, according to the diachronic comparison of aerial  
249 photographs, evidence for at least two snow avalanche events can be found indirectly as they apparently  
250 destroyed parts of forested stands C1-C2 between 1957–1962 and 2003–2009.

#### 251 4.3. Age structure of the stands

252 Visual cross-dating of tree-ring samples was carried out by means of the skeleton plot method and primarily  
253 based on the narrow rings of 1500, 1643, 1668, 1741, and 1906. After cross-dating, data on pith ages at breast  
254 height indicate that the 306 trees sampled on the Ravin de la Salce slope are on average 171 years old ( $\pm 102$   
255 years). The oldest tree selected for analysis attained sampling height in 1398 (618 rings in 2016) while the  
256 youngest tree reached breast height in 2010. Figure 4 shows that trees older than 300 years are mainly located  
257 along the upper transect (T1) where the average age of individuals is 206 years ( $\pm 114$  years). On T3, the mean  
258 age of sampled trees is lower, especially for E1 and C1 paths ( $126 \pm 81$  years). The number of trees ( $n=15$ )  
259 considered as a minimum for analysis in our 4-step procedure was exceeded in 1779 at E1, 1720 at E2, 1813 at

260 C1 and 1791 at C2. The sample size shows a clear increase in the 1860-70s at E1, E2, and C1, and in the 1920s  
261 at C2. A second step or increase is observed in the 1980s at E1 (Fig. 5).

#### 262 *4.4. Distribution of growth disturbances and chronology of avalanche events*

263 Sampled cores allowed identification of 1591 GD in the tree-ring series for the period 1720–2016, of which 314  
264 (19.4%) were considered strong avalanche indicators (Classes 3 or 4). Table 3 summarizes the types of GD as  
265 well as their intensity. TRDs and CW were the GDs most frequently (76.6%) identified in the samples, followed by  
266 growth suppressions (GS; 20%). By contrast, only 51 injuries were sampled, which represents 3.2 % of the dated  
267 disturbances. In total, 60.6% of the GDs were rated as weak, 20.0% as median and 16.2% as strong. The oldest  
268 GD identified in the tree-ring series was dated to 1496 CE, the most recent to 2016. Nearly every year exhibited  
269 GD in a small number of trees for the period 1780-2016 at E1 and E2. GDs were scarcer before 1920 at C1 and  
270 C2.

271 The event-response histograms depicted in Fig. 5 summarize all reactions recorded in the trees along the four  
272 avalanche paths. In total, 22 (1779-2016), 23 (1720-2016), 2 (1812-2016), and 5 (1894-2016) avalanche events  
273 were reconstructed at sites E1, E2, C1, and C2, respectively. The highest percentages of disturbances were  
274 recorded in 1909 with It of 41.94 and 31.1 and a Wit of 1.39 and 0.78 at paths E1 and E2, respectively. In 2009,  
275 growth disturbances reached It values of 13.33 (Wit: 0.31), 23.88 (Wit: 0.93), and 26.03 (Wit: 1) at paths E1, C1,  
276 and C2, respectively. Finally, a large proportion of disturbances were dated to 1961 at paths E1, E2, and C1 (It:  
277 17.65, 26.09, 17.54%; Wit: 0.47, 0.66, 0.53).

278 Based on potential interferences between the avalanche and exogenous signals in the dendrochronological  
279 series (step 2), and on the basis of the Weighted Index Factor (Wit; step 3, Fig. 6) that includes simultaneously for  
280 the type and intensities of growth disturbances, 16 and 10 events occurring during 19 different years were  
281 assigned with very high and high levels of confidence, respectively. By comparison, 24 events (22 years)  
282 characterized by a majority of weak and medium GDs, were reconstructed with a medium and low level of  
283 confidence. Amongst the 20 potential events that coincide with LBM outbreak episodes or extreme climatic years,  
284 9 were excluded from the reconstruction and 11 were rated with a low level of confidence. With respect to the  
285 1791-2014 and 1809-1998 periods – delimited by the first and the last observed events – and at the level of the  
286 slope scale, the mean recurrence intervals of snow avalanches are 10 and 9 years at E1 and E2, respectively.  
287 They exceed 20 years (24 years, 1961-2009; and 23 years, 1894-2009) at C1 and C2. The decades 1931-1940 (7  
288 events) and 1971-1980 (6 events) are characterized by the highest avalanche activity; conversely, no event was  
289 reconstructed for the periods 1829-1853 and 1937-1956. In total, nine events occurred synchronously at E1 and  
290 E2, namely in 1909, 1934, 1936, 1961, 1973, 1979, 1998, 2004, and 2011 (Fig. 7).

#### 291 4.4. *Spatial extent of reconstructed events*

292 Sampling along transects only allows a partial reconstruction of the spatial extent of past avalanche events and  
293 an estimation of the minimum longitudinal extent of past events. In total, 15 events reached the distal segment of  
294 the talus, 24 were reconstructed at the median transect level and 13 were limited to the upper part of the  
295 avalanche paths. All the events retrieved at C1 and C2 reached the lowest transect. Conversely, at E1 and E2, 37  
296 out of 45 (82%) snow avalanches were limited to the upper (35.1%) or the median (64.9%) transects.

297 Figure 8 shows two high-magnitude events reconstructed from the dendrogeomorphic approach in 1962 and  
298 2009. Based on the EPA inventory, we could reasonably attribute the 30 and 10 GDs observed at E2 and C1,  
299 respectively, to the event reported on 7 February 1961. This hypothesis is further supported by the diachronic  
300 analysis of the aerial photographs of 1956 and 1962 showing that a large part of the stands was destroyed at C1  
301 and that larch trees were removed from the main track and in the lowest portion of E2, Fig. 8). In the same way,  
302 the snow avalanche documented on 17 December 2008 was retrieved through tree-ring analyses at C1 (16 GDs)  
303 and C2 (19 GDs) and could be precisely delineated based on the aerial photographs from 2005 and 2010.

304 Before 1945, aerial photographs are not available for our study site. The topographic maps of 1896 and 1930 did  
305 not provide insights into possible changes in the spatial extent of the forest stand. As a consequence, the events  
306 reconstructed with a high level of confidence in 1897, 1920, 1928, and 1930 could not be confirmed through  
307 diachronic analysis.

### 308 **5. Discussion**

#### 309 5.1. *Accuracy of the reconstructions*

310 The study we report here employs dendrogeomorphic techniques on four adjacent, albeit differently structured,  
311 avalanche paths from the Queyras massif (French Alps), with the aim to compare their potential for a continuous  
312 reconstructions of past avalanche activity. In the global warming context, such reconstructions have proven to be  
313 particularly important to complement incomplete historical record and for the detection of potential climate-related  
314 trends in avalanche activity (Ballesteros-Cánovas et al., 2018). To reach this goal, we used the 4-step procedure  
315 developed by Favillier et al. (2017) (i) to disentangle snow avalanche signals in tree-ring series from signals  
316 induced by other external disturbances and (ii) to estimate the robustness of our tree-ring based snow avalanche  
317 reconstruction depending on the total number of disturbances (GD) and the percentage of trees impacted. Based  
318 on this procedure, 52 snow avalanche events were reconstructed in 38 different avalanche years. The  
319 reconstruction therefore complemented the historical chronology significantly with 10 new snow avalanche winters  
320 between 1930 and 2008, and by extending the series back to 1791 CE at E1. In total, 70% of the avalanche years  
321 listed in the EPA were retrieved, especially on paths E1 and/or E2 with the dendrogeomorphic approach, namely  
322 in 1930 (E1, C2), 1959 (E2), 1961 (E1, E2, C2), 1973 (E1, E2), 1977 (E1), 2003 (E1), and 2009 (E1, C1, C2).

323 Amongst these avalanche years, five could be reconstructed with very high levels of confidence. In particular, the  
324 extreme avalanche cycle of 16 December 2008, when 10 snow avalanches were reported in the Ristolas  
325 municipality (Eckert et al., 2010b; Gaucher et al., 2009), could be reconstructed with the highest level of  
326 confidence on paths E1, C1, and C2. On C1 and C2, the absence of EPA records renders a comparison  
327 impossible. On paths E1 and E2, the convergence rate between the EPA and the tree-ring reconstruction  
328 significantly exceeds those reported by previous studies made in the French Alps by Corona et al. (2012, 43%),  
329 Corona et al. (2013, 43%), Schläppy et al. (2013, 38%) and Schläppy et al. (2014, 33-45%). This synchronicity  
330 confirms the potential of forested avalanche paths for a detailed reconstruction of past avalanche activity. Albeit  
331 the fact that GDs were observed in tree-ring series in 1947 (14), 1951 (8), and 1986 (8), these events listed in  
332 historical records were not confirmed with dendrogeomorphic analysis as the  $l_t$ , GD, or  $W_{it}$  values did not exceed  
333 the required thresholds. This lack may be attributed to the stringency of the procedure employed here, designed  
334 to limit the introduction of noise but could equally be related to an over-sensibility of the dendrogeomorphic  
335 approach. Indeed, one should indeed keep in mind that the  $l_t$ , GD, and  $W_{it}$  thresholds used in the first and third  
336 steps are empirical. As no consensus exist in literature, they have been synthesized from Corona et al. (2014),  
337 Favillier et al. (2017), Kogelnig-Mayer et al. (2011) and Schnewly-Bollschweiler et al. (2013) but cannot be  
338 considered as absolute values suitable for all sites. Similarly, in the second step, the threshold of four mechanical  
339 disturbances was arbitrary chosen to disentangle snow avalanche events from climate and larch budmoth  
340 outbreaks (Favillier et al., 2017) and may therefore lead to the omission of minor events and to an  
341 underestimation of past avalanche activity. In addition, (i) snow avalanches reported in historical chronicles have  
342 to be of sufficient magnitude to have impacts on trees, but (ii) not too major as they would then destroy large parts  
343 of the forest stand and thereby remove evidence of past and subsequent events or disturb tree growth in such a  
344 way that younger events cannot be identified in the tree-ring record (e.g. Carrara, 1979; Kogelnig-Mayer et al.,  
345 2011). As a consequence, and despite our high success rate, the number of reconstructed events has to be seen  
346 as a minimum frequency of natural avalanche activity.

## 347 5.2. Two different avalanche dynamics

348 In this study, we deliberately chose contiguous avalanche paths with different morphometric characteristics and  
349 forest cover, with the aim to detect differences in their potential to record past events in trees. On the one hand,  
350 paths E1 and E2 are characterized by forested release areas, located at altitudes <2340 m asl and the presence  
351 of a very dense shrub cover (mainly *R. ferrugineum*), with an average height of about 0.70 m. Both paths have  
352 limited areas (<25ha), their length does not exceed 1000 m, and they are almost completely covered by open  
353 larch stands. On the other hand, on paths C1 and C2, snow avalanches are commonly triggered naturally from  
354 unforested release zones located above 2290 m asl and covered by shrubby grassland. Their lengths exceed  
355 1500 m and they show a marked transverse vegetation zonation (Malanson and Butler, 1986) with an inner zone



356 colonized by shrubs and shade-intolerant pioneer tree species and forest vegetation (mainly European larch) in  
357 the outer zone. The performed snow avalanche simulations reveal that maximum velocities and maximum  
358 pressures are significantly higher in these paths than on paths E1 and E2.

359 As expected, avalanche dynamics strongly differ from C1/C2 to E1/E2. On paths C1 and C2, all snow avalanches  
360 reach the lower sections of the slope and are reconstructed with a high level of confidence. Avalanches in paths  
361 C1 and C2 are often accompanied by large forest removal, such as in the 1960s and after 2009 according to  
362 archival documents, and reveal the intense and destructive nature of snow avalanches in these paths.  
363 Paradoxically, the recurrence intervals calculated on path C1 (24 years over the period 1961-2009) and C2 (23  
364 years over the period 1894-2009) are much lower than those calculated for paths E1 and E2. This paradox can  
365 neither be explained by path characteristics nor by the vegetation structure that could plead for a higher frequency  
366 of snow avalanches on paths C1 and C2. By contrast, we can reasonably hypothesize that they result from a gap  
367 in the dendrogeomorphic approach. More explicitly, it is likely that the periodic destruction of the forest stands by  
368 high-magnitude snow avalanches, comparable to those observed in 1962 or 2009, jointly limits the length of the  
369 reconstruction as well as the number of the reconstructed events (Corona et al., 2012). In addition, despite the  
370 presence of multi-century-old larch trees along the outer margins of both paths, no avalanches could be  
371 reconstructed prior to the end of the 19<sup>th</sup> century, thus suggesting that the lateral extents of snow avalanches  
372 during the Little Ice Age did not exceed those of the 20<sup>th</sup> century.

373 On the contrary, on paths E1 and E2, the reconstructions derived from tree-ring analyses span longer periods  
374 (1791-2016 and 1809-1998, respectively), and exceed those derived for paths C1 and C2 by more than one  
375 century. Comparable decadal avalanche recurrence intervals, 2.5 times higher than on paths C1/C2, are  
376 reconstructed on paths E1/E2. We assume that the intensity of past avalanche events has been more moderate.  
377 This assumption is supported by a vast body of evidence such as (1) the lower altitude of vegetated release  
378 areas, (2) higher forest coverage, (3) the output of the RAMMS simulations, (4) the presence of older trees, (5)  
379 the diachronic analysis of aerials photographs showing only limited changes in forest cover, and (6) more  
380 heterogeneous runout distances with 29, 46, and 25% of the reconstructed event reaching the upper, medium,  
381 and lower sampling transects, respectively.

382 These results have strong implications for dendrogeomorphic studies. Indeed, to evidence the potential impacts of  
383 global warming on snow avalanches, tree-ring reconstructions aim at investigating snow avalanche–climate  
384 linkages (Casteller et al., 2011; Decaulne et al., 2014; Dubé et al., 2004; Gądek et al., 2017; Germain et al., 2009,  
385 2005; Hebertson and Jenkins, 2003; Martin and Germain, 2017, 2016; Muntán et al., 2009; Schläppy et al., 2016;  
386 Voiculescu et al., 2016) and at comparing current activity with colder periods such as the Little Ice Age (see e.g.,  
387 Ballesteros-Cánovas et al., 2018; Corona et al., 2013; Giacona et al., 2018). These studies generally focus on

388 long-lived stands and should rely on reconstructions that are as complete and continuous as possible. In this  
389 context, our study confirms that a careful selection of avalanche paths is a very critical prerequisite as it  
390 conditions both the length and the reliability of the reconstructions. In detail, it shows the great potential of  
391 forested slopes affected by snow avalanches of low to medium magnitudes, as they have the best boundary  
392 conditions to yield comprehensive, long-range reconstructions that can then be used for the detection of climate-  
393 driven trends or shifts. Although we are aware that our approach does not cover the entire avalanche regime (i.e.  
394 from very small to extremely large events), these results are all the more interesting as avalanche activity on  
395 these paths is more susceptible to be strongly affected by global warming as (1) warmer winter temperatures and  
396 decreasing days with a minimum snow depth required for avalanches will probably further reduce the importance  
397 of avalanche disturbances in forested terrain in the future (Castebrunet et al., 2014) and (2) warmer temperature  
398 during the growing season will probably further facilitate forest expansion and productivity (Bebi et al., 2009) at  
399 these sites. One should yet keep in mind that these recommendations are strictly focused on comprehensiveness  
400 of all avalanches, regardless of whether they represent a hazard or not, and that the time-consuming sampling  
401 methodology presented here, may not be necessary or appropriate for locations where the priority is on identifying  
402 the largest magnitude, most hazardous snow avalanches that cause the greatest impacts to people and  
403 infrastructure.

## 404 **6. Conclusions**

405 In this study, a dendrogeomorphic approach has been used to reconstruct past avalanche activity on four  
406 contiguous paths located in the upper Guil valley (Queyras massif, French Alps), and characterized by different  
407 structures and forest covers. In total, 306 *Larix decidua* Mill. trees were sampled along three altitudinal transects  
408 to reconstruct 52 avalanche events. Despite the fact that several limitations may persist in terms of the arbitrary  
409 thresholds chosen for the detection of events and the exclusion of noise from reconstructions, our results show  
410 very different avalanche dynamics in different avalanche couloirs of the same slope. Unsurprisingly, on paths C1  
411 and C2, characterized by high-altitude release areas that are only covered by shrubby vegetation, high-magnitude  
412 events reach the lower transect and cause damage to the forest stand. By contrast, on paths E1 and E2, a forest  
413 cover up to the release areas limits the intensity and the spatial extent of past events. More interestingly, the  
414 frequency of events reconstructed on the latter paths is 2.5 times higher, reconstructions cover a longer time span  
415 and the convergence rate with events listed in the EPA archive attests clearly to the reliability of the reconstructed  
416 avalanche history. These results have particularly important implications for avalanche reconstructions aiming at  
417 deciphering avalanche activity fluctuations in the current context of global warming. They suggest that a careful  
418 selection of the couloirs is essential and that a priority should be given to forested paths since (i) they allow for  
419 exhaustive and (ii) reliable reconstructions over (iii) long periods of time.

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681 **Captions**

682 Figure 1. Location of the study site in the Guil valley (Queyras massif, French Alps) (a) and delineation of the four  
683 avalanche paths on the Ravin de la Salce slope (b).

684 Figure 2. Synoptic diagram of the 4-step approach used for the detection of avalanche events in tree-ring series,  
685 adapted from Favillier et al. (2017).

686 Figure 3. (a) Maximum velocities and (b) maximum pressures computed with the RAMMS snow avalanche model.  
687 Avalanche extensions obtained with RAMMS are used in this study to delineate avalanche paths E1-C2.

688 Figure 4. Age structure of the forest stand growing at the Ravin de la Salce slope.

689 Figure 5. Event-response histograms showing the total number of growth disturbances (GD, in red and orange)  
690 and the percentage of trees responding to an event (in green) at each of the four paths. Orange bars show the  
691 total number of growth reductions which are possibly related to larch budmoth outbreaks or to climatic extremes.  
692 The dashed lines denote the GD and It thresholds used to reconstruct past avalanche events. The solid lines  
693 denote sample depth, i.e. the number of trees available for analysis for each year of the reconstruction.

694 Figure 6. Results of the 4-step procedure. Reconstructed event characteristics take into account possible  
695 interference with climate or larch budmoth outbreaks, and include the level of confidence and the minimum slide  
696 extent.

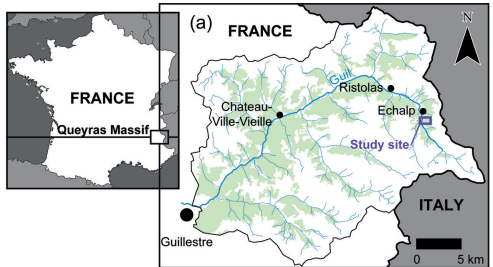
697 Figure 7. Avalanche events reconstructed for the period 1720-2016 at the four avalanche paths. Symbol sizes are  
698 proportional to the level of confidence, whereas the color range denotes the minimum slide extent. Grey bands  
699 represent years associated to LBM outbreaks. Vertical lines show snow avalanche events documented in  
700 historical archives (black), as well as extremely dry (orange), cold (blue) summers and pointer years (green).

701 Figure 8. Location of trees disturbed in 1961 and 2008 and presumably corresponding to avalanches that  
702 occurred (c) on February 7, 1961 and (f) on December 17, 2008 and diachronic comparisons of aerial  
703 photographs (IGN) highlighting the evolution of the forest stand between 1956 and 1962 (a, b) and between 1988  
704 and 2009 (d,e).

705 Table 1. Larch budmoth events and pointer years (according to Saulnier et al., 2017), as well as extremely cold  
706 and dry summers (Efthymiadis et al., 2006) in the French Alps. All these years have been carefully analyzed due  
707 to probable interferences between snow avalanche damage in trees, as well as LBM and climatic signals that may  
708 induce growth reductions comparable to those observed after snow avalanches in the tree-ring series.

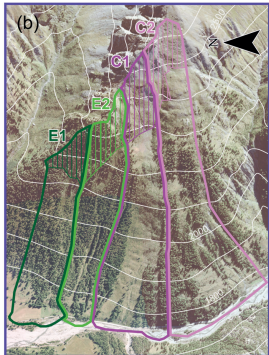
709 Table 2. Geomorphic characteristics and soil occupation of the studied avalanche paths and their release zones.

710 Table 3. Intensity of reactions and types of growth disturbances (GD) assessed in the 306 larch trees selected for  
711 analysis.



□ Avalanche corridor    ▨ Release area

0 250 500 1 000 Meters



## Step 1

GD and It distinction

## Step 2

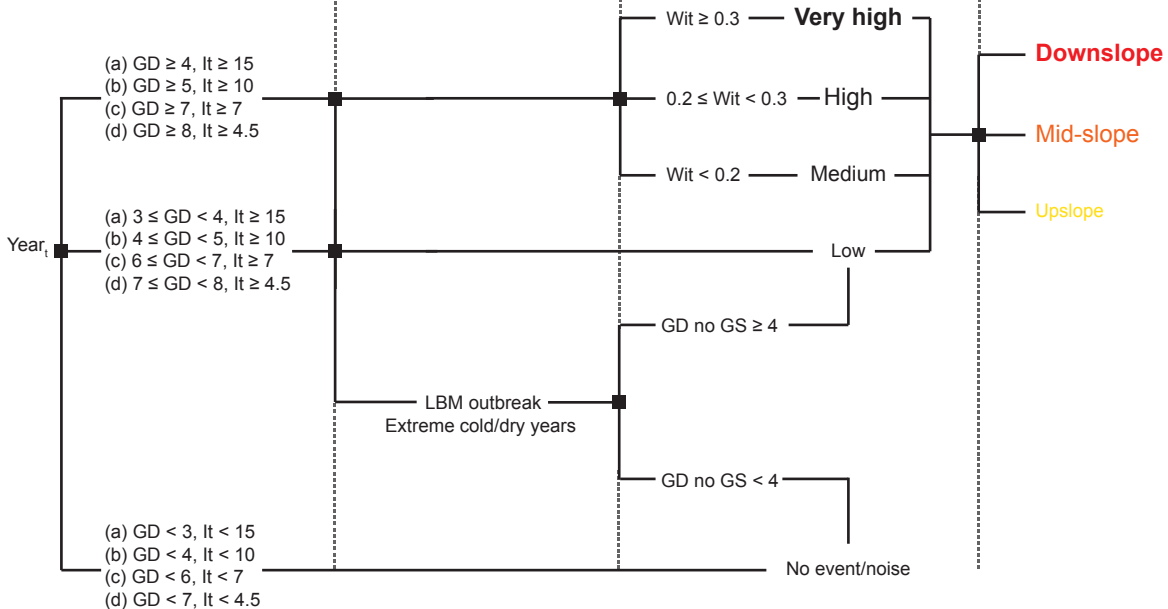
LBM outbreak distinction

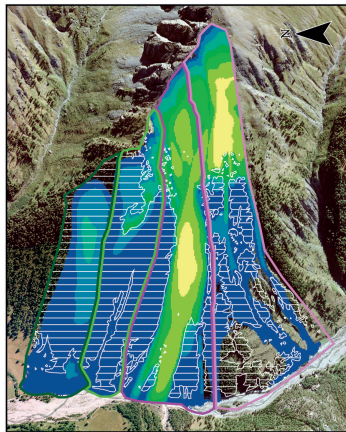
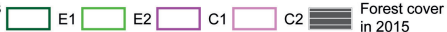
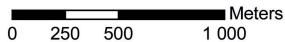
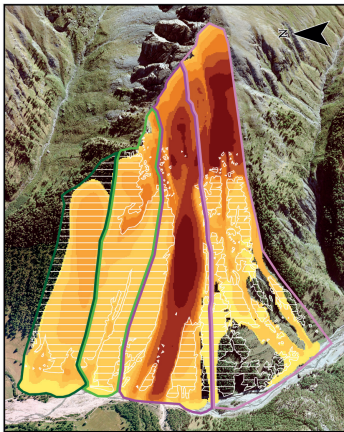
## Step 3

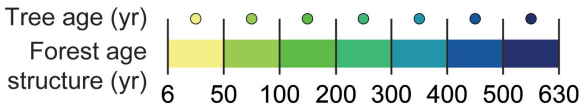
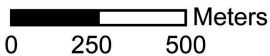
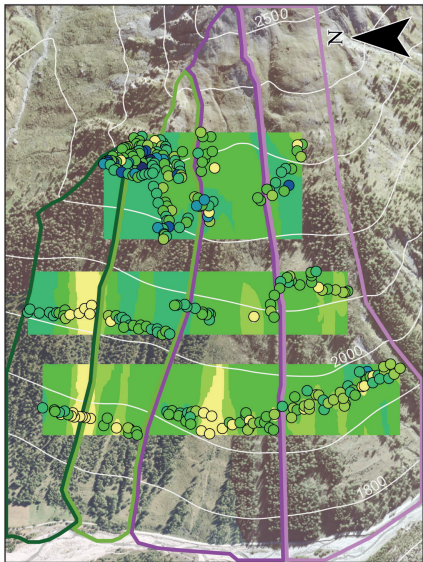
Level of confidence  
in event detection

## Step 4

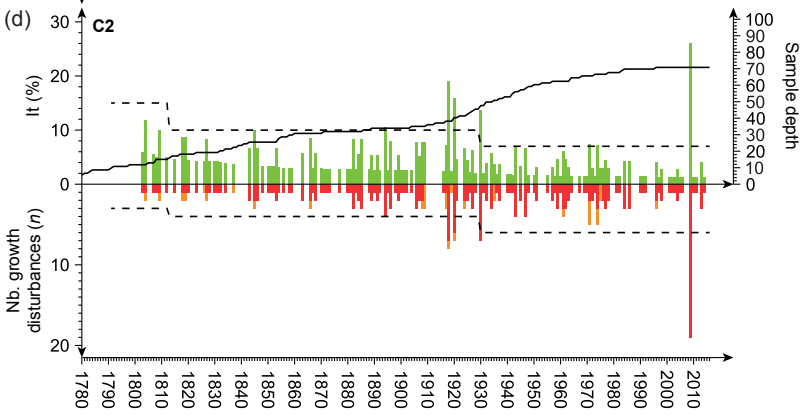
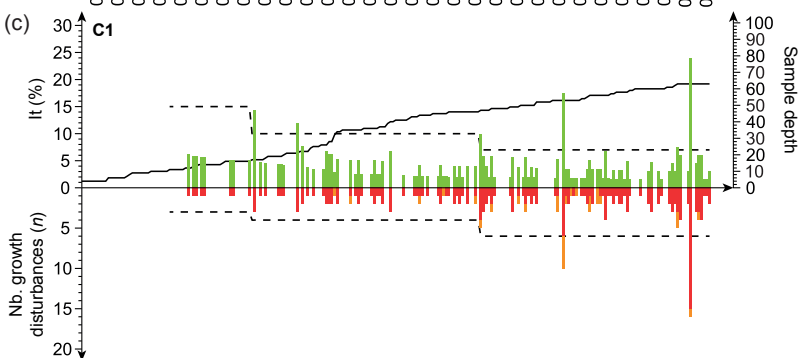
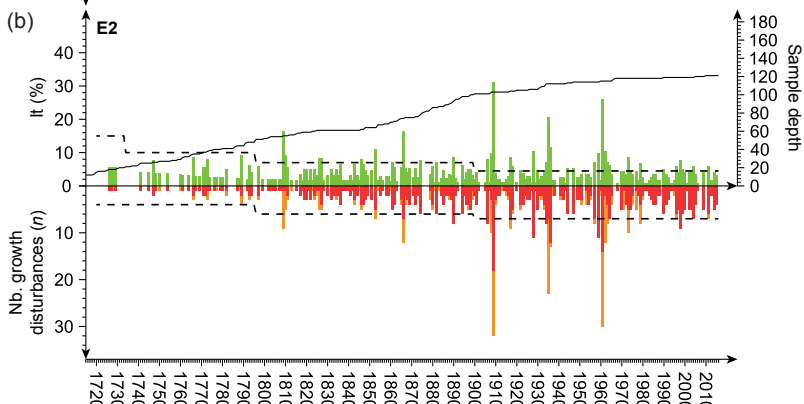
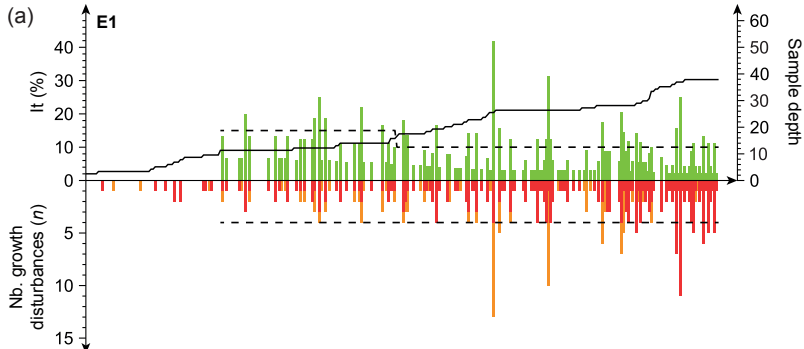
Avalanche size classification











## Step 1

GD and It distinction

## Step 2

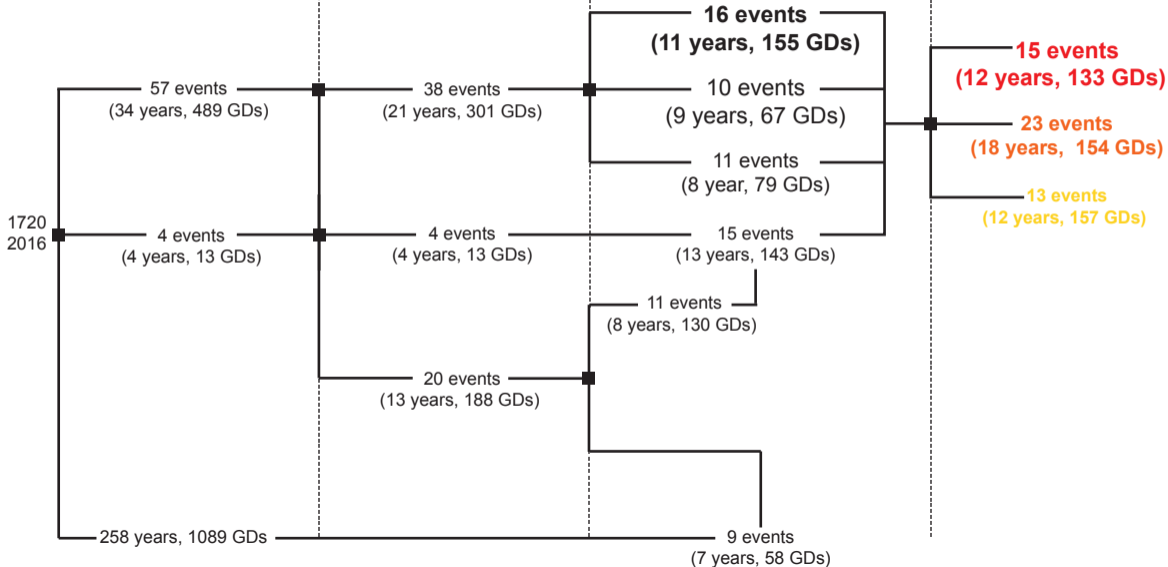
LBM outbreak distinction

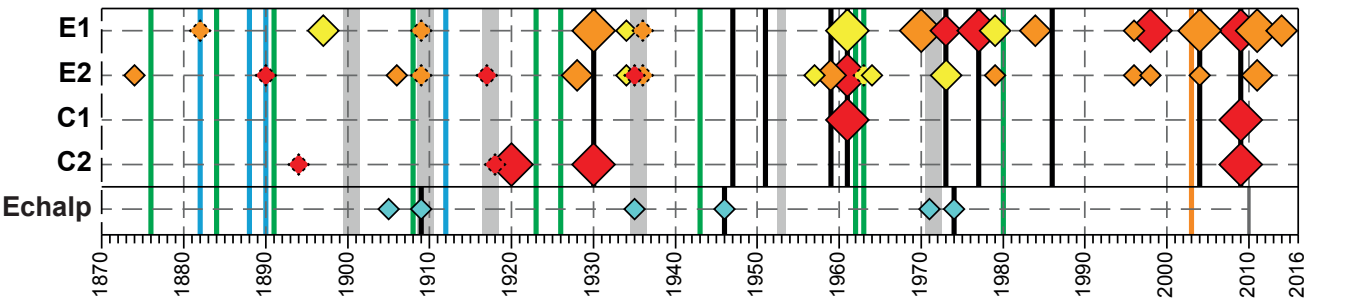
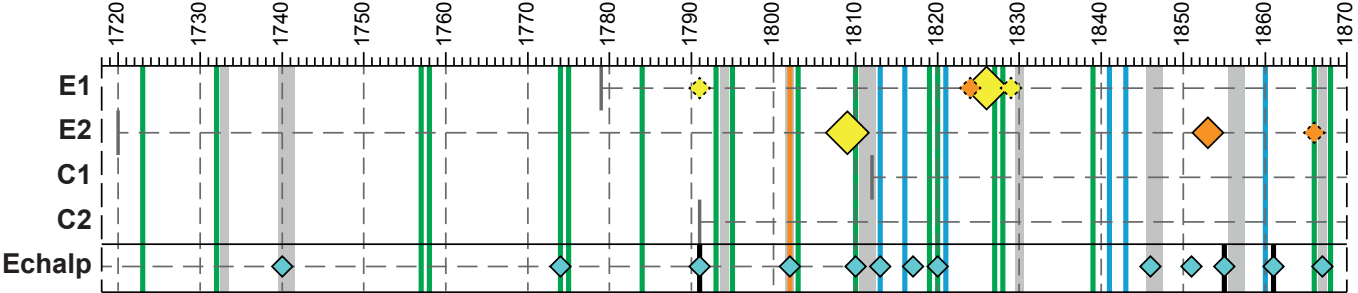
## Step 3

Level of confidence  
in event detection

## Step 4

Avalanche size classification

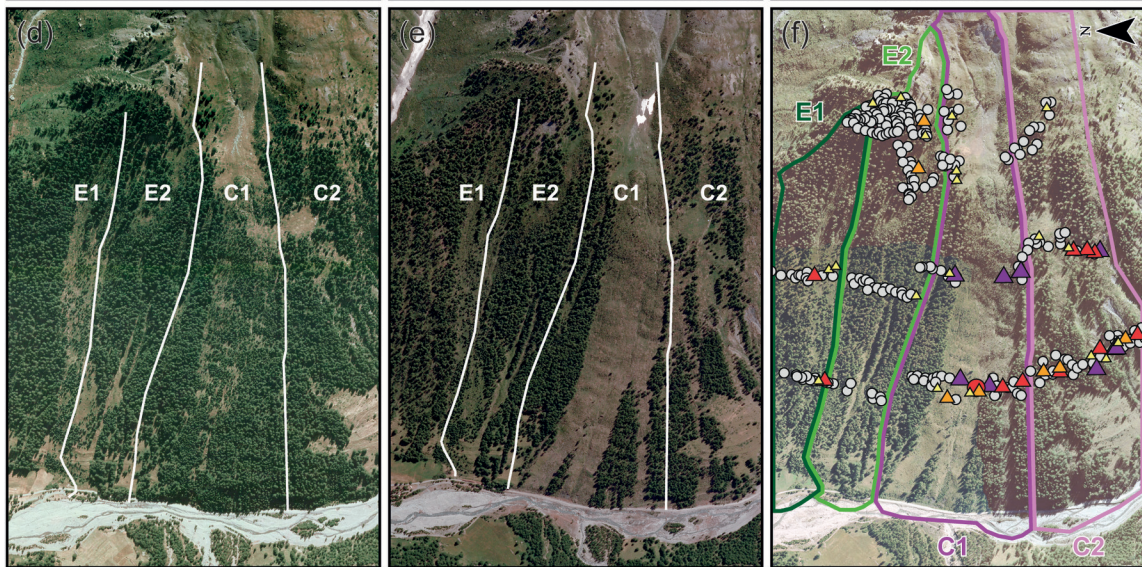




| Documented event    | Pointer Year    | Drought year    | Year with an extremely cold summer    | LBM outbreak

Confidence level    ♦ Low    ◊ Medium    ◻ High    ◻ Very High

Minimum sliding extent (MSE)    ◻ Upslope    ◻ Midslope    ◻ Downslope



0 100 200 400 600 Meters

Intensity	0	1	2	3	4
TRD, CW & CT		△	△	△	
GS	○	○	○	○	
Injury					△

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2005**	1884*	1818*
1980	1883	1815*
<b>1971</b>	1876	<b>1812</b>
1963	1868	<b>1811</b>
1962	<b>1867</b>	1810
1943	1866	1804**
<b>1936</b>	1862*	1803
<b>1935</b>	<b>1857</b>	<b>1802</b>
1926	<b>1856</b>	1795
1923	<b>1847</b>	<b>1794</b>
1918	<b>1846</b>	1793
<b>1917</b>	1845*	1784
1914*	1843*	1775
1911*	1839	1774
1910	1830	1758
<b>1909</b>	1828	1757
1908	1827	<b>1741</b>
1900	1823*	<b>1740</b>
1892*	1821	<b>1733</b>
1891	1820	1732
1890*	1819	1723

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**LBM-outbreak year, Pointer year, \***

Path	Avalanche path					Release area						
	Aspect	Length (m)	Width (m)	Area (ha)	Mean slope (°) (SD)	Release altitude (m)	Deposit altitude (m)	Mean slope (°) (SD)	Area (ha)	Forest cover in 1945 (%)	Forest cover in 2015 (%)	
E1	WN	1240	240	19.7	25.1 (9.2)	2110-2200	1745	34.5 (2.4)	4.3	76.4	100	
E2	WN	1290	255	25.3	27.8 (5.6)	2140-2340	1745	35.0 (2.3)	6.4	46.9	54.7	
C1	WN	1580	300	42	26.4 (6.6)	2290-2520	1760	33.1 (3.3)	6.9	1.9	1.5	
C2	WN	1600	366	55	26.6 (7.3)	2430-2620	1790	32.5 (3.9)	6.9	0	0	
Echalp	W	1200	200	<i>n.p.</i>	32 ( <i>n.p.</i> )	2100-2450	1700	36 ( <i>n.p.</i> )	<i>n.p.</i>	<i>n.p.</i>	<i>n.p.</i>	

*n.p.* not provided

<b>Type / intensi</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total</b>
Injuries	-	-	-	53 (3.2%)	53 (3.2%)
TRD, CT, CW	810 (51.3%)	220 (13.9%)	187 (11.4%)	-	1217 (76.6%)
GS	147 (9.4%)	97 (6.1%)	77 (4.7%)	-	321 (20.2%)
<b>Total</b>	<b>957 (60.6%)</b>	<b>317 (20%)</b>	<b>264 (16.2%)</b>	<b>53 (3.2%)</b>	<b>1591 (100%)</b>

