Tree-Ring Dating of Snow Avalanches in Glacier National Park, Montana, USA

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1 Introduction

Snow avalanches are major hazards to humans occupying or visiting mountain ranges around the world. Accurate dating of past high-magnitude snow avalanches is important for a better understanding of their frequency, extent, and climatic driving factors. As climates change, prediction of shifts in avalanche frequency and/or magnitude are better enabled when a thorough understanding of past avalanche occurrences exists.

Tree rings are a primary data source for the dating of past snow-avalanche occurrence. A recent development in dendrogeomorphology, the use of traumatic resin ducts in annual rings of select conifers, has shown great promise for expanding the utility of tree-ring dating of geomorphic processes such as avalanches, rockfalls, and debris flows (see below). This work has, to date, been restricted almost exclusively to the analysis of geomorphic processes in the Alps of central Europe. In this work, we seek to determine if traumatic resin duct analysis can be used to assist in the dating of snow avalanches in the mountains of western North America. We also bring together past work on tree-ring dating of snow avalanches in a major American national park, in order to more fully assess the synoptic climatic patterns associated with major avalanche winters there.

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2 Glacier National Park Study Area

Glacier National Park, Montana (henceforth GNP), and its Canadian neighbor Waterton Lakes National Park (WLNP), Alberta, collectively comprise the Waterton-Glacier International Peace Park along the 49th parallel (Fig. 1). Both Parks were extensively glaciated during the Pleistocene, creating an avalanche-prone landscape

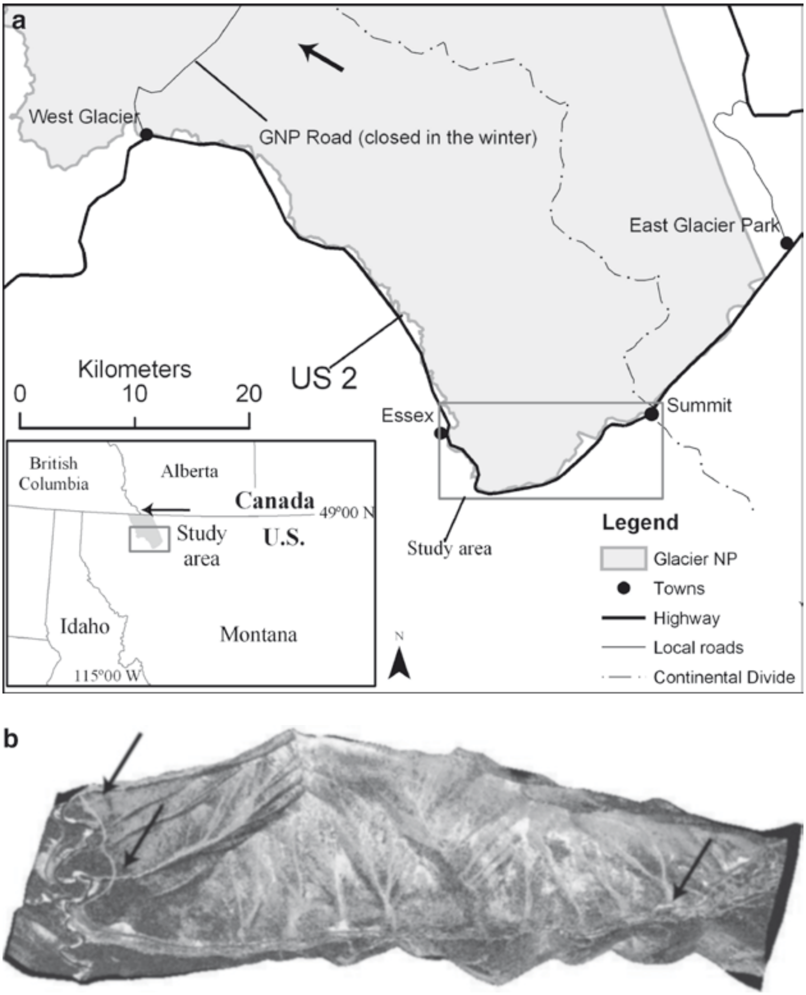

Fig. 1 (**a**) (*above*) Map of US Highway two study area along southern boundary of Glacier National Park, Montana, USA. *Arrow in inset map* points to Waterton Lakes study site in Alberta. *Arrow on main map* points to Snyder Lake study site. (**b**) (*below*) Three-dimensional view of the study area and the numerous snow-avalanche paths. *Left black arrow* points Goat Lick avalanche path, *middle black arrow* to I-Beam path, *right arrow* to Shed 7 path. Three-dimensional image is comprised of 1-m Ikonos image merged with and draped over a 10-m Digital Elevation Model

of steep mountainous slopes and deep U-shaped valleys. Elevations range from ca. 960–1,000 m asl in the glacial valleys in western Glacier Park to more than 3,000 m on the Parks' highest peaks. GNP is split approximately in half by the Continental Divide, producing differing local climatologies; the western half experiences a modified Pacific-maritime climate, with maximum precipitation levels on the high western slopes near the Continental Divide. All of WLNP is east of the Continental Divide, and shares with the eastern half of GNP a more severe and windy, interior continental climate (Butler et al. 1992).

More than 1,200 avalanche paths exist in the Parks (Butler et al. 1992). Tree-ring dating of snow avalanches has been carried out in the central and southern portions of GNP (locations shown in Fig. 1) (Butler 1979; Butler and Malanson 1985; Butler and Sawyer 2008), and in 2001 a pilot study was also carried out in adjacent WLNP; those data are reported here for the first time. This latter study was initiated to determine if broad regional patterns of avalanching that have been reported from GNP (Butler 1986, 1989; Butler and Sawyer 2008; Reardon et al. 2008) extend as far north as WLNP.

Butler (1986, 1989) identified two broad-scale synoptic patterns that produce widespread avalanching in the study area: pronounced meridional flow associated with Arctic air outbreaks resulting in catastrophic avalanching caused by heavy snowfall from rapid advection of warm, moist Pacific air over the Arctic air; or strong zonal flow with frequent storms from the Pacific Ocean to the west, resulting in heavy snowfalls. Reardon et al. (2008) noted that the meridional flow pattern characterized almost all major avalanche events in John F. Stevens Canyon along the southern border of GNP, the area of the Park with the greatest avalanche hazard for human activity. Over 40 snow-avalanche paths are located within this canyon, with the paths primarily located between the towns of Essex and Summit (Fig. 1). Snow avalanches there frequently disrupt highway and rail traffic on US Highway 2 (US 2), and the Burlington Northern – Santa Fe Railroad (BNSF) that runs parallel to US 2 (Butler and Malanson 1985, 1990; Sawyer and Butler 2006; Reardon et al. 2008). The bulk of these hazardous snow avalanches originate on unmanaged slopes to the north in GNP, with some also coming from the adjacent unmanaged National Forest to the south. Although this region is sparsely populated, transportation through JFS Canyon serves as an important link between several otherwise isolated communities. When US 2 is closed by avalanches, a 300-km detour is required in order to drive from the western to the eastern side of GNP. Avalanche closure of the tracks of the BNSF creates costly interruptions and stoppages in the transport of goods between Midwestern US cities and major Pacific coast ports, and creates the potential for hazardous cargo spills in the pristine environment of the canyon.

3 Tree-Ring Features Analyzed for Dating Snow Avalanches

When snow avalanches impact forests, trees may be tilted and/or uprooted, trunks can be scarred, branches may be trimmed, surrounding trees may be removed, and material may be deposited against or around the trunk of trees.

Typical tree-ring features analyzed for the study and dating of snow avalanches include corrasion scars initiated by impact; initiation and continuation of reaction wood in response to tilting; suppression rings associated with stress caused by tilting, burial, and/or branch trimming; or release rings created as a tree responds to the removal of competing neighboring trees (Germain et al. 2005; Decaulne and Sæmundsson 2008; Casteller et al. 2008; Reardon et al. 2008; also see Butler and Sawyer 2008, and Stoffel and Bollschweiler 2008, for recent reviews of earlier papers describing dendrogeomorphic techniques employed in the study of snow avalanches). These tree-ring features allow for to-the-year identification of past snow avalanche occurrence. Most practitioners have agreed that corrasion scars and reaction wood growth provide the most unequivocal evidence for avalanche-induced trauma that can be separated from climatic variations that can also induce suppression/release ring patterns similar to those avalanching may initiate (Germain et al. 2005; Butler and Sawyer 2008; Decaulne and Sæmundsson 2008; Reardon et al. 2008).

The newest tree-ring technique that furthers the dating of snow avalanches is the use of traumatic resin ducts (TRD) in conifers scarred and tilted by avalanche activity. Larocque et al. (2001) used TRD initiated by basal stem burial, together with corrasion scars and reaction wood, to date slushflows in the Gaspé peninsula of Québec, Canada. More recently, Stoffel and associates have initiated the widespread use of TRD as a tool in dendrogeomorphology that provides to-the-year, and in some cases seasonal, dating of geomorphic process occurrences, including snow avalanches (Stoffel et al. 2006; Bollschweiler et al. 2008; Stoffel 2008; Stoffel and Bollschweiler 2008; Stoffel and Hitz 2008). TRD appear under a microscope as asymmetric, atypical cells differing in appearance from normal earlywood or latewood cells (excellent examples of TRD photomicrographs appear in Stoffel and Bollschweiler (2008)).

4 Tree-Ring Analysis of Snow Avalanches in Glacier National Park

Tree ring sampling described in this section employed standard dendrogeomorphic techniques. Species were recorded in the field for each tree; cores or cross-cut discs were collected and air-dried, and subsequently sanded; cross-dating, in accordance with the methods of Stokes and Smiley (1968), was employed; and tree-ring event responses were recorded for each year following Shroder (1978, 1980).

The first application of tree-ring analysis for the dating of past high-magnitude avalanche events was from the central portion of GNP in the Snyder Creek valley (Fig. 1) (Butler 1979). Tree rings from that study were collected in 1975, and extend back to the early twentieth Century. Butler (1979), using a relatively high minimum threshold cutoff, identified major avalanche events in the valley in 1945, 1950, 1954, 1963, 1965, 1966, 1972, and 1974. A re-examination of these data, utilizing a lower minimum threshold of 20% as advocated by Butler and Sawyer (2008), adds the winters of 1933, 1948, and 1957 to this data set (Table 1).

Table 1 Comparison of high-magnitude snow avalanche years with high SWE years

Snyder Creek	Goat Lick	I Beam	Shed 7	Waterton	High SWE[a]
	1925				
1933					
	1935		1935		
	1937				
					1939
					1943
1945	1945	1945			
		1947			1947
1948			1948		
					1949
1950	1950		1950		1950
					1951
		1952	1952		
1954		1954	1954		1954
					1956
1957	1957		1957		
		1959			
1963	1963		1963		
		1964			
1965	1965		1965		1965
1966					
					1967
			1969		
			1970	1970	
1972	1972	1972	1972	1972	1972
1974		1974	1974		1974
[b]					
			1976		
	1979	1979	1979		
	1982[c]	1982	1982	1982	
	[b]				
			1985		
		1987	1987		
				1988	
			1989		
		1991	1991	1991	1991
		1996		1996	1996
		1997			1997
				[b]	
		2002	2002		2002

[a]SWE data from Reardon et al. (2008)
[b]Last tree-ring year for Snyder Creek, 1975; for Goat Lick, 1983; for Waterton, 2001; for I Beam and Shed 7, 2002
[c]Goat Lick experienced large avalanche below level of sampled trees

Butler and Malanson (1985) created tree-ring histories of high-magnitude avalanches for the Goat Lick and Shed 7 paths in the Stevens Canyon region of GNP (Fig. 1) (all avalanche path names in Stevens Canyon are informal names used by the US Geological Survey). Those samples were collected in 1983, and the ages of the samples extend back into the 1920s (Table 1). Years of major avalanche events from these paths were broadly similar both to each other and to the Snyder Creek record from central GNP (Table 1); in 6 years all three paths experienced large avalanches, and in four additional winters one of the two southern paths matched with Snyder Creek.

Butler and Sawyer (2008) extended the Shed 7 path history to that shown in Table 1, and also created the first chronology for the I Beam path, located between the Goat Lick and Shed 7. Although the I Beam chronology was only based on a sample of ten trees uprooted by avalanching in 2002, the record cross-dated with four major avalanche winters from Snyder Creek, and with 6 from either or both Goat Lick and Shed 7.

Recently, Reardon et al. (2008) used dendrogeomorphic techniques to create a chronology of high-magnitude avalanching on another avalanche path in Stevens Canyon, Shed 10.7, located a few kilometers down canyon from Shed 7. An exact comparison of their record with the others described here is hampered by their use of a 10% minimum threshold event-response value. Nevertheless, in comparing their record to the records from Goat Lick and Shed 7, they noted that 10 years identified in their study corresponded to those at either Goat Lick or Shed 7, and 4 avalanche years (1935, 1950, 1957, and 1979) were common to all three paths (Reardon et al. 2008). It is also notable that two of these years (1950 and 1957) correspond to the record from Snyder Creek, roughly 40 km to the northwest (Fig. 1). Although the tree-ring record for Snyder Creek ends in 1975, a visit there in 1983 revealed widespread damage very probably attributable to a high-magnitude avalanche on that path in 1979 (Butler 1985) that would also match with Shed 10.7 as well as with Goat Lick, I Beam, and Shed 7.

Because the comparison of the Snyder Creek record with the Stevens Canyon records reveals such widespread temporal correspondence, a preliminary reconnaissance of an avalanche path along the Cameron Lake road in WLNP (Fig. 1) was undertaken in 2001, with ten cross-cut samples collected from damaged trees in the runout zone. Sampled trees in this pilot project were small, and the tree-ring record only extends back into the 1960s. This record only overlaps the Snyder Creek record by about 10 years, and only about 20 years for the Goat Lick record. Nevertheless, the WLNP record corresponds with every other sample path from Snyder Creek and Stevens Canyon in 1972; with every available Stevens Canyon path in 1982 and 1991; and at least one other sampled path in two of the other three recorded years of high-magnitude avalanche activity. This path did not record a 1979 event, but the sampled trees were probably simply too small (and possibly protected beneath the snowpack) to be affected by an avalanche in that year.

5 Implications for the Avalanche Climatology of the Region

Widespread avalanching during many winters, from the eastern side of the Continental Divide in WLNP to Stevens Canyon on the western side of the Divide on the southern tip of GNP, as well as at points throughout the Parks including Snyder Creek (Butler 1979, 1986) is evidence of a regional avalanche climatology covering the entire Peace Park. Reardon et al. (2008) suggested that these periods of widespread avalanching coincide with episodes of meridional flow and intrusion of cold Arctic air masses over which moist Pacific air is subsequently advected, leading to heavy snowfall and avalanching. Rainfall often accompanies this advection and acts as an additional catastrophic avalanche trigger of wet-snow avalanches (Reardon et al. 2008), a conclusion also noted previously by Butler (1986). Most years with major avalanches coincide with years in which the El Niño Southern Oscillation (ENSO) and mean January-February Pacific Decadal Oscillation (PDO) indices were neutral (Dixon et al. 1999; Reardon et al. 2008).

Reardon et al. (2008) compared their avalanche chronology of high-magnitude avalanches at Shed 10.7 with the annual 1 March snow water equivalent (SWE) snow course record from Marias Pass, located on the Continental Divide 16 km northeast of Shed 10.7 at Summit (Fig. 1). Their results demonstrated a strong correlation between positive snowpack anomalies (in excess of 10% above the long-term mean) and winters with high-magnitude avalanches. In Table 1, we tabulate

Fig. 2 Tree sampling areas on Shed seven avalanche path (*arrows*). Note downed trees on roof of railroad snowshed man stands on, and on ground beyond snowshed

these same years against our chronologies of high-magnitude avalanche winters at Snyder Creek, Goat Lick, I Beam, Shed 7, and Waterton. The results illustrate a good relationship between episodes of widespread avalanching (years 1950, 1954, 1965, 1972, 1974, 1991, 1996, and 2002) and years with high SWE anomalies, not only in Stevens Canyon but at Snyder Creek in central GNP (1950, 1954, 1965, 1972, and 1974) and in WLNP (1972, 1991, 1996).

Interestingly, the most widespread avalanching in recorded history occurred in February 1979 (Butler and Malanson 1985; Butler 1986; Sawyer and Butler 2006; Reardon et al. 2008), but that year does not coincide with a high positive SWE anomaly. Park Service officials in GNP noted that "just about every place in the park that can avalanche has avalanched yesterday and today (Butler 1986, p. 79). The catastrophic avalanching was triggered by a "Pineapple Express" of moisture-laden Pacific air flowing in from the southwest, producing widespread extended rainfall on a deep but not abnormally thick snowpack (Butler 1986).

6 Initial Observations on Traumatic Resin Ducts and Their Use for Dating Snow Avalanches in Glacier National Park

The particular benefit of TRD is their circumferential extent (on average, in almost one-fifth of the total circumference; Bollschweiler et al. 2008). This circumferential extent makes identification via increment-core sampling much easier, whereas in

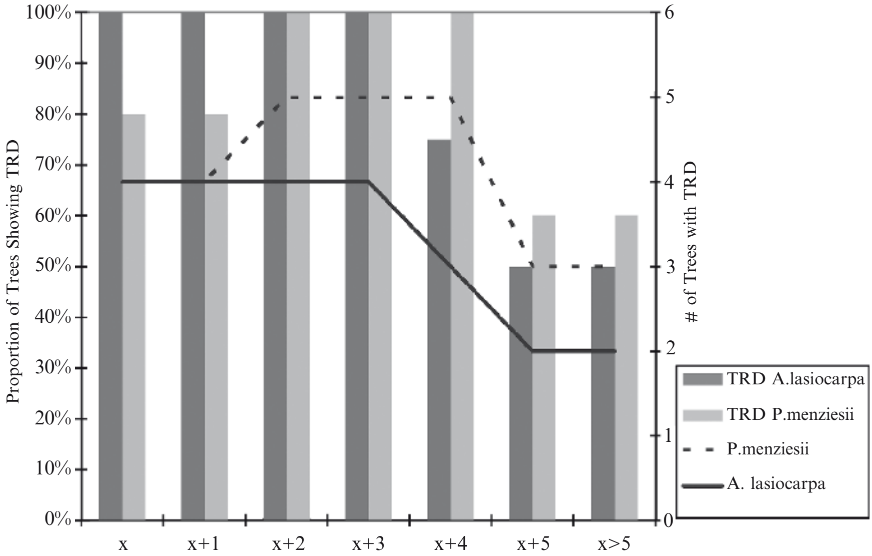

Fig. 3 Graph illustrating number of years' persistence of TRD after initiating scarring event, and percentage of samples per year illustrating presence of TRD

the past the use of cores for dating snow avalanches has been particularly challenging when trying to date onset of corrasion scar growth. The seasonality of TRD occurrence within an annual tree ring can also assist in differentiating between geomorphic processes such as snow avalanches and debris flows (Stoffel et al. 2006), or avalanches and rockfalls (Stoffel and Hitz 2008).

The aforementioned work by Larocque et al. (2001) is the only known application of TRD for dendrogeomorphic purposes in North America. The bulk of analyses of TRD (also called traumatic resin canals) in North America have focused on biotic infections as causal agents (Cruickshank et al. 2006). TRD are known to develop in North American species of the genera *Abies* (fir), *Picea* (spruce), and *Pinus* (pine), and in the species *Pseudotsuga menziesii* (Douglas fir) (Cruickshank et al. 2006).

Widespread avalanching occurred throughout the JFS Canyon region, stopping traffic on both US 2 and the BNSF, in the winter of 2001–2002. Large, mature conifers were uprooted and deposited by avalanches in the furthest reaches of individual path runout zones, outside the boundary of GNP (Fig. 2), providing an opportunity for tree-ring sampling of downed trees without sacrificing living trees within or along the margins of avalanche paths in the protected national park.

Cross sectional discs were collected from ten uprooted trees in the I Beam path and 12 trees in the Shed 7 path. Analyses of the corrasion scars and reaction wood from these discs provided the chronology of high-magnitude avalanche winters for each path described herein and by Butler and Sawyer (2008). Because of the serendipitous deposition of avalanche-damaged trees from which cross-cut samples could be extracted, we also used these samples to determine if TRD occurred in their circumferences.

We examined each of the cross-cut samples under a binocular microscope for the presence of TRD in the annual rings. The majority of the samples examined did not possess corrasion scars; these samples also did not illustrate TRD. TRD were identified, in association with corrasion scars, in five Douglas fir (*Pseudotsuga menziesii*) and four subalpine fir (*Abies lasiocarpa*) samples. We recorded the longevity (how many years duration) of TRD in every case where TRD were initiated. The angular circumferential extent of the TRD in each annual ring was also recorded. We also noted any delays in initiation of TRD between the ring in which scarring occurred and the ring in which TRD were initiated. We employed the Mann-Whitney U test, because of the small sample size, to determine if there existed any difference in the longevity of TRD between Douglas fir and subalpine fir samples; we did the same to determine if there existed any difference between the angular extent of TRD between the two species.

Every corrasion scar examined, in both species, also illustrated the initiation of TRD. In nearly every case (all but one, a Douglas fir), TRD were initiated in the same annual ring as the year in which scarring occurred (Fig. 3); the lone exception had a 2-year lag response. In all cases, TRD endured for at least 4 years (Fig. 3), after which drop-off occurred. Nevertheless, most samples showed a continuation of TRD in annual rings beyond 4 years after scarring initiated TRD production. The Mann Whitney test illustrated that no difference in TRD longevity existed between the two species under examination.

The angular extent of TRD associated with individual scars varied, depending on the size and severity of the corrasion scar. In general, year two often had the widest angular extent of TRD, followed by a relatively rapid drop-off in circumferential extent. Occasional secondary increases in extent were noted; we have no explanation for such features at this time. The Mann Whitney test illustrated no difference in the angular extent of TRD between Douglas fir and subalpine fir.

These initial observations showed the presence of TRD in association with corrasion scars from a year of known avalanching, establishing the utility of TRD in tree-ring studies of avalanching in North America. Our next step is to go back through our samples collected from 1975 to 2002, and seek out TRD to discern if we can identify previously unrecorded avalanche episodes contained therein.

7 Conclusion

This study is the first known illustration of traumatic resin ducts in avalanche-affected tree rings in western North America. TRD were identified in avalanche-affected tree rings from both Douglas fir and subalpine fir, two species with widespread distribution throughout the western cordillera of North America. The two sampled species showed virtually no difference in the form, longevity, or angular extent of TRD in affected annual rings. Given the absence of a difference in their utility, and their respective widespread distributions in the western USA and Canada, the potential exists for using TRD in annual rings of affected trees throughout the region. Future studies should also focus on examining additional widespread genera such as *Picea*, *Larix* (both certainly useful genera in studies in the Alps by Stoffel and associates), and *Pinus* to determine their possibility in dendrogeomorphic studies of snow avalanches. Attention should also be given to intra-annual variations in positioning of TRD, as described by Stoffel et al. (2006) and Stoffel and Hitz (2008), to determine if snow avalanches induce TRD at different points within an annual ring than do other geomorphic processes.

Examination of the avalanche chronologies from across GNP and an initial chronology from WLNP illustrates the widespread nature of high-magnitude snow avalanche winters in the area. Although exceptions occur, such as in the catastrophic avalanche cycle of February, 1979, the most widespread signals coincide with years of anomalously high snowpacks (SWE), and are triggered by meridional intrusions of cold Arctic air that cause advection of moist Pacific air, inducing heavy snowfall and in some cases rain-on-snow events.

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References

Bollschweiler M, Stoffel M, Schneuwly D, Bourqui K (2008) Traumatic resin ducts in *Larix decidua* stems impacted by debris flows. Tree Physiol 28:255–263

Butler DR (1979) Snow avalanche path terrain and vegetation, Glacier National Park, Montana. Arct Alp Res 11:17–32

Butler DR (1985) Vegetational and geomorphic change on snow avalanche paths, Glacier National Park, Montana, USA. Great Basin Nat 45:313–317

Butler DR (1986) Snow-avalanche hazards in Glacier National Park, Montana: meteorologic and climatologic aspects. Phys Geogr 7:72–87

Butler DR (1989) Snow-avalanche dams and resultant hazards in Glacier National Park, Montana. Northwest Sci 63:109–115

Butler DR, Malanson GP (1985) A history of high-magnitude snow avalanches, southern Glacier National Park, Montana, USA. Mt Res Dev 5:175–182

Butler DR , Malanson GP (1990) Non-equilibrium geomorphic processes and patterns on avalanche paths in the northern Rocky Mountains, USA. Z Geomorphol 34:257–270

Butler DR, Sawyer CF (2008) Dendrogeomorphology and high-magnitude snow avalanches: a review and case study. Nat Haz Earth Syst Sci 8:303–309

Butler DR, Malanson GP, Walsh SJ (1992) Snow-avalanche paths: conduits from the periglacial alpine to the subalpine-depositional zone. In: Dixon JC, Abrahams AD (eds) Periglacial Geomorphology. Wiley, London, pp 185–202

Casteller A, Christen M, Villalba R, Martinez H, Stöckli V, Leiva JC, Bartelt P (2008) Validating numerical simulations of snow avalanches using dendrochronology: the Cerro Ventana event in Northern Patagonia, Argentina. Nat Haz Earth Syst Sci 8:433–443

Cruickshank MG, Lejour D, Morrison DJ (2006) Traumatic resin canals as markers of infection events in Douglasfir roots infected with *Armillaria* root disease. Forest Pathol 36:372–384

Decaulne A, Sæmundsson Þ (2008) Dendrogeomorphology as a tool to unravel snow-avalanche activity: preliminary results from the Fnjóskadalur test site, Northern Iceland. Norsk Geografisk Tidsskrift 62:55–65

Dixon RW, Butler DR, DeChano LM, Henry JA (1999) Avalanche hazard in Glacier National Park: an El Niño connection? Phys Geogr 20:461–467

Germain D, Filion L, Hétu B (2005) Snow avalanche activity after fire and logging disturbances, northern Gaspé, Quebec, Canada. Can J Earth Sci 42:2103–2116

Larocque SJ, Hétu B, Filion L (2001) Geomorphic and dendroecological impacts of slushflows in central Gaspé peninsula (Québec, Canada). Geogr Ann 83A:191–201

Reardon BA, Pederson GT, Caruso CJ, Fagre DB (2008) Spatial reconstructions and comparisons of historic snow avalanche frequency and extent using tree rings in Glacier National Park, Montana, USA. Arct Antarc Alp Res 40:148–160

Sawyer CF, Butler DR (2006) A chronology of high-magnitude snow avalanches reconstructed from archived newspapers. Disas Prevent Manage 15:313–324

Shroder JF Jr (1978) Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. Quat Res 9:168–185

Shroder JF Jr (1980) Dendrogeomorphology: review and new techniques of tree-ring dating. Prog Phys Geogr 4(2):161–188

Stoffel M (2008) Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26:53–60

Stoffel M, Bollschweiler M (2008) Tree-ring analysis in natural hazards research – an overview. Nat Haz Earth Syst Sci 8:187–202

Stoffel M, Bollschweiler M, Hassler G-R (2006) Differentiating past events on a cone influenced by debris-flow and snow avalanche activity – a dendrogeomorphological approach. Earth Surf Process Land 31:1424–1437

Stoffel M, Hitz OM (2008) Rockfall and snow avalanche impacts leave different anatomical signatures in tree rings of juvenile *Larix decidua*. Tree Physiol 28:1713–1720

Stokes MA, Smiley TL (1968) An introduction to tree-ring dating. University of Chicago Press, Chicago