Geomorphology of snow avalanche impact landforms in the southern Canadian Cordillera

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Snow avalanche impact landforms (SAILs) are typically elliptical-shaped depressions bounded by an arcuate ridge located at the base of avalanche paths. The geomorphology of these features is controlled by the topography of the avalanche path, the availability of unconsolidated debris in the impact area and the ability of the avalanche impacts to displace the available debris in the direction of avalanche flow. Ground-based snow avalanches move debris by bulldozing, and airborne snow avalanches move sediment by excavation on impact.

This paper reports on the geomorphology, and surface age and stability of three SAILs in the southern Canadian Cordillera. Dendrochronology and lichenometry were used to date geomorphic activity at the sites. Evidence of present SAIL stability suggests they result from episodic, high-magnitude avalanche impact events over many hundreds of years. All three landforms share common morphologies: a water-filled bowl-shaped depression distally bounded by an arcuate ridge-oriented transverse to the avalanche path. Despite sharing many attributes, field investigations revealed that the origin of each SAIL was a function of the local variations in snow avalanche path topography and availability of unconsolidated debris in the impact

La géomorphologie des formes de relief résultant des effets des avalanches de neige dans le sud de la Cordillère canadienne

De manière générale, les formes de relief résultant des effets des avalanches de neige se caractérisent par des dépressions elliptiques délimitées par des crêtes arquées situées à la base des couloirs d'avalanche. La géomorphologie de ces éléments de terrain dépend entièrement des conditions topographiques du couloir d'avalanche, de la présence d'amas de débris meubles dans la zone d'écoulement, et de la capacité des effets des avalanches pour transporter les débris dans le sens de l'écoulement. Les avalanches coulantes emportent tous les débris en surface sur leur passage, tandis que les avalanches en aérosol emportent les sédiments en creusant des excavations. Cet article rend compte de la géomorphologie, de l'âge à la surface et de la stabilité de trois formes de relief résultant des effets des avalanches de neige dans le sud de la Cordillère canadienne. Des analyses de dendrochronologie et de lichénométrie in situ ont permis d'établir des chronologies des phénomènes géomorphiques. Les données disponibles sur la stabilité des effets des avalanches de neige sur les formes de relief indiquent que celles-ci sont le résultat

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area. The snow avalanche path associated with the Blackhorn site has a gentle gradient, which suggests that this SAIL is a result of ground-based avalanches. The SAIL at Spoon Lake appears to be a consequence of a resistant geologic feature that focuses snow avalanches in the impact area and results in explosive excavation. The morphology of the snow avalanche track at Peyto Lake causes large snow avalanches to become airborne prior to impacting and excavating an impact pool. All three SAILs examined in this paper are historically persistent landforms and these observations support previous findings indicating that SAILs require hundreds of years to develop.

Key words: snow avalanche impact landforms (SAILs), plunge pools, dendrochronology, lichenometry

des événements épisodiques d'avalanches d'intensité supérieure survenues pendant plusieurs centaines d'années. Les trois formes de relief présentent les mêmes caractéristiques morphologiques, à savoir, une dépression en forme de bol, et remplie d'eau, qui est délimitée de manière distale par des crêtes arquées et orientées en section transverse par rapport au couloir d'avalanche. Toutefois, d'après les relevés de terrain, si elles partagent un nombre d'attributs, l'origine de chacune des formes de relief résultant des effets des avalanches de neige peut s'expliquer par les variations locales en matière de topographie du couloir d'avalanche et la présence d'amas de débris meubles dans la zone d'écoulement. L'inclinaison douce du couloir d'avalanche au site de Blackhorn laisse croire que la forme de relief est le résultat des effets des avalanches coulantes. La forme de relief dans le secteur du lac Spoon semble être la conséquence de la force de résistance d'un élément géologique qui canalise les avalanches dans la zone d'écoulement et y creuse des excavations. La morphologie du couloir d'écoulement dans le secteur du Lac Peyto provoque des avalanches de grande ampleur sous forme d'aérosol avant de percuter et d'excaver le bassin d'impact. Il ressort de cette étude que ces trois formes de relief résultant des effets des avalanches de neige perdurent dans le temps et que ces observations corroborent les conclusions d'autres recherches qui ont montré que l'évolution des formes de relief s'étend sur plusieurs centaines d'années.

Mots clés: formes de relief résultant des effets des avalanches de neige, marmites de géants, dendrochronologie, lichénométrie

Introduction

Snow avalanche impact landforms (SAILs) are geomorphic features that result from snow avalanche activity (Matthews and McCarroll 1994). These landforms typically consist of bowl-shaped depressions bounded by a distal ridge and have been described using a large variety of terms (see Matthews and McCarroll 1994; Luckman *et al.* 1994 and references therein) and, following these papers, we will use the term SAILs for these features.

SAILs have only rarely been documented in western Canada (Smith *et al.* 1994). Although their apparent scarcity is partially a function of the conditions and requirements necessary for their formation and persistence, it is equally true that only a limited amount of attention has so far been given to locating SAIL sites in this region. The purpose of this paper is to describe three SAILs that we identified within the southern Canadian Cordillera, including two that were located in coastal mountain ranges with different geologic and climatic settings than those previously described in the literature. The goal of our field investigations was to determine the surface age and stability of these landforms using dendrochronological and lichenometric research methods, with the expectation that our findings

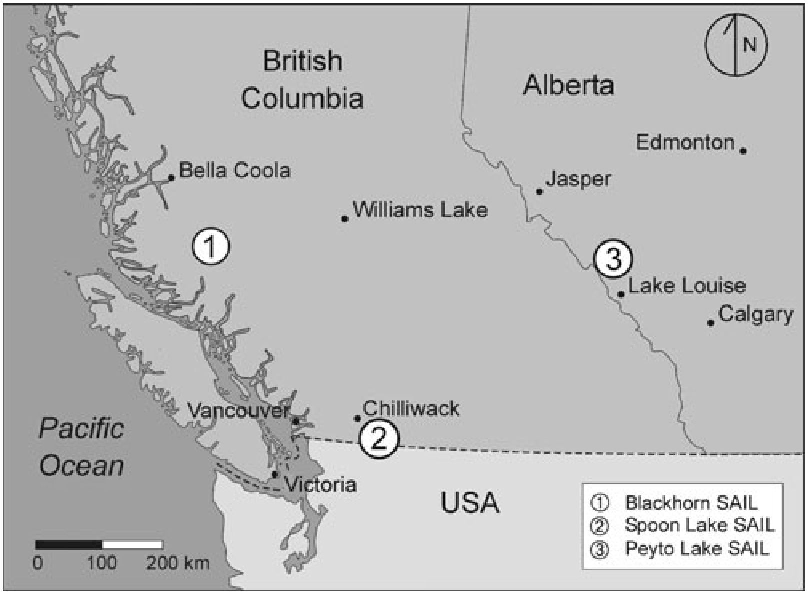

Figure 1
Site location map

would assist in identifying the circumstances necessary for their formation and persistence. Detailed studies were completed at SAILs located at: Blackhorn Mountain in the Nuit Range, central Coast Mountains, British Columbia; Spoon Lake in the Skagit Range, northern Cascade Mountains, British Columbia; and, Peyto Lake in the Waputik Range, Canadian Rocky Mountains, Alberta (Figure 1 and Table 1).

Research Background

Previous research has shown that SAILs typically do not result from a single catastrophic snow avalanche event (Liestøl 1974; Corner 1980; Smith *et al.* 1994; Owen *et al.* 2006); their development appears to be controlled by avalanche path topography, the availability of sediment in the impact area and impact forces sufficient to move this debris. Path topography determines whether snow avalanches remain ground based, moving available debris by bulldozing, or whether they become airborne, moving the sediment by explosive impact. Repeated avalanches are usually required in order for a sufficient amount of debris to accumulate, and episodic, high-magnitude avalanche events are assumed to be necessary to create and maintain a SAIL (Liestøl 1974; Corner 1980).

SAILs vary in appearance and size. Corner (1980) identified three distinct morphologies, avalanche impact tongues, pits and pools. Tongues are arcuate crescent-shaped ridges located on the distal bank of a stream. Pits are bowl-shaped depressions bound by an arcuate crescent-shaped ridge, and are often water filled. Pools differ from pits in that the ridges are partially or entirely submerged. SAILs have been recorded in varying sizes ranging from 10–20 metres to 200–300 metres in diameter (Corner 1980; Fitzharris and Owens 1984).

The characteristic crescent-shaped ridge of a SAIL typically projects several metres above the impact depression and tends to be positioned transverse to the avalanche path (Corner 1980; Ballantyne 1989; Smith *et al.* 1994). The ridges are typically composed of rock, soil and organic debris (Smith *et al.* 1994). Ridge dimensions and the rate of development are site specific,

Table 1
Locational and morphological characteristics of the study sites. Numbers in *italics* represent estimated values and a hyphen indicates the value is unknown

	Blackhorn	Spoon Lake	Peyto Lake
Locational Characteristics			
Latitude	51°36′40″N	49°10′25″N	51°43′08″N
Longitude	124°49′40″W	121°40′45″W	116°31′22″W
Elevation of SAIL (metre asl)	1,580	1,470	1,860
Aspect	NW	WSW	E
Track morphology			
Longitudinal profile	Concave	Concave	Convex
Morphology of track	Chute	Jump	Chute/fall
Confined / unconfined	Both	Unconfined	Both
Track dimensions			
Slope of track (°)	14–37	9–45	16–80
Length of track (metre)	825	700	630 (430)
Maximum fall (metre)	350	350	350 (215)
Width of track (metre)	60–120	62	50
Pool dimensions			
Length (metre)	85	62	50
Width (metre)	43	38	32
Width to length ratio	2.0	1.6	1.5
Maximum depth (metre)	6	5	2
Approximate volume (metre^3)	*9,000*	*4,000*	*1,300*
Ridge dimensions			
Maximum proximal slope height (metre)	4.5	10	1.5
Maximum distal slope height (metre)	3	–	5.5
Maximum width (metre)	20	55	34
Mean proximal slope angle (°)	36	58 (*31*)	11
Mean distal slope angle (°)	23	8	19
Volume above water (metre^3)	*4,000*	*22,000*	*6,300*
Total volume (m^3)	*10,000*	–	*26,000*

and are a reflection of high-magnitude snow avalanche characteristics (type, size, frequency, impact pressures), availability of unconsolidated debris, local topography and the size of the target impact area (Corner 1980; Matthews and McCarroll 1994).

Three mechanisms have been proposed to explain SAIL formation.

- SAIL development occurs at the base of steep avalanche tracks that terminate abruptly in unconsolidated debris (Schytt 1965; Peev 1966; Liestøl 1974; Corner 1980; Fitzharris and Owens 1984; Ballantyne 1989; Matthews and McCarroll 1994; Smith *et al*. 1994; Owen *et al*. 2006). Explosive avalanche impacts remove debris from the impact area, primarily in the direction of avalanche flow (Liestøl 1974);
- SAILs develop at the base of gentle slopes where ground-based snow avalanches bulldoze or shovel debris in the direction of the avalanche flow (Davis 1962; Nyberg 1989; Smith *et al*. 1994);
- Fitzharris and Owens (1984) propose a third explanation that requires an abrupt change in path topography (e.g., protrusion on the track, convexity in slope) that causes snow avalanches to become airborne prior to plunging to the base of the track. This explanation, like the first, would result in an explosive impact force upon contact with the debris at the base of the track.

Smith *et al*. (1994) concluded that the snow avalanche impact pressures necessary to create and maintain SAILs likely exceed 1 MPa and may only occur once every 50 to 150 years. If this is the case, high-magnitude avalanches are essential for the SAIL shape to be maintained over time; otherwise smaller avalanches will slowly infill the pools with debris (Liestøl 1974; Smith *et al*. 1994).

Table 2
Living tree-ring chronologies used to cross-date detrital wood from the Blackhorn and Peyto Lake SAILs

Attribute	Blackhorn SAIL		Peyto Lake SAIL	
Source	This study	This study	Schweingruber (1983)	Carter *et al.* (1999)
Species	Subalpine fir	Whitebark pine	Engelmann spr.	Engelmann spr.
Site Characteristics				
Location	Liberty Glacier	Liberty Glacier	Peyto Lake	Hilda Creek
Latitude	51°35′45′′N	51°35′45′′N	51°45′N	52°11′30′′N
Longitude	124°49′40′′W	124°49′40′′W	116°13′W	117°08′30′′W
Elevation (metre asl)	1,730	1,730	2,050	2,075
Series statistics *				
Number of cores	38	32	26	16
Series correlation	0.566	0.501	0.721	0.514
Mean sensitivity	0.189	0.184	0.187	0.184
Autocorrelation	0.805	0.894	0.814	0.816
Length (years)	296	364	350	413
Range (years AD)	1705–2001	1637–2000	1634–1983	1586–1998

* Mean series correlation is a measure of the degree to which a series responds to common external factors. Mean sensitivity is an index that measures the relative difference between ring widths from one year to the next. Autocorrelation is a measure of the correlation of a year's growth to the preceding and following year's growth.

Figure 2
View downslope towards the Blackhorn SAIL from midslope position on the avalanche track (15 July 2001)

Liestøl (1974) suggested that the presence of water at the base of the track (e.g., river, lake) is a fundamental ingredient for SAIL development. However SAILs have been observed where water is not present, and therefore water does not play a critical role in their formation (Corner 1980; Ballantyne 1989; Smith *et al.* 1994).

The frequency of high-magnitude snow avalanche events at SAILs has been described using dendrogeomorphic evidence (Liestøl 1974; Smith *et al.* 1994; Owen *et al.* 2006), lichenometric dating (Ballantyne 1989; Matthews and McCarroll 1994), ^{14}C-dating of organic material buried in the ridge (Corner 1980; Smith *et al.* 1994), historical photographic evidence, observation of ridge stratification, contemporary avalanche activity building the ridge (Smith *et al.* 1994) and debris infill in the pool (Corner 1980). It is

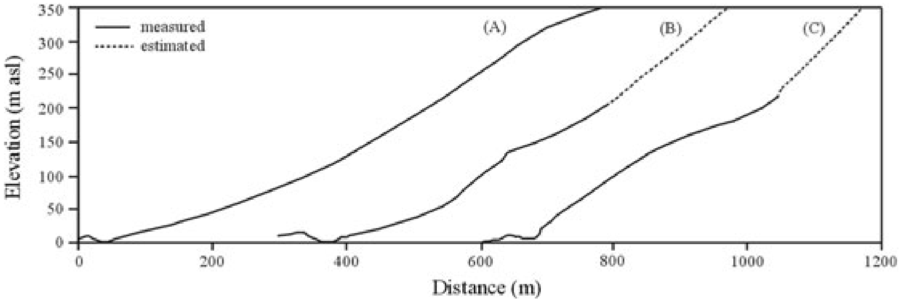

Figure 3
Longitudinal snow avalanche track profiles at Blackhorn (A), Spoon Lake (B) and Peyto Lake (C)

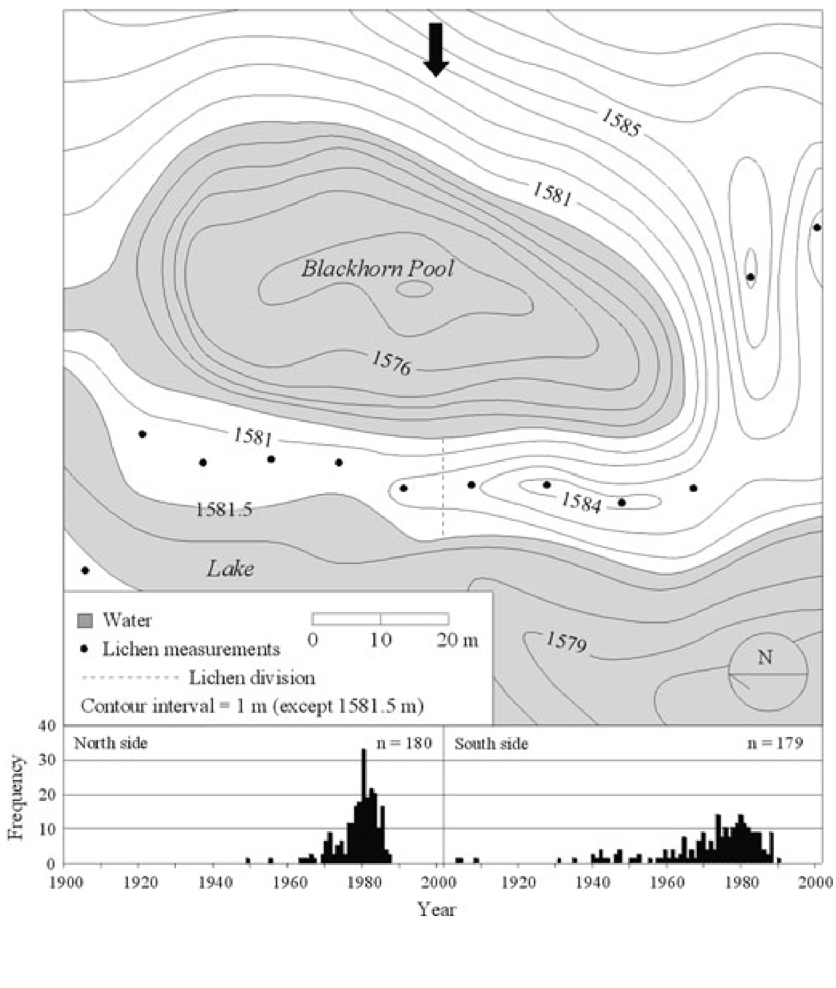

Figure 4
Contour map of the Blackhorn SAIL. Arrow illustrates the direction of snow avalanche flow. Shown below are age-frequency histograms illustrating the time of lichen establishment on the north and south arms of the distal ridge crest

suggested that most SAILs have developed within the last few thousand years, with many possibly maintained throughout the Holocene (Corner 1980; Fitzharris and Owens 1984; Matthews and McCarroll 1994; Smith *et al*. 1994). Matthews and McCarroll (1994) were able to date SAIL development in southern Norway to the Little Ice Age interval in the nineteenth century using lichen simulation modeling. Corner (1980) used ^{14}C evidence to date SAIL development in northern Norway from 13,000 years B.P. to present.

Methods

Geomorphic and bathymetric mapping was undertaken at three sites. At each site a grid was established by running transects (10 metre apart) from a baseline. Track morphology, and pool and ridge dimensions were recorded using a tape measure and an Abney level. Bathymetric surveys of the SAIL pools were undertaken along transects by lowering a weighted tape measure from a raft at 5 metre intervals. Using these points, schematic contour maps and avalanche path profiles were created.

Dendrochronology was used to describe snow avalanche frequency and magnitude (Burrows and Burrows 1976). Increment cores, cross-sections and wedges were cut from dead and living trees at each site. Existing local tree-ring chronologies were identified or established by extracting two increment cores at breast height from 10 to 20 living trees per species in a given area. The ring widths were measured to the nearest 0.01 millimetre using WinDENDRO (Version 6.5A-C, 2002a, Regent Instruments Inc., Québec, CA) and the individual series were cross-dated using the COFECHA program (Holmes 1983) to create living tree-ring chronologies. The death dates of avalanche-killed trees were determined by cross-dating to local living chronologies using both standardized ARSTAN and measured ring widths (millimetre).

A historic record of snow avalanche disturbance was established using both the disturbance response of trees and the age of trees (Shroder and Butler 1987; Butler *et al*. 1987). The disturbance response of trees to snow avalanche events were dated using scars on trees; the initiation of abrupt reaction wood; abrupt changes in ring width and the kill dates of trees (Potter 1969; Smith 1973; Glen 1974; Burrows and Burrows 1976; Carrara 1979; Shroder 1980).

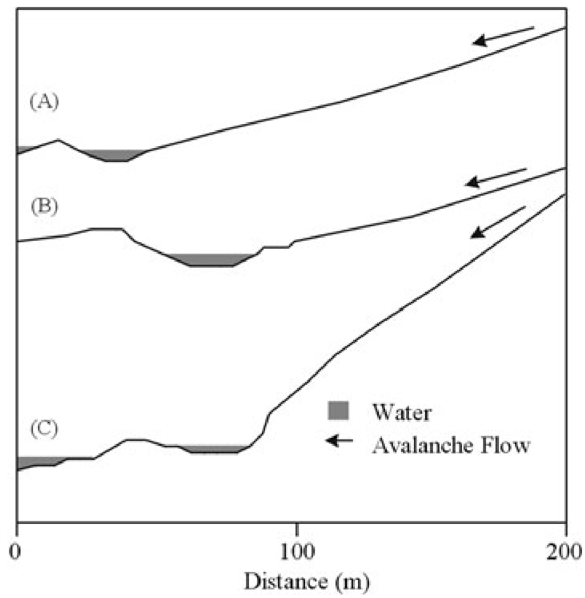

Figure 5
Profiles of the SAILs at: (A) Blackhorn, (B) Spoon Lake and (C) Peyto Lake. Vertical scale not exaggerated

Event-response indexes (ERI) were created by plotting the response of trees (living and avalanche killed) to determine the frequency and magnitude of snow avalanche disturbances (Schweingruber 1988). The ERI was calculated by dividing the total number of avalanche events determined by dendrogeomorphology by the number of trees sampled, and then multiplying by 100 (Schweingruber 1988). Lower than expected ERI values sometimes arise for large avalanche events that happened in the past and/or where the evidence has not survived. Butler *et al*. (1987) suggest that the minimum ERI value used to determine geomorphic activity should be user defined based on the site(s) under study. High-magnitude snow avalanche events that excavate sediment from the impact area at the base of the path were identified using a 10 percent cut-off (Larocque *et al*. 2001), observing clusters of kill dates of trees, and by determining the establishment age of trees on the track and SAIL. Snow

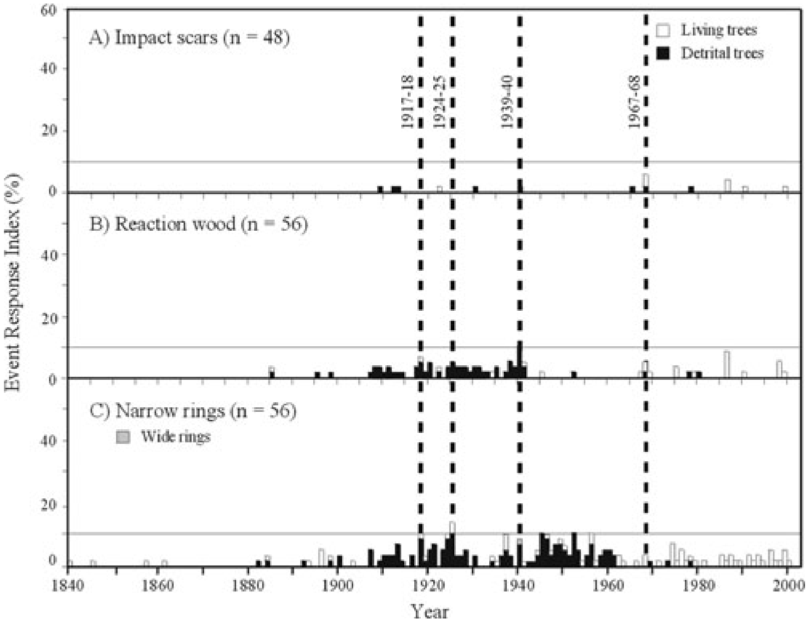

Figure 6
Blackhorn SAIL ERI illustrating impact scars, reaction wood and narrow rings. Vertical lines illustrate high-magnitude snow avalanche events identified using dendrochronology

avalanche frequency was calculated by subtracting the year of earliest recorded high-magnitude event from the sample year (2003) and dividing by the number of recorded high-magnitude events.

Lichenometry was used to determine relative surface age and stability of exposed rock surfaces on the distal ridges (Gellatly 1982; Innes 1985; McCarroll 1994). In this instance, the a- and b-axes of circular to near circular *Rhizocarpon geographicum sp*. thalli were measured to the nearest 0.1 mm using digital callipers. The longest diameter method (Karlén 1973; Proctor 1983) was used to estimate surface age using existing local lichen curves (Luckman 1977; Larocque and Smith 2004).

Observations

Blackhorn

The SAIL is positioned within the runout zone of an avalanche path found on the northwest slope of Blackhorn Mountain (3,033 metre asl) in the Nuit Range on the leeward side of the Coast Mountains, British Columbia (Figure 1 and Table 2), approximately 1.5 kilometre down valley of the outermost terminal moraine of White Saddle Glacier (Larocque and Smith 2003). The local mountains are composed of fine-grained volcanic andesite and diorite, with a mixture of metamorphosed sedimentary and intrusive rocks. The track has a gently concave longitudinal profile steepening downslope from 14 to 37° (Figures 2 and 3). It is bare of vegetation, except along its lower reaches where thickets of alder (*Alnus tenuifolia*) and willow (*Salix* spp.) whitebark pine (*Pinus albicaulis*) and subalpine fir (*Abies lasiocarpa*) saplings are encroaching on the lateral track margins, where avalanche scars are evident on the trunks of mature trees.

The elliptical pool is 85 metre long, 43 metre wide and has a maximum depth of 6 metre (Figures 4 and 5). The water level in the pool is maintained by flow from the adjacent lake through the coarse rock matrix of the ridge. Avalanche-killed trees were observed floating on the surface of the pond and along the shoreline.

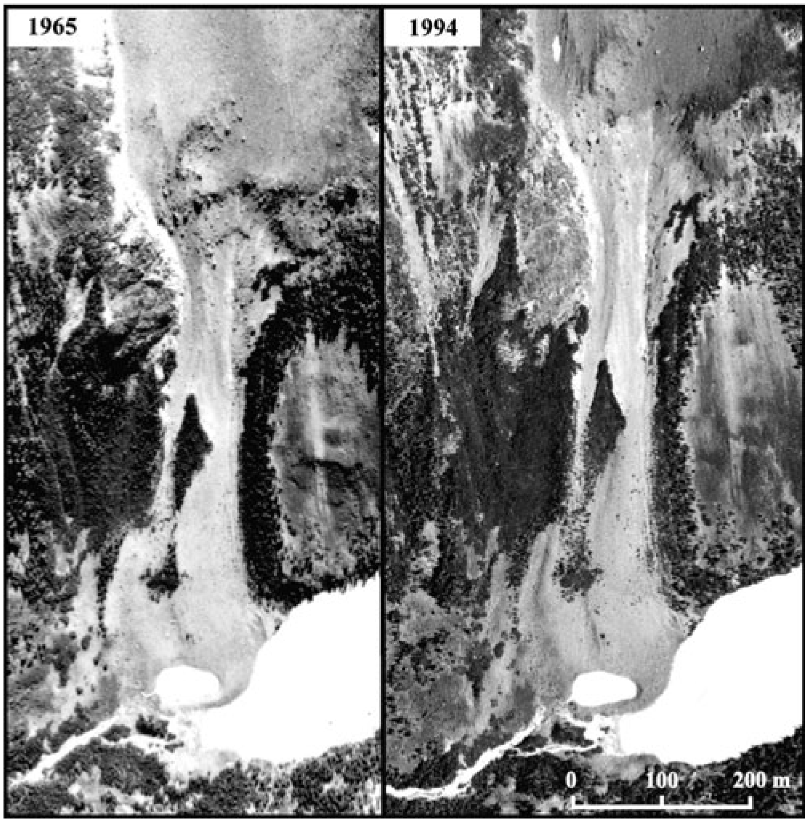

Figure 7
Aerial photographs of the Blackhorn SAIL in 1965 (BC5151:220) and 1994 (BCC94067:136)

The SAIL's distal ridge is composed of a matrix of unconsolidated sediments with numerous cobbles and boulders. The ridge crest is mantled with large boulders that individually have masses estimated as greater than 4,300 kg. Lower relief areas of the distal ridge are characterized by a surface composed mainly of pebbles and cobbles. The ridge is sparsely vegetated with alder and willow shrubs. *Melanelia stygia* (black lichen) are abundant on the distal slope of the landform, with *R. geographicum* present in smaller numbers.

Increment cores were collected from living trees and cross-sections were cut from detrital trees found on the avalanche path associated with the SAIL, on an island in the adjacent lake, and on the mountain slope across the lake from the SAIL. Of the cross-sections collected (n = 47), 76.6 percent cross-dated with the local living chronologies (Table 2). Twenty-eight detrital trees found scattered on the SAIL ridge near the pool outlet (missing both bark and perimeter wood) had outermost dates ranging between 1950 and 1971. Avalanche scars on the living trees found on the island date to 1967–68, whereas those on the downslope face of trees 100 metre across the lake date to 1921–22 and 1989–90. Our dendrochronological evidence documents high-magnitude snow avalanche events that occurred in 1917–18, 1924–25, 1939–40 and 1967–68 (Figure 6).

To assess the relative surface stability of the ridge, we measured 30 of the largest *R. geographicum* thalli found at 12 different points (n = 360, Figure 4). Lichen age was established using the growth curve developed for the nearby

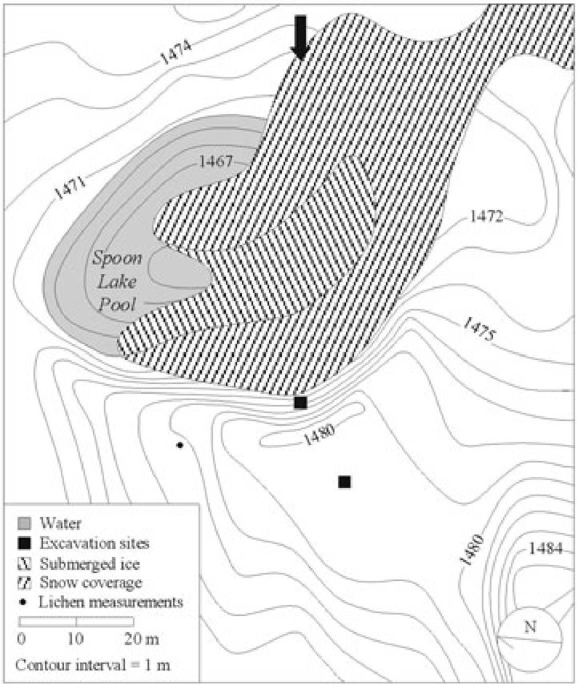

Figure 8
Contour map of the Spoon Lake SAIL. Arrow illustrates the direction of snow avalanche flow

Mount Waddington area (Larocque and Smith 2003). The age-frequency distribution shows no well-developed peaks and troughs (Figure 4), suggesting that the establishment of *R. geographicum* was continuous from the 1960s through to the late 1980s. The lichen data were subsequently partitioned into subgroups to illustrate the lichen age-frequency distribution on the north and south sides of the ridge (Figure 4). While lichens found along the north side indicate that this area has been stable since the mid-1960s, lichens populating the topographically higher south side of the ridge show that it has been unaffected by erosion or deposition since at least the late 1930s.

Our observations at the Blackhorn SAIL suggest that wet, full-depth spring snow avalanches are likely responsible for its formation and maintenance. These snow avalanches were presumed to be of large magnitude as they were able to transport very large boulders. Our dendrochronological and lichenometric observations, however, illustrate this site is only infrequently impacted by snow avalanche events of this magnitude. A comparison of aerial photographs taken in 1965 and 1994 (Figure 7) shows that the SAIL has maintained the same shape and size over a 30-year period, substantiating our lichenometric findings that the morphology of the pool and ridge has changed little over the past 60 years.

Spoon Lake

The Spoon Lake SAIL is positioned directly below the west-southwest face of Lady Peak (2,190 metre asl), 18 kilometre east of the city of Chilliwack on Cheam Ridge in the Skagit Range, Cascade Mountains, British Columbia (Figure 1). The bedrock geology consists of fine-grained volcanic rock with a small quantity of carbonate conglomerates (Monger 1989).

Two concave snow avalanche paths converge at Spoon Lake (1,470 metre asl). The starting zone of the primary track is located immediately

Figure 9
Spoon Lake SAIL partially covered by a snow avalanche deposit, snow and seasonal ice. Note person on ridge crest for scale (29 July 2002)

Table 3
Living tree-ring chronologies used to cross-dated detrital wood from Spoon Lake SAIL

Attribute		Spoon Lake SAIL	
Source	Huisman (1996)	Huisman (1996)	Huisman (1996)
Species	Mtn. hemlock	Subalpine fir	Yellow cedar
Site characteristics			
Location	Mt. Cheam	Mt. Cheam	Mt. Cheam
Latitude	49°11′85′′N	49°11′85′′N	49°11′85′′N
Longitude	121°40′85′′W	121°40′85′′W	121°40′85′′W
Elevation (metre asl)	1,460	1,460	1,460
Series statistics*			
Number of cores	37	41	39
Series correlation	0.596	0.642	0.482
Mean sensitivity	0.274	0.235	0.227
Autocorrelation	0.682	0.794	0.814
Length (years)	364	408	469
Range (years AD)	1637–2000	1592–1999	1531–1999

* Mean series correlation is a measure of the degree to which a series responds to common external factors. Mean sensitivity is an index that measures the relative difference between ring widths from one year to the next. Autocorrelation is a measure of the correlation of a year's growth to the preceding and following year's growth.

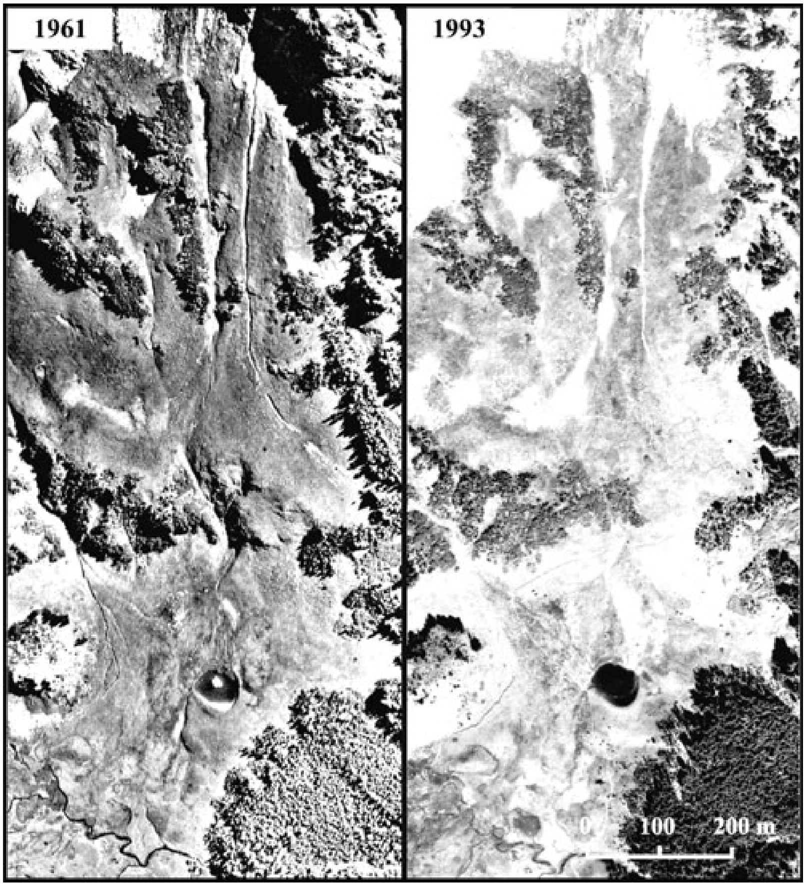

Figure 10
Aerial photographs of the Spoon Lake SAIL in 1961 (BC4016:2) and 1993 (BCB93032:171)

above the SAIL on an unconfined slope below Lady Peak; the track gradient is relatively uniform (30–35°), except where a bedrock outcrop inclined 20° at its upper end and located 130 vertical metre from the pool creates a jump morphology (Figure 3). A second path originates from a southwest facing slope on Cheam Ridge and is channelled through a deeply incised gully before terminating at the SAIL. The lower portions of both paths are covered with scattered islands of mountain hemlock (*Tsuga mertensiana*) and subalpine fir krummholtz.

The SAIL's pool is positioned with its long axis perpendicular to the primary avalanche path. The pool is 62 metre long, 38 metre wide and has a maximum depth of 5 metre (Figure 8). When the pool was visited in July 2002 there was evidence that an avalanche from the previous winter occurred with sufficient force to break and displace the seasonal ice in the pool (Figure 9). The SAIL's ridge rises 10 metre above the pool surface and extends down valley approximately 55 metre before terminating within a mature subalpine forest. The ridge crest is almost completely covered by an assemblage of low-lying vascular plants. Surface exposures show that it is composed largely of unconsolidated silts and sands. Aerial photographs from 1961 and 1993 (Figure 10), as well as our observations in 2003, show that the shape and size of the pool and ridge has been maintained without change for at least 40 years.

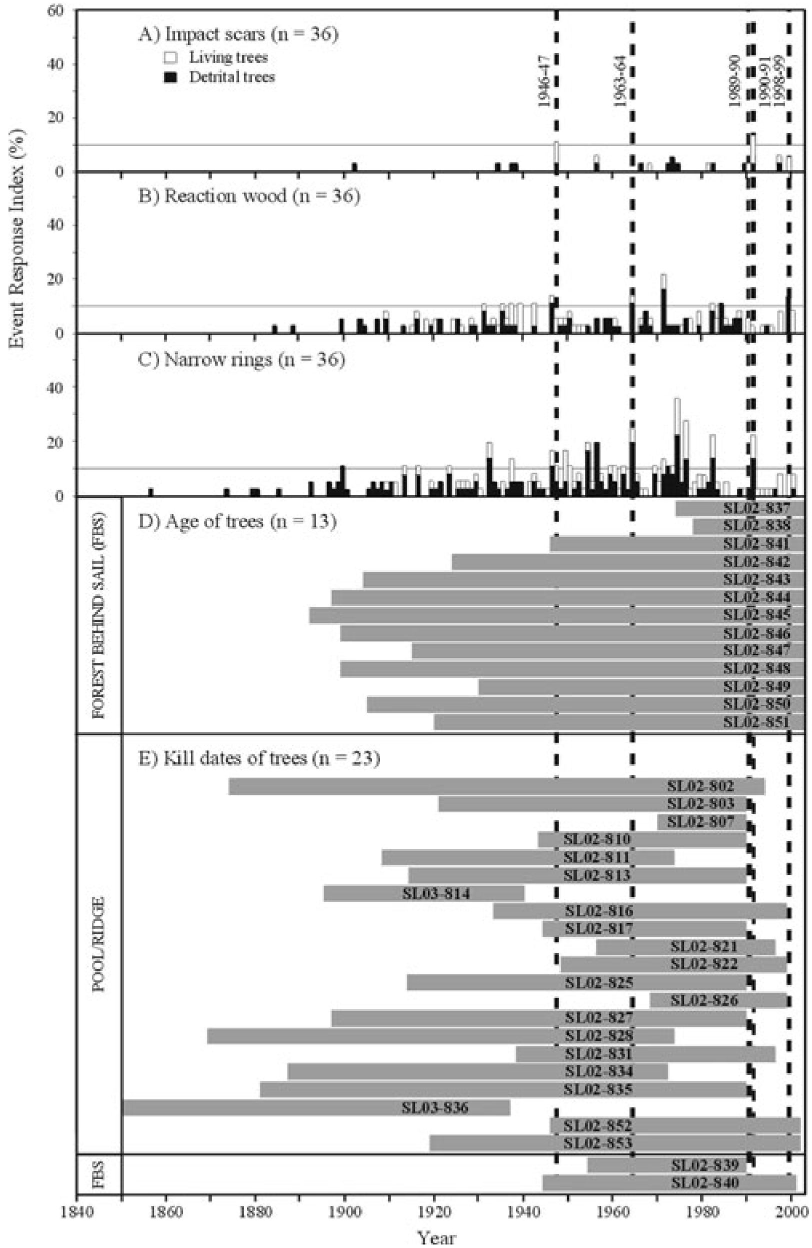

Figure 11

Spoon Lake SAIL ERI illustrating impact scars, reaction wood and narrow rings. The age of trees in the area surrounding the SAIL (D) and the kill dates of cross-dated detrital trees found associated with the SAIL (E) are also shown. Vertical lines illustrate high-magnitude snow avalanche events identified using dendrochronology

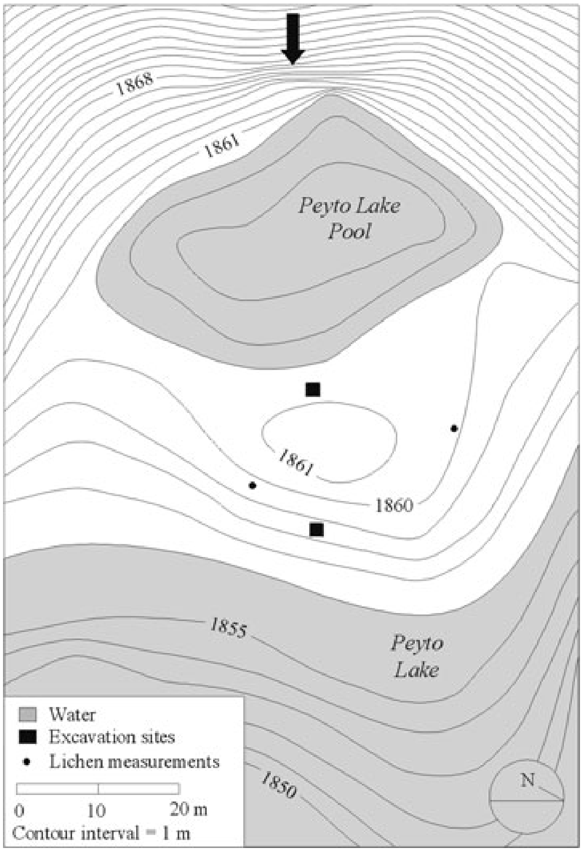

Figure 12
Contour map of the Peyto Lake SAIL. Arrow illustrates the direction of snow avalanche flow

Tree-ring samples collected at the site include 53 cross-sections collected from living and detrital trees located within the pool and on the ridge, as well as from within the standing forest distal to the SAIL. Of the detrital cross-sections collected (n = 40), 58 percent were cross-dated to local living tree-ring chronologies (Table 3). Our ERI calculations indicate that low-magnitude snow avalanches extend downslope to terminate in the vicinity of the SAIL in most years (Figure 11). Nonetheless, our observations in 2003 suggest that such events are unlikely to be responsible for excavating the pool. Our tree-ring data do indicate, however, that high-magnitude snow avalanche events occur approximately every 11 years at the site. Notable events, similar to those that occurred in the winters of 1946–47, 1963–64, 1989–90, 1990–91 and 1998–99, would likely be required to excavate and deposit the boulders (masses estimated to exceed 1,000 kilogram) found on the ridge (Figure 11).

Peyto Lake

The Peyto Lake SAIL is located below the east face of Caldron Peak (3,050 metre asl) on the southwest shoreline of Peyto Lake, in northern Banff National Park, Canadian Rocky Mountains, Alberta (Figure 1). Caldron Mountain is composed of fine-grained sedimentary rocks, thickly interbedded with carbonate rocks characteristic of the Waputik Range (Alberta Geological Survey 1999). The more resistant carbonate bedrock creates cliffs, and the less resistant siltstones,

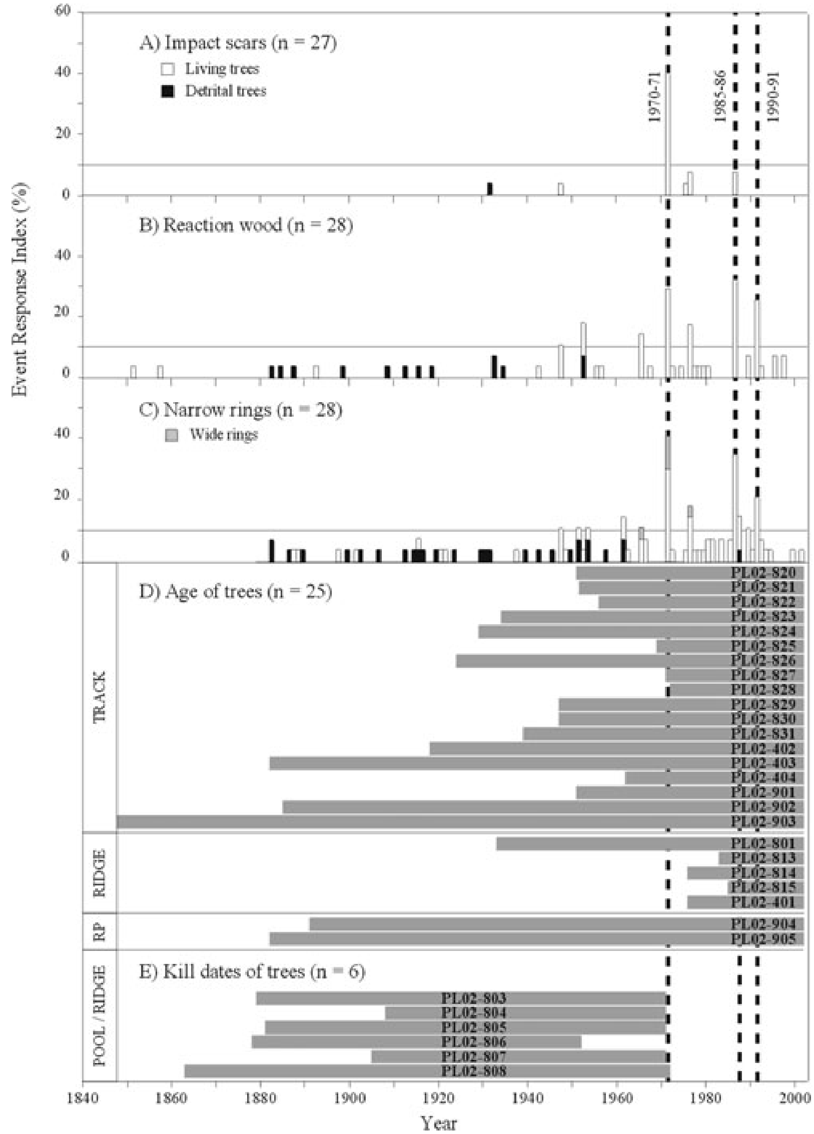

Figure 13

Peyto Lake SAIL ERI illustrating impact scars, reaction wood and narrow rings. The age of trees growing on different areas within the site (D) and the kill dates of detrital trees (E) found associated with the SAIL are shown. Vertical lines illustrate well-recorded snow avalanche events using dendrochronology

mudstones and sandstones produce low-gradient slopes abundantly covered with weathered rock debris.

The SAIL is located at the base of a convex avalanche path (Table 1; Figure 3). The upper portion of the path is unconfined and flows into a triangular catchment area. The lower portion of the track has a narrow chute morphology, except at the very base where it drops 10 metre vertically (Figure 3). Scarred mature Engelmann spruce and subalpine fir situated on the periphery of the avalanche track and the lower portion of the path delineate the boundaries of major avalanche events.

The elliptical pool has its long axis perpendicular to the avalanche path, is 50 metre long, 32 metre wide and has a maximum depth of 2 metre (Figure 12). The adjacent ridge is covered by low-lying vegetation and willows. Few cobbles and boulders were exposed on the ridge surface, and limited exposures suggest that the mound is largely composed of unconsolidated fine sediments. *R. geographicum* were present in limited numbers ($n = 14$) on two surface boulders, and their ages were estimated using a regional lichen growth curve (Luckman 1977), which dated the deposition of the boulders on the surface of the mound between 1978 and 1982. Aerial photographs of the SAIL in 1952 and 1997, and our observations in 2003, indicate that it has maintained the same size and shape for at least the last 50 years.

Increment cores were collected from living trees located on the SAIL and on the upslope snow avalanche path. Trees bordering the avalanche track ranged in age up to 170 years. The oldest tree and shrub on the ridge was 26 years old. Dated avalanche scars found on living trees surrounding the ridge (> 121 years old) and the cross-dated kill dates of logs found floating within the pool indicate that large snow avalanche events occurred in 1970–71, 1985–86 and 1990–1991 (Table 2; Figure 13). Our ERI calculations suggest lower magnitude snow avalanche events reach the SAIL on average every 1.7 years. Snow avalanche events large enough to cause erosion/deposition on the SAIL occur on average every 8.3 years (Figure 13).

Conclusions

The three SAIL sites we examined share common morphologies. The features reported here are best described as 'pits' using Corner's (1980) morphological classification scheme, and are comparable to those previously examined in the Canadian Rocky Mountains in terms of the shape and volume of the distal ridges (Smith *et al.* 1994).

All of the SAILs examined in this paper are persistent and stable landform elements of the valleys where they are located. Our observations confirm that SAIL formation is a function of the variation in snow avalanche path topography, availability of unconsolidated debris in the impact area and snow avalanche impact pressures sufficient to excavate the available debris. Although we examined SAILs located in different geologic and climatic regions than those previously examined in western Canada, no process variations were revealed. Our observations suggest that ground-based snow avalanches excavated the Blackhorn pool by bulldozing sediment onto the adjacent mound; while airborne snow avalanches explode upon impact at the Spoon Lake and Peyto Lake sites to catastrophically scatter sediment from the pools to the mounds. Similar to previous findings, our field evidence of long-term SAIL development and stability supports previous research indicating that the geomorphology of these features is largely the result of hundreds, if not thousands, of years of snow avalanche activity.

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