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Snow-Avalanche Impact Pools in the Canadian Rocky Mountains

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Abstract

Three snow-avalanche impact pool and mound complexes in the Canadian Rocky Mountains are described. Recent and historical evidence of fresh ejecta and the depth, stratification, and ^{14}C-ages of material in the mounds suggests they develop primarily by episodic, high magnitude, snow-avalanche events rather than by single catastrophic avalanches. Limited evidence indicates such events may have a recurrence interval of 50 to 150 yr.

The pool/mound complexes develop as a consequence of snow avalanche impact forces sufficient to excavate and eject valley-bottom sediments. Erosion of a pit results when the avalanche collides with the valley bottom and bodily lifts, scoops, and/or bulldozes unconsolidated sediment along its trajectory path. This erodes a depression and builds a distal embankment of debris. Volumetric estimates of sediment excavated from the pools range from 3000 to 10,000 m^3 and are less than the estimated mound volumes. This suggests that additional sediment is supplied to the mounds from the upper part of the avalanche track.

Questions remain concerning the mechanics of formation, age, and long-term evolution of such features due to the infrequent occurrence of significant events at these sites. Theoretical calculations indicate that avalanche impact pressures in excess of 1 MPa and a sharp break of slope are probably the main factors controlling the occurrence and distribution of pool/mound complexes. Their development is also probably favored where steep avalanche tracks terminate in lakes or loose unconsolidated sediments.

Introduction

Snow-avalanche impact pits (Corner, 1980) are large circular to semicircular erosional hollows located at the foot of long, steep avalanche slopes (e.g., Fitzharris and Owens, 1984; Nyberg, 1985). They are especially conspicuous where they intercept the local water table and are transformed into water-filled pools (e.g., Davis, 1962; Liestøl, 1974). Most avalanche pit/pool sites are bordered by arcuate debris accumulations up to several meters in height on the downpath side (e.g., Schytt, 1965; Corner, 1980). These deposits consist of rock, soil, and organic debris that is almost certainly the product of avalanche-induced transportation (Peev, 1966; Ballantyne, 1989; Luckman et al., 1994) although some authors have suggested a protalus (Fitzharris and Owens, 1984) or even meteoritic origin (Corner, 1975, 1980). Avalanche impact landforms have received scant attention in the North American cordillera (Luckman, 1977), and no detailed studies have been reported from Canada. This paper describes the morphology and recent history of three avalanche impact pools in the Canadian Rocky Mountains. Observations of the geomorphic effects of avalanche impact are presented for each site and the origin of these features discussed with respect to the magnitude/frequency of the events responsible for their formation.

PREVIOUS RESEARCH

Avalanche impact landforms have been described in a limited number of regional case studies from alpine areas around the world (e.g., Corner, 1980; Fitzharris and Owens, 1984) and the resulting small lakes are most commonly referred to as avalanche plunge pools (Liestøl, 1974), avalanche impact pools (Corner, 1980), or avalanche tarns (Fitzharris and Owens, 1984). No specific term has been developed for the deposits that occur downtrack of these pools but they are referred to as avalanche mounds in this paper. Matthews and McCarroll (1994) have recently coined the term snow-avalanche boulder rampart to describe distinctive landforms created by avalanche impact in river courses (see also Liestøl, 1974, Fig 1). These distal features are composed of avalanche and reworked fluvial debris deposited on the distal (downtrack) bank of the river as a splay or asymmetric ridge of debris that thins away from the river and is elongated parallel to the streamcourse. Although they share a similar avalanche origin there are major differences in morphology and sedimentary characteristics between these features and the avalanche mounds described below.

Although there has been considerable recent attention to the geomorphic significance of snow avalanches in the American cordillera (e.g., Caine, 1969; Gardner, 1970, 1983; Luckman, 1977, 1978, 1988; Tarquin, 1977), only two papers present observations on avalanche impact landforms in this area. Davis (1962) briefly described ridges and water-filled depressions at the base of avalanche tracks in the Sierra Nevada, California. He called these features avalanche scour pits and assumed they were formed by snow avalanches "shovelling" the soil outward and forward to form raised embankments of rock and soil. The only reference to avalanche impact forms in the Canadian Rockies is by Butler (1989) in a brief descriptive account of avalanche path characteristics in Waterton-Glacier International Peace Park. He made passing reference to submerged depressions bounded by distal ridges and suggested these forms were indicative of the cumulative effect of immense impact forces.

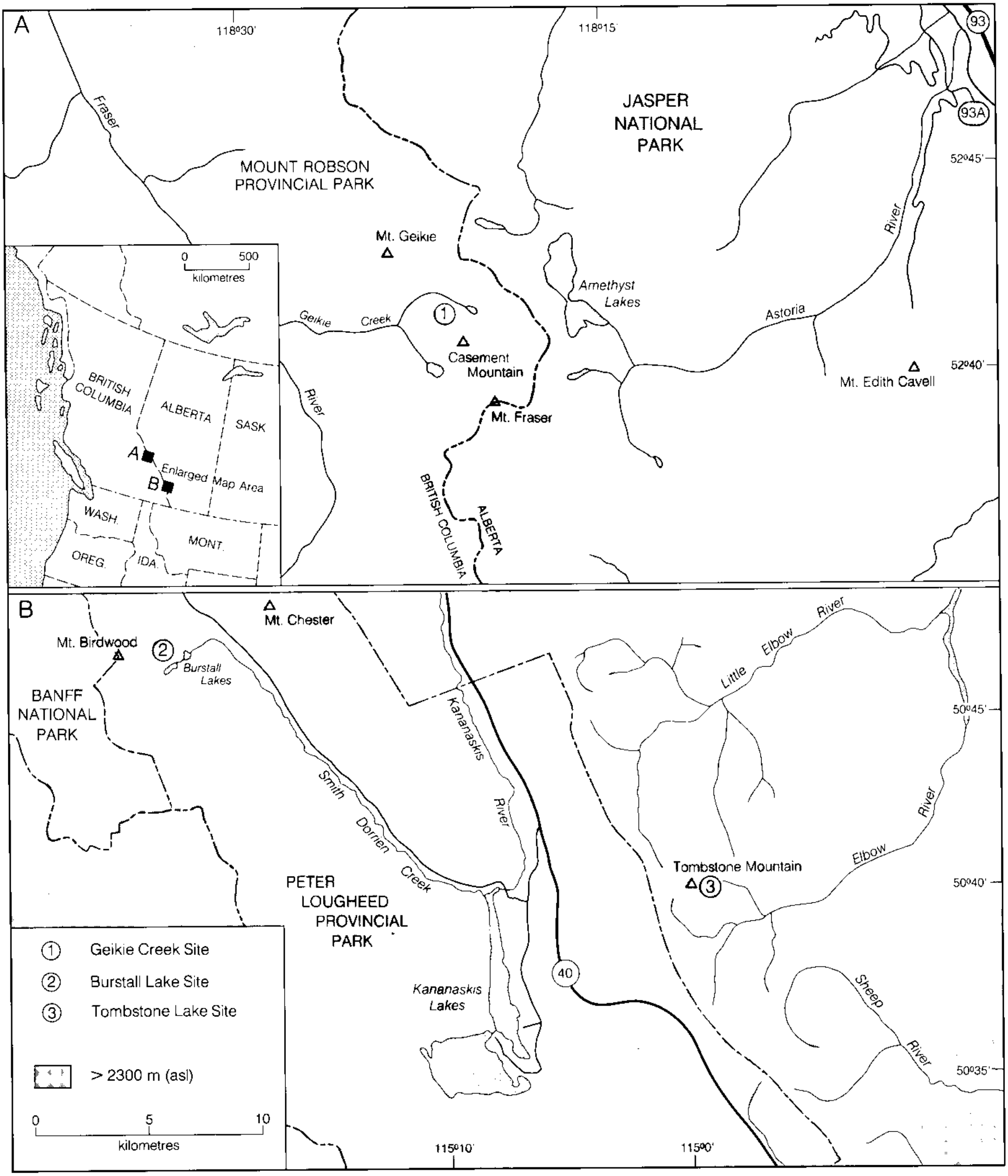

FIGURE 1. Site location map.

Study Sites

Well-developed avalanche impact landforms occur at a number of sites in the southern Canadian Rockies. Detailed studies have been carried out at Geikie Creek (Mount Robson Provincial Park, British Columbia), Upper Burstall Lake (Peter Lougheed Provincial Park, Alberta), and Tombstone Lake (Kananaskis Country, Alberta, see Fig. 1) over the last decade and are described below (Table 1).

GEIKIE CREEK SITE

The Geikie Creek site is located below the north face of Postern Mountain (2630 m a.s.l.), 400 m downvalley from the Little

TABLE 1

Locational and morphological characteristics of study sites

	Geikie Creek	Upper Burstall Lake	Tombstone Lake
Locational characteristics			
Latitude	52°41"30'N	50°47"00'N	50°41"20'N
Longitude	118°21"15'W	115°20"00'W	115°00"10'W
Aspect	North	Southwest	Northeast
Approximate pool elevation (m a.s.l.)	1675	1974	2170
Morphological characteristics			
Dimensions of track			
Maximum ground length (m)	1000	900	875
Maximum fall (m)	1000	580	750
Local slope gradient	26–51°	27–36°	21–45°
Dimensions of pool			
Down track (m)	22	45	25
Across track (m)	55	50	45
Maximum depth (m)	5	9	7
Approximate volume (m^3)	3600	10000	3000
Dimensions of mound			
Maximum height (m)	4	17	9
Approximate volume (m^3)	7700	58000	11000

Ice Age terminal moraines of Bennington Glacier (McCarthy, 1985). The site consists of a water-filled pool and a distal mound of angular boulders deposited on the flat sandy alluvial fill of Geikie Creek valley (Figs. 2 and 3).

The avalanche track at the Geikie site begins on a narrow bedrock bench at 2400 to 2500 m a.s.l. and runs over 1000 m down a 30- to 60-m-wide, 5- to 10-m-deep U-shaped gully with gradients varying between 26 and 51° (Table 1). This gully channels avalanches and runoff over a low cliff 30 to 50 m above and 50 to 100 m from the avalanche pool. A short avalanche-scoured talus slope occurs between the cliff and the pool (Fig. 4). The pool is roughly oval in shape with its long axis aligned transverse to the bedrock face (Figs. 2–4). There is no surface outlet but the pool maintains a constant water level related to the local groundwater table.

No major changes in the shape or size of the pool are apparent

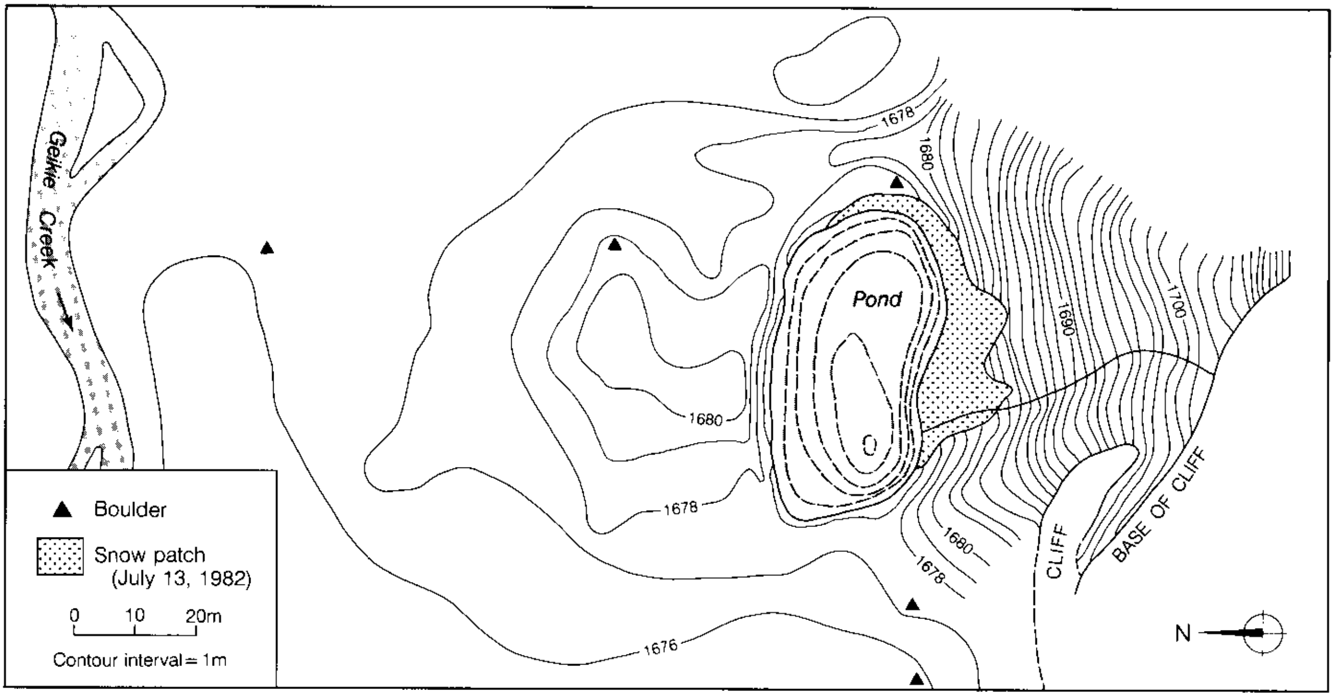

FIGURE 2. Topographic map of the Geikie Creek avalanche impact site. Note that the elevation datum is approximate. Survey by B. H. Luckman and A. B. Beaudoin, 13 July 1982. Bathymetry by D. P. McCarthy and G. W. Frazer, August 1982.

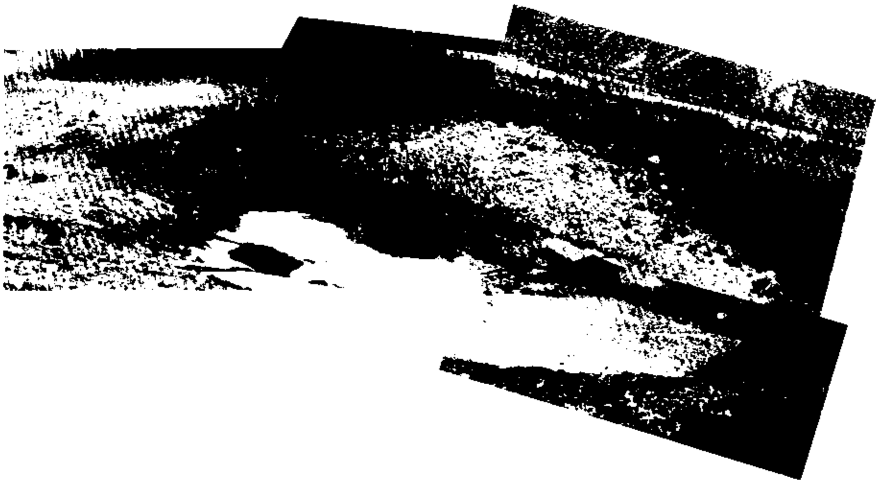

FIGURE 3. Photo mosaic of Geikie Creek avalanche impact site from the base of the cliff, July 1982. Note the sediment-laden avalanche snow in the pond and the bouldery proximal slope of the mound.

in photographs dating from 1921 to 1992. However, photographs from the summers of 1921, 1948, and 1973 show dirty ice or snow in the pool while adjacent sections of the valley floor were snow free. In the summer of 1982 the pool was covered by a 1- to 2-m-thick floating mass of debris-rich ice and snow which did not melt completely until the first week of August (Fig. 3).

The pool is bordered on the west and east by a low grass- and sedge-covered ridge composed of soil and coarse debris (Fig. 3). It is fronted by a much larger mound of angular blocks and boulders which rises to 4 m above the adjacent valley floor (Figs. 2 and 3). A dense tangle of dead, tilted, and extensively damaged conifers fringes the outer perimeter of the mound (Fig. 4). The

FIGURE 4. Aerial Photographs of the Geikie Creek avalanche impact site. The upper photograph was taken on 20 September 1963 (A18218-27), the lower photograph on 13 August 1973 (BC7543-157). Although there is a 10-yr period between these images, other small-scale photography (McCarthy, 1985, Table 6.1) indicates that the disturbance took place between the summer of 1970 and 1972.

mound surface has a freshly disturbed appearance and a sparse lichen cover, in sharp contrast to the mature lichen communities found on nearby talus slopes (see Fig. 4 and Rowley, 1992), and attests to recent severe disturbance. In 1982 several recently deposited boulders and numerous perched pebbles were observed on or against the proximal side of trees growing on the avalanche mound. Examination of historical aerial photography indicates that major changes in the surface characteristics of the mound took place in the early 1970s. Although the images in Figure 4 were taken 10 yr apart, examination of smaller scale photography indicates the changes took place between the summers of 1970 and 1972. The 1971/72 winter was an exceptionally heavy avalanche winter in the Canadian Rockies (Luckman, 1988). Comparison of these images indicates destruction and/or burial of vegetation on the crest and upper slopes of the mound and emplacement of fresh debris. Detailed examination of earlier photography and visits over the last 10-yr indicate no comparable events over a 70-yr period (1921–1992).

Minimum estimates of historical avalanche frequency at this site were obtained through photographic and dendrogeomorphic evidence. Snow avalanche damage to trees results in growth distortions that are clearly detectable in the tree-ring record. Dendrochronological studies were carried out on 14 sanded and polished cross-sectional discs collected from trees close to the avalanche pool in 1982 (McCarthy, 1985). Damage events were dated as the year of a corrasion scar, the first year of a reaction (compression) wood series or years with locally missing rings in each cross section (see Burrows and Burrows, 1976; Frazer, 1986). Avalanche years were identified as years in which damage events were recognized in the ring-width records of at least two trees on different parts of the mound area.

Dendrochronological analysis identified 11 avalanche events crossing the mound between ca. 1880 and 1973 giving an average return interval of about 8 yr. This is clearly an underestimate because of the relatively small number of trees sampled, the recent destruction of many trees on the mound and the nature of the evidence used. The physiological response of trees to avalanche impact (e.g., reaction wood series) may continue for several years after the event, masking subsequent damage to the same tree (Burrows and Burrows, 1976; Frazer, 1986). The tree-ring data confirm that snow avalanching in 1971/72 and 1972/73 caused more damage to vegetation growing on the mound than was experienced over the previous 50 yr. Significantly, the long-term growth disturbances introduced by these events make it impossible to distinguish any record of snow avalanching between 1972 and 1982. The likelihood of similar gaps in the historical record is high and suggests that the above data underestimate the frequency of large snow avalanches at this site.

The avalanche mound at Geikie Creek is smaller than the others described in this paper and is the only site where the avalanche track does not extend into a lake. The mound is built over fine-grained floodplain sediments and the creek is presently confined to the opposite side of the valley. The presence of abandoned channels and shallow ponds close to the southern valley wall downstream of the mound suggest that the initiation of the mound/pit feature could have taken place in a channel or shallow backwater pond close to the southern valley side and that the river has subsequently been diverted across the flat floodplain to its present position. This raises the possibility that, in suitable conditions (strongly focused avalanche impact, easily eroded and broad floodplain sediments where the river is free to change course) avalanche plunge pools may develop from impacts into rivers (see Matthews and McCarroll, 1994).

FIGURE 5. Vertical aerial photograph of Burstall Lake avalanche impact site from 9 September 1958 (AS747-5034).

BURSTALL LAKE SITE

The Burstall Lake site is located on the north shore of Upper Burstall Lake below the south face of an unnamed mountain summit (2560 m a.s.l.) at 1966 m a.s.l. (Fig. 1). The site is characterized by a circular, water-filled, pool and a prominent vegetation-covered mound (Figs. 5 and 6).

The avalanche track above the Burstall site is contained within vertically standing beds of Palaeozoic limestone (Fig. 7). It has a total relief of 580 m and a gradient between 27 and 36° (Table 1). A prominent, vegetation-covered, debris flow deposit extends from the upper reaches of the track to treeline. Dendrochronological analysis of krummholz at mid-slope indicates an almost annual incidence of avalanches (Heaver, 1990).

The Burstall avalanche pool is almost circular with a maximum depth close to 9 m in 1988 (Fig. 6, Table 1). Bathymetric profiling indicates that the pool is bowl-shaped with a deep central depression covered by a thick mat of submerged branches and trunks. Water levels in the pool have remained at least 8 m above those of nearby Upper Burstall Lake throughout the period of record (1949–1991). Water levels in the pond remain relatively stable, but may rise up to 1 m following snowmelt and precipitation events.

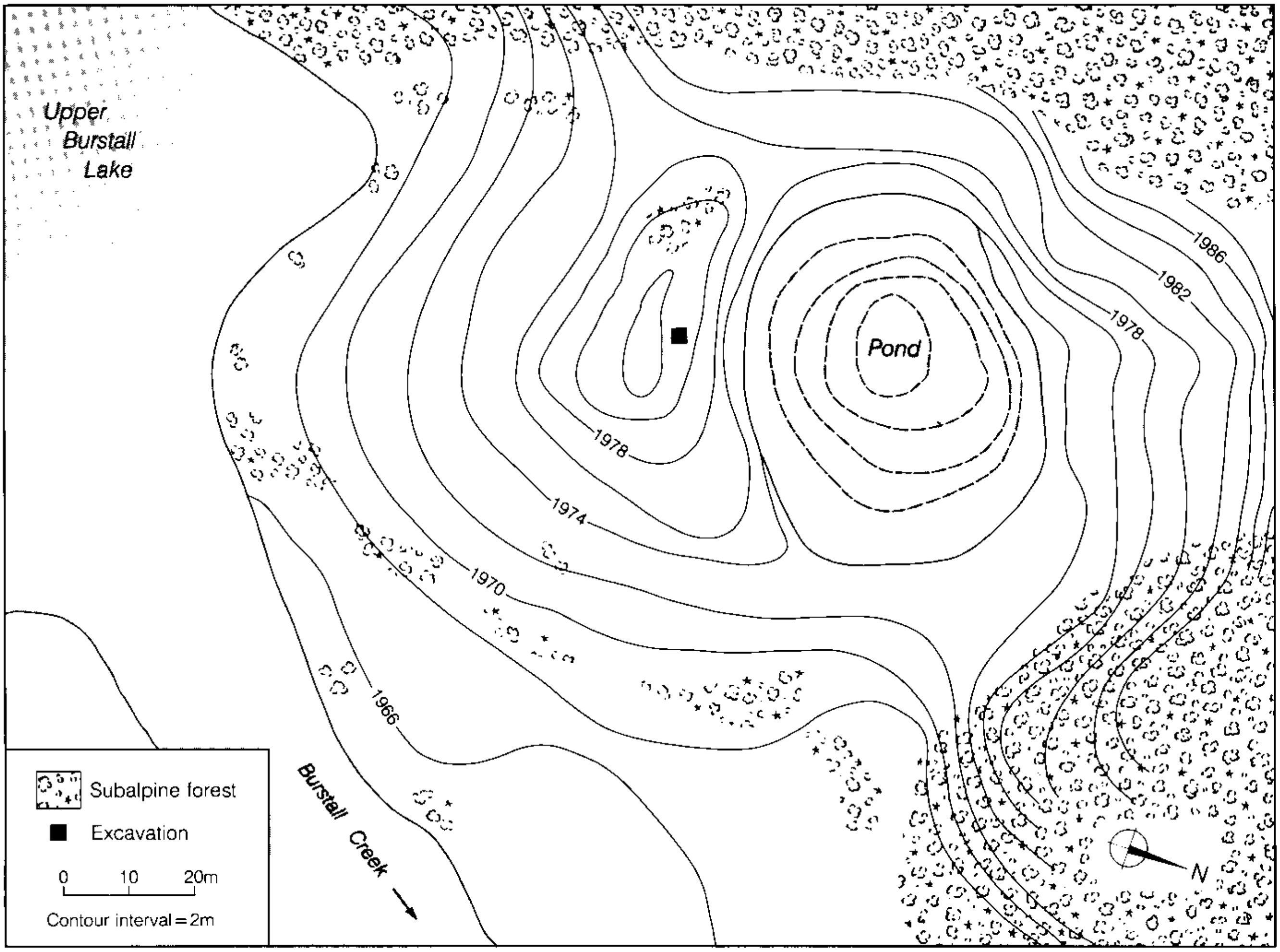

FIGURE 6. Topographic map of Burstall Lake site. Note that the elevation datum is approximate. Survey and bathymetry by G. Blahut, W. Mehew, and D. Smith on 16 August 1988.

The avalanche pool is flanked by a prominent crescent-shaped mound with a steep proximal rim (25–40°). The crest of the mound reaches 8 to 9 m above the pool surface and almost 17 m above the waterline in Upper Burstall Lake (Fig. 6). The distal slopes of the mound are subdued and taper gently from the crest to the lake edge (Fig. 5). The avalanche mound is completely vegetated and dominated by sedges, *Salix* spp., and isolated stands of subalpine spruce/fir. Limited exposure in scars on the proximal slope of the mound show that it consists of a mixture of coarse sands, pebbles, and talus fragments.

In 1988 and 1989, a 3.1-m-deep pit was dug into the proximal slope of this mound (Fig. 6), about 4 m vertically below the crest. The deposits in this excavation showed a weakly developed stratigraphy parallel to the present slope surface (ca. 25° at this point) and contained wood and branch fragments. Three samples from depths between 1.45 and 2.48 m were recovered and yielded similar radiocarbon ages (Table 2). Natural variability in ^{14}C production results in a wide calendric age range for ^{14}C dates in this time frame (cf. Luckman, 1986; Stuiver and Reimer, 1993). Nonetheless, the similarity of these three dates suggests that the wood fragments could have been deposited by a single avalanche or a series of closely spaced events. Examination of contemporary depositional events at this site (see below) indicates that single events may deposit over 1 m of sediment on some areas of the mound. Accumulation depths of 2.5 m in the last 300 to 500 yr suggest that the recurrence intervals of such large depositional events is probably of the order of centuries rather than decades.

The internal characteristics of the mound deposit at this site were investigated by geophysical surveys in the summer of 1990. A GEONICS EM-31 (Geonics Limited, Mississauga, Ontario) was used to prepare an electromagnetic induction map of the mound (e.g., Bevan, 1983). Interpretation of these data suggest that the mound is a relatively coherent mass of unconsolidated sediment. There are no indications of any major stratigraphic boundaries or sills within the mound which might explain the persistent water levels noted in the pond.

In 1989, 46 discs and 22 increment cores were obtained from trees in the lower portion of the track and mound (Heaver, 1990). Dendrochronological analyses identified 37 avalanche events in the lower track between 1920 and 1990. Twenty of these events were also identified on the distal slope of the avalanche mound. These data suggest a minimum recurrence interval of about once every second year for avalanches in the track but that almost half (45%) of these avalanches terminate at the mound. Avalanches spill over the crest and onto the distal slope of the mound about once every 3.5 yr with major events recognized in 1956/57, 1973/74, 1980/81, 1983/84, and observed in 1989/90.

Spectacular confirmation of the role of snow avalanches at the Burstall site was provided during the winters of 1988/89 and 1989/90. On 6 July 1989 the pool was filled with a mixture of avalanche snow, broken pieces of pond ice (ca. 40 cm thick),

FIGURE 7. Burstall Lake avalanche impact site, July 1988.

waterlogged tree trunks, branches and clods of soil and talus (Fig. 8). However, there was no evidence that this avalanche overfilled the pool. Several large, partially waterlogged, tree trunks remained partially buried by avalanche snow filling the pool and protruded upwards from the surface (Fig. 8). These trunks were floating in the pool in 1988 and their orientation in 1989 indicated that the avalanche mass struck the center of the pool. In addition, the proximal slope of the mound was covered with a semicircular ridge of avalanche snow, capped with bottom sediments from the pool and waterlogged branches. This material was clearly pushed up from the bottom of the pool during avalanche impact.

Avalanche activity at this site during the 1989/90 season was of greater magnitude and quite different in character from that observed in the previous year. In the spring of 1990 the pond was filled with snow (Fig. 9) and large quantities of sediment were splayed across the mound surface (Fig. 10). Unlike the situation in 1989, this avalanche carried a slurry of woody debris and sediment up and over the mound. Although some of this debris was deposited on the distal slope of the mound (Fig. 9), a substantial mat of floating debris was present in the lake encircling the mound, indicating that some sediment was transported beyond the visible perimeter of the mound into Upper Burstall Lake.

Virtually all of the sediment and woody debris deposited on the distal slope of the avalanche mound originated from within the pond. There was no indication of fresh avalanche scour upslope from the mound and only a few trees within the avalanche track showed evidence of recent scarring. Consequently, the veneer of coarse sediment which blanketed a wide area of the mound with deposits up to 30 cm thick must have been excavated from the bottom of the pond. This observation is supported by the discovery of weathered and sediment-covered logs and branches on the distal slope of the mound. These include the two large logs pictured in Figure 8 which were transported ca. 30 m down the distal flank of the avalanche mound during the 1990 event.

The geomorphic impact of the 1990 avalanche was substantial (Fig. 9). It is estimated that at least 200 to 300 m^3 of sediment was transported from the bottom of the pond to the mound surface by this single event. Dendrochronological evidence suggest that events of this magnitude are infrequent. Prior to 1990 several large trees grew along the distal fringe of the mound adjacent to Upper Burstall Lake (Fig. 7). Most of these trees, including the oldest individual present (92 yr in 1989) were destroyed by the 1990 event.

TOMBSTONE LAKE SITE

The Tombstone Lake avalanche impact site is found below the east face of Tombstone Mountain at 2180 m a.s.l. in Kananaskis Country, Alberta (Fig. 1). This site has an oval-shaped pool and a tapering distal mound of coarse bouldery talus abutting Upper Tombstone Lake (Fig. 11). It is located immediately below a steeply sloping open-cirque basin facing to the northeast (Fig. 12, Table 1). The avalanche track begins at an almost-vertical free face and drops onto an amphitheater-shaped debris slope that feeds through a narrow bedrock-controlled funnel at mid-slope. The funnel focuses snow avalanches into an eroded (20–30 m wide, 3–4 m deep) chute centered on the avalanche pool.

The Tombstone avalanche pool is 25 m wide and 45 m long, with an estimated maximum depth of ca. 7 m. Water levels in the pond rise and fall in concert with those in Upper Tombstone

TABLE 2

^{14}C dated wood fragments from excavation at Burstall Lake site[a]

Sample number	Length (cm)	Increment rings	Depth from surface (m)	Radiocarbon age (BP)	Calendar date (2σ)
AECV-692C	19	12	1.45	350 ± 90	AD 1414 (1516, 1591, 1621) 1954
AECV-693C	30	16	2.25	370 ± 90	AD 1407 (1488, 1609, 1611) 1954
AECV-1045C	5	6	2.45	340 ± 160	AD 1302 (1520, 1569, 1627) 1955

[a] Radiocarbon dates provided by Radiocarbon and Tritium Laboratory, Alberta Environmental Centre, Vegreville, Alberta. Calendar age equivalents from Radiocarbon Calibration Program (CALIB, Rev. 3.0.3; Stuiver and Reimer, 1993) and are accompanied by the intercept years and potential range of years represented (two sigma).

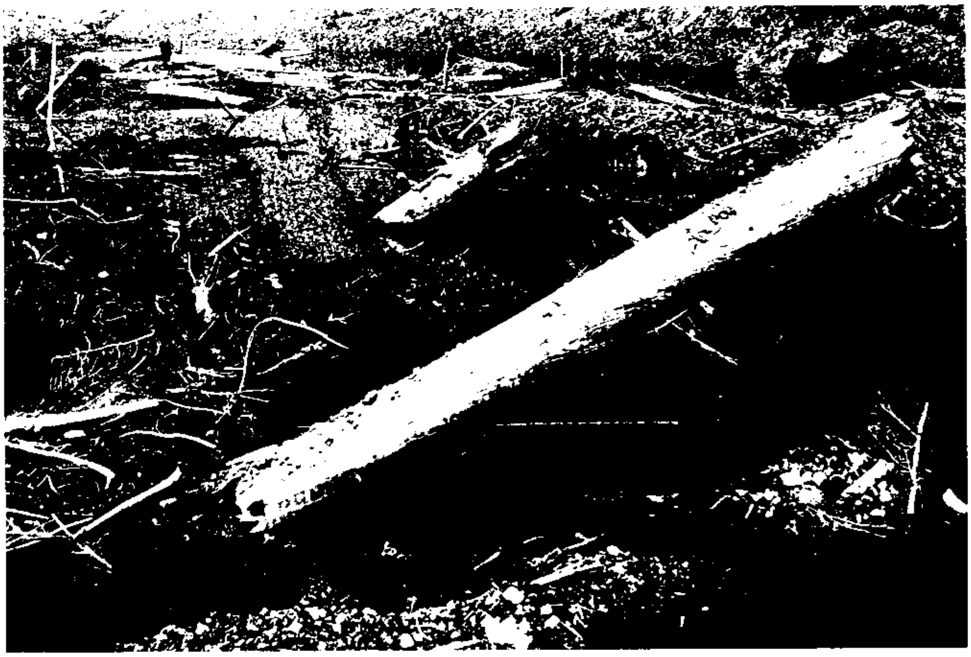

FIGURE 8. Burstall impact pool, July 1989. Note the pool is completely filled with mixture of sediment-laden avalanche snow and woody debris.

Lake. The avalanche pool is bounded on three sides by a 9 m high bouldery mound with a gently tapering distal slope (6–12°). This surface becomes progressively fresher and coarser in appearance as one approaches the crest of the mound from Tombstone Lake. Perched boulders are numerous throughout this area. The proximal slopes of the mound are steep (30–33°), unstable, and extend below water line into the impact pool. Excavations in the proximal face in 1989 revealed numerous broken and shattered tree trunks and branches.

There are no living trees on the avalanche mound. Accordingly, in 1989, a dendrochronological survey was done using trees on the opposite (eastern) shore of Upper Tombstone Lake. Although avalanche-damaged trees occur in this area, only one significant avalanche event was identified (1973/74) based on approximately 200 yr of record from 10 trees. Therefore, the largest avalanches at this site extend completely across the lake perhaps on a timescale of no more than once every few decades, and possibly as little as once every few centuries.

Discussion

Evidence of recent and historical avalanche activity at the study sites confirms that the mounds are built by snow avalanche activity and that debris is transported onto the mounds from the depressions. However, excavations and observations of disturbance at these sites shows the mounds and pools contain an admixture of old and modern material that makes it difficult to establish a chronology of debris accumulation. Nevertheless, evidence of fresh ejecta and the depth, stratification, and ^{14}C-ages of material in the mounds suggest a long history of episodic deposition. These data, plus observations of contemporary process activity, suggest that the pool-mound complexes develop

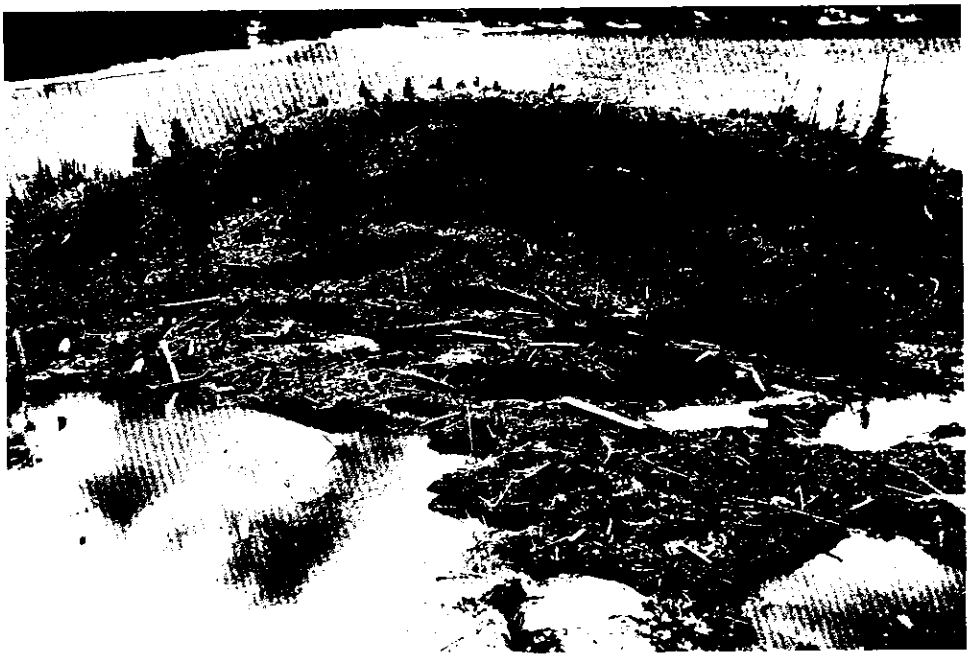

FIGURE 9. Burstall avalanche impact pool and mound, June 1990, with debris splayed up and over the proximal mound slope. Note the figures standing on the crest of the mound for scale.

FIGURE 10. Distal slope of the Burstall impact mound, June 1990.

primarily by episodic, high-magnitude snow-avalanche events rather than a single catastrophic avalanche. Limited evidence from the Geikie and Burstall sites suggests such events may have a recurrence interval of 50 to 150 yr; smaller, more frequent avalanches and rockfalls may provide sporadic debris input to the pool or mound surface, but it is the large, high-velocity avalanches that create and maintain this distinctive form.

The cumulative geomorphic work performed by these avalanches is impressive. Volumetric estimates of the quantity of sediment excavated from the pools range from 3000 to 10,000 m^3 (Table 1). Significantly, each mound contains substantially more sediment than could have been supplied by the adjacent pit (even allowing for a 30% void ratio in the mound). This additional material probably represents debris that has been derived from the upper part of the avalanche track and has been transported across the pool, either directly or by periodic evacuation of sediments accumulating in the pool between major erosional events.

FIGURE 11. The Tombstone avalanche impact site, July 1978.

FIGURE 12. Vertical aerial photograph of the Tombstone Lake avalanche impact site from 25 August 1958 (AS748-5030).

Two explanations have been proposed to account for avalanche pit/pool and mound development. The first notes that avalanche pool development is favored in locations where relatively high-angle avalanche tracks intercept either valley floors or lake shorelines, which suggests that the pits/pools are a consequence of snow-avalanche impact forces sufficient to excavate and eject valley-bottom sediments (Schytt, 1965; Peev, 1966; Liestøl, 1974; Corner, 1980; Fitzharris and Owens, 1984). Erosion of a pit results when the avalanche collides with the valley bottom and bodily lifts, scoops and/or bulldozes unconsolidated sediment along its trajectory path. This mechanism has the effect of eroding a depression, which may then fill with water, and building a distal embankment of debris. Liestøl (1974) suggested that water plays a vital role in accentuating the shock waves generated by subsequent avalanches, enhancing further development of the feature. It is possible that the forces operating in dry pits or in shallow river beds produce slightly different landforms (e.g., the "avalanche impact tongues" of Corner [1980] or the "snow-avalanche boulder rampart" of Matthews and McCarroll [1994]). This variation in depositional form is envisioned by Luckman et al. (1994) to represent end members of a range of landforms produced by snow-avalanche impact forces.

The second explanation attempts to account for the origin of features associated with low-gradient slopes. At such sites it has been suggested that the pits develop when slush or snow avalanches flow along the ground and scour or push valley-bottom sediments away from the slope base (Nyberg, 1985, 1989). Alternatively, protalus ramparts created by debris sliding over snow (e.g., Ballantyne, 1987) or snow avalanche mound deposits (e.g. Peev, 1966) may create comparable topographic situations. None of the latter group of scenarios would appear to fit the examples described from the Canadian Rockies where an impact mechanism seems most likely.

TABLE 3

Theoretical impact pressures generated by extreme snow avalanches at the study sites

	θ	c	ρ (kg m^{-3})	v (m s^{-1})	P (MPa)	P sin θ (MPa)
Geikie site	41°	1.5	100	85.1	1.1	0.7
			350		3.8	2.5
		2.0	100		1.5	1.0
			350		5.0	3.3
Burstall site	34°	1.5	100	63.1	0.6	0.4
			350		2.0	1.1
		2.0	100		0.8	0.5
			350		2.8	1.6
Tombstone site	30°	1.5	100	65.9	0.6	0.3
			350		2.1	1.1
		2.0	100		0.7	0.4
			350		3.0	1.5
Mellor (1978)					0.01–0.6	
Fitzharris and Owens (1981)	38°	1.5	150	60	1.1	0.7
Shimizu et al. (1980)				60	1.4	

θ = average slope gradient; c = coefficient dependent on deformation of snow; ρ = density of dry avalanche snow 100 kg m^{-3} and wet avalanche snow 350 kg m^{-3} (Schaerer, 1981); v = avalanche velocity (m s^{-1}) estimated by program ACCEL (Cheng and Perla, 1979); P = peak pressure calculated as $c\rho v^2$ (Schaerer, 1981); P sin θ = corrected peak pressure (the correction is to adjust for the acute angle at which avalanches strike the valley floor, see Fitzharris and Owens, 1984).

The location of these pool and mound complexes below steep avalanche slopes is almost certainly a contributing factor to their development. The patterns of avalanche damage at each site show that large impact stresses must be generated when the avalanches reach the valley floor. These impact stresses may be estimated using a relationship developed by Schaerer and Salways (1980) to derive the initial peak pressures occurring on a unit surface perpendicular to the avalanche flow. Following Schaerer and Salways (1980) peak impact pressures (P) were estimated as $P = c\rho v^2$, where c = coefficient dependent on the deformation of snow, ρ = density (kg m^{-3}) of snow, v = avalanche velocity (m s^{-1}) estimated by program ACCEL (Cheng and Perla, 1979). To account for the fact that avalanches strike the valley floor at an acute angle, these peak pressure were corrected (P sinO, where Θ = valley side slope) following Fitzharris and Owens (1984). Observations in the vicinity of the Burstall and Tombstone sites indicate that dry snow avalanches are common in the early winter, whereas wet and mixed snow avalanches can be expected in late winter and spring (de Scally, 1984; Johnson et al., 1985). As no direct observation of avalanche snow densities are available for either the Geikie or Kananaskis area, the values cited by Schaerer (1981) may be used to provide a range of impact pressures. The data in Table 3 demonstrate that the calculated impact pressures for the Canadian Rockies sites are of similar magnitude to those calculated for similar sites by Fitzharris and Owens (1984).

Although calculations such as these indicate avalanche impacts generate considerable pressures and field observations verify that impact erosion occurs, the exact erosional mechanism remains an enigma. Clearly, in all three sites described above, snow avalanches plunge into water-filled pits with an explosive force that must first drive the water downward to the pit floor (cf. Liestøl, 1974; Vila, 1987). Almost instantaneously, the rapidly moving (63–85 $m\ s^{-1}$, Table 3) mass of water and snow encounters the pit floor and is deflected upwards and outwards (cf. Gault et al., 1968). This diversion of flow initiates further excavation by plucking and entrainment mechanisms generated by the force of impact.

Deposition of sediment on the avalanche mound follows the hydrodynamic ejection of debris at the periphery of the pond. Progressive accumulation of weakly stratified deposits on the mound occurs over long periods of time. Evidence of erosion and deposition at these sites demonstrates that both large and small caliber debris can be ejected from the pool and that a considerable thickness (20–30 cm observed, perhaps up to 1 m) of colluvium can be deposited on the crest and distal slope of such mounds in a single event. This implies that deposits as massive as those investigated here are the consequence of long-term activity. Debris may also be added to the mounds by other forms of avalanche activity. If the depression containing the pool is filled by deposits from numerous small avalanches early in the season, later "dirty" avalanches may runout over these deposits directly onto the mound beyond, subsequently ablating their debris content onto the distal slopes of the mound.

Conclusions

Avalanche impact pools are a relatively common, but little-studied landform in the Canadian Rocky Mountains. Observations at three sites indicate that debris from impact pools is hydrostatically ejected and redistributed over the distal mound by snow avalanches. While the presence of a water body demonstratively accentuates impact pool-mound development (e.g., Schytt, 1965; Liestøl, 1974), it is clearly not an essential ingredient.

Questions remain concerning the mechanics of formation and the age and long-term evolution of such features. Excavations and ^{14}C-dating of material show the mounds contain both organic and clastic debris derived from the pool and the avalanche track upslope. Observations of contemporary activity indicate that up to 1 m of fresh sediment may be deposited on the mounds from the pool by single avalanche events but ^{14}C dating, stratigraphy, and observations from historical photographs suggest that such events have recurrence intervals of centuries rather than decades. Limited observations of activity indicate that these features are not the result of single catastrophic events but have been developing throughout the Holocene at these sites. The magnitude-frequency spectrum of significant events at these sites presents considerable problems for investigation of the mechanics and chronology of impact pool-mound development. Theoretical calculations indicate pressures in excess of 1 MPa may result from avalanche impact. The main factors controlling the occurrence and distribution of these features is the presence of a sharp break of slope at the foot of a steep avalanche track. The development of avalanche pits/pools and mounds is also favoured where these steep tracks terminate in lakes or loose unconsolidated sediments.

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