The July 29, 1998, debris flow and landslide dam at Capricorn Creek, Mount Meager Volcanic Complex, southern Coast Mountains, British Columbia

Michael J. Bovis and Matthias Jakob

Abstract: A very large debris flow was triggered during a period of record-breaking high temperatures in upper Capricorn Creek, within the Mount Meager Volcanic Complex, a part of the Garibaldi Volcanic Belt of the southern Coast Mountains. The debris flow deposit impounded Meager Creek, creating an 800 m long landslide-dammed lake. The total event volume was 1.2×10^6 m^3. The debris flow was followed by three days of almost continuous hyperconcentrated flow surges, which caused significant fluvial aggradation in the Meager Creek flood plain below the Capricorn Creek confluence. Within a few days of the formation of the landslide dam, a spillway notch had been cut through the deposit, thereby preventing the occurrence of a catastrophic dam break. The landslide, which triggered the debris flow, originated in deep volcanic colluvium having a previous history of progressive slope deformation, a consequence of glacial downwasting since the Neoglacial maximum. This paper highlights an important landslide response to recent glacial retreat and suggests that similar events could reoccur within Capricorn Creek, as well as at other sites where steep colluvial and weak bedrock slopes have been glacially debuttressed.

Résumé : Au cours d'une période de températures élevées record, une très grande coulée de débris a été déclenchée dans le ruisseau Capricorn supérieur, à l'intérieur du complexe volcanique du mont Meager, lequel fait partie de la ceinture volcanique Garibaldi des montagnes du sud de la Côte. La coulée de débris a bloqué le ruisseau Meager créant ainsi un lac de 800 mètres de long bloqué par un glissement de terrain. Le volume total en jeu pour l'événement était de $1,2 \times 10^6$ m^3. Trois jours de sauts de débit hyperconcentrés, presque continuels, ont suivi la coulée de débris et cela a causé un important alluvionnement fluviatile dans la plaine d'inondation du ruisseau Meager, en aval de la confluence avec le ruisseau Capricorn. Quelques jours après la formation du barrage par glissement de terrain, un déversoir a été taillée à travers le dépôt évitant ainsi une rupture catastrophique du barrage. Le glissement de terrain qui a causé la coulée de débris a pris naissance dans des colluvions volcaniques profonds qui avaient déjà une histoire antécédente de déformation de pente progressive, une conséquence de la fonte glacière depuis le maximum de l'époque néo-glaciaire. Ce document souligne une importante réponse par glissement de terrain à un retrait glaciaire récent et suggère que des événements semblables pourraient encore survenir dans le ruisseau Capricorn et à d'autres sites de colluvions abruptes et de pentes de roc faibles où les contreforts ont été enlevés par glaciation.

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Introduction

On July 29, 1998, a 550 000 m^3 debris slide released from upper Capricorn Creek basin in the Mount Meager Volcanic Complex (Figs. 1, 2), triggering a debris flow which ran 6 km down Capricorn Creek. The debris slide that triggered the debris flow originated from a thick blanket of poorly consolidated colluvium on the south flank of the Mount Meager stratovolcano (Fig. 3). The slide was initiated by accelerated snowmelt during a record-breaking heat wave in late July 1998. Approximately 1.2×10^6 m^3 of material were delivered to the Meager Creek confluence, creating a landslide dam (Fig. 4). When the site was first visited by the authors on August 2, 1998, a 800 × 150 m landslide-dammed lake had formed. By August 12, an 8–10 m deep spillway had been cut through the dam causing significant lowering of the lake level, thereby preventing a catastrophic dam break. Complete lake drainage was prevented by a mass of coarse sediment and a log jam forming an outlet sill for the new lake. Over the ensuing year, the remains of the landslide dam were eroded and the lake was completely drained as a result of erosion during a severe rainstorm in August of 1999 (J. Goates, Pemberton Helicopters, personal communication, 1999).

The event is the latest in a long series of catastrophic mass failures within the Meager Creek area in the past century and, in terms of sediment discharge, renders Meager Creek basin one of the most geomorphically active within the Canadian Cordillera (Jordan 1987; Jordan and Slaymaker

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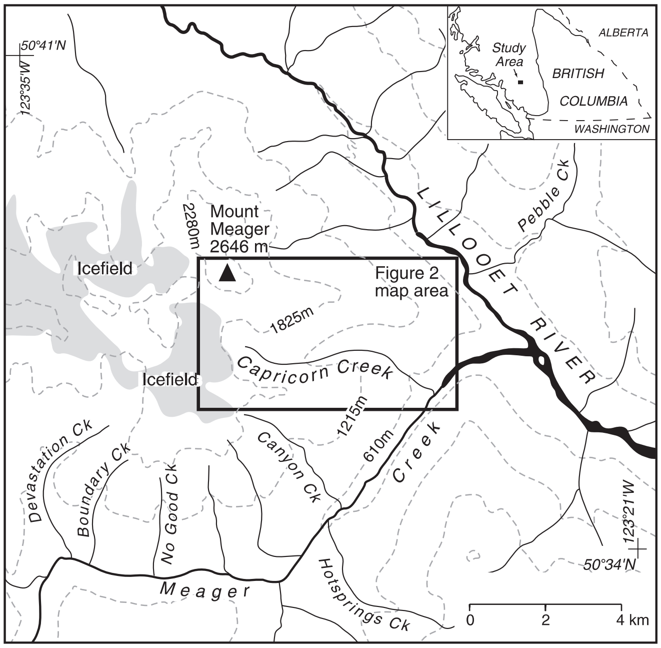
Fig. 1. Location of the study basin within the Meager Creek volcanic area.



1991). In this paper, we document this latest extreme event and discuss its probable geologic and climatic causes. We examine the instrumented climatic record for evidence of common antecedents to similar events within the historical period. Although the latest Capricorn Creek event can be tied to a specific climatic trigger, there is evidence that glacial downwasting and resultant slope debuttressing since the attainment of the Neoglacial maximum have been important precursors to this and other large slope failure events within the historical period. An extensive system of tension cracks and uphill-facing scarps occurs within the area of the Neoglacial overlap directly adjacent to the site of the 1998 failure. The cracks, which would have facilitated rapid infiltration of meltwater in late July 1998, are visible on air photographs dating back to the early 1960s, but are not apparent on 1948 air photographs. This suggests a delayed movement response to slope debuttressing since the commencement of Neoglacial retreat. The potentially unstable masses bounded by these tension cracks could trigger other large debris flows in future.

Study area

Mount Meager Volcanic Complex

The Mount Meager Volcanic Complex is a high-relief area containing several deeply eroded dormant-to-extinct stratovolcanoes of Late Pliocene to Holocene age (Read 1978; Green et al. 1988; Stasiuk et al. 1996; Hickson et al. 1999). The most recent eruption occurred only 2350 years ago at Plinth Peak, depositing the Bridge River tephra over a wide region of south-central British Columbia (Clague et al. 1995). The volcanic rock assemblage is generally poorly consolidated, and steep slopes are prone to catastrophic collapse (Evans 1987; Hickson et al. 1999).

The complex is drained by 15 small basins, all capable of delivering large debris flows and debris avalanches. At least six events from various Meager Creek sub-basins have caused temporary impoundments of Meager Creek in the past 60 years (Jordan 1994; Jordan and Slaymaker 1991; Jakob 1996). This unusually high level of mass movement activity is due in part to the existence of steep, high relief areas carved into relatively weak volcanic assemblages, in part to the humid climate, and in part to very rapid recession of glaciers in the past 150 years.

The high frequency of catastrophic mass movements within Capricorn Creek and other basins tributary to Meager Creek causes the latter to have a disproportionately high sediment load relative to its drainage area and discharge (Jordan 1987; Jordan and Slaymaker 1991). It is a dominant coarse-sediment source for Lillooet River, which abruptly changes its morphology from a single-thread, meandering channel to a broad, braided system at the Meager Creek confluence. The 1998 debris flow at Capricorn Creek caused notable further aggradation along the lower Meager Creek flood plain (Fig. 5).

Capricorn Creek basin

Capricorn Creek (14.4 km^2) has a local relief just exceeding 2000 m and is one of the largest basins draining the southern flank of the Mount Meager Volcanic Complex (Fig. 2). The creek is prone to creating landslide dams, since it enters Meager Creek at a right angle, a geometry which promotes deposition and channel blockage rather than downstream transport (Fig. 4). The upper basin above about 1700 m is underlain mainly by dacitic lavas, breccias, and tuffs of the Plinth and Capricorn assemblages (Read 1978). The remainder of the basin is underlain by highly fractured felsic to intermediate intrusive rocks of Mesozoic age. Both the volcanic and basement rocks are subject to rapid weathering, and thick colluvial blankets are common on slopes less than about 35°.

The uppermost 2.9 km^2 of the basin are covered by Capricorn Glacier and prominent Neoglacial moraines and trimlines exist (Fig. 6). At the time of the Neoglacial maximum, ice covered approximately 6.3 km^2 of the basin; since then, Capricorn Glacier has receded by 3 km and downwasted by more than 200 m. This degree of retreat is typical of larger glaciers in the southern Coast Mountains (Ryder and Thomson 1986) and has resulted in widespread debuttressing of bedrock and drift-covered slopes. Since the 1998 failure lies well within the area of Neoglacial overlap in upper Capricorn Creek basin (Fig. 2), downwasting of Capricorn Glacier would have caused progressive steepening of the colluvial slope as the slope-foot buttress point provided by the glacier shifted to progressively lower elevations. Thus, glacial retreat is a likely contributory cause for this event and possibly other large failures within the Meager Creek area.

Although rockslides have occurred from both volcanic and granitic areas within the upper basin (notably areas R1, R2: Figs. 2, 6), numerous smaller landslides and debris flows are caused by failure of colluvial and glacial drift materials (Fig. 6). Earlier landslide deposits, such as the R1 rock avalanche unit (area D in Figs. 2, 6), are periodically reworked by subsequent debris flows (notably the 1998 event de-

Fig. 2. Topographic map of Capricorn Creek basin showing the detachment zone and trajectory of the 1998 debris flow. Also shown are earlier rock avalanche features (R1, R2) and the present and Neoglacial extents of Capricorn Glacier. Topographic profile A–A′ is shown in Fig. 7.

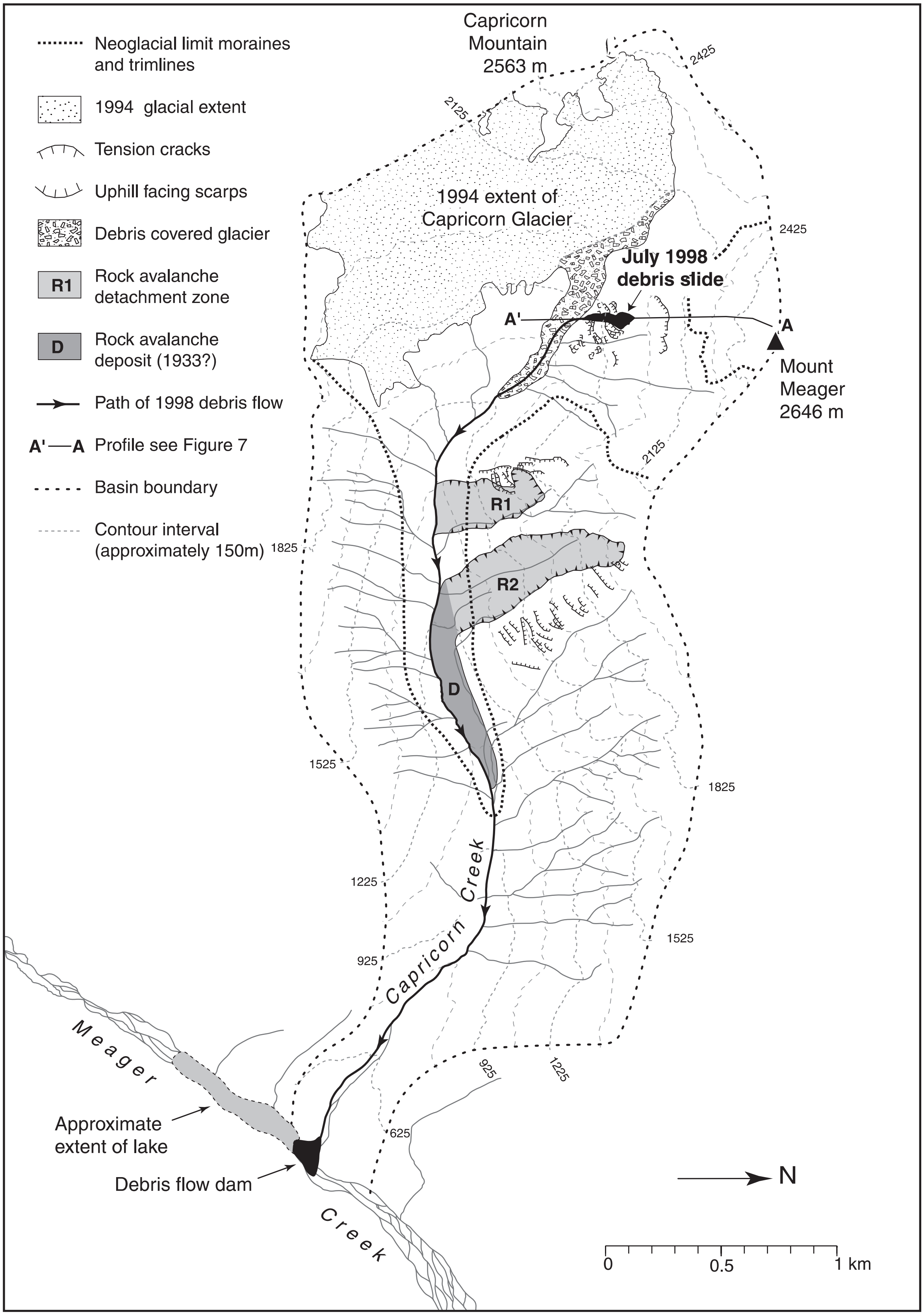
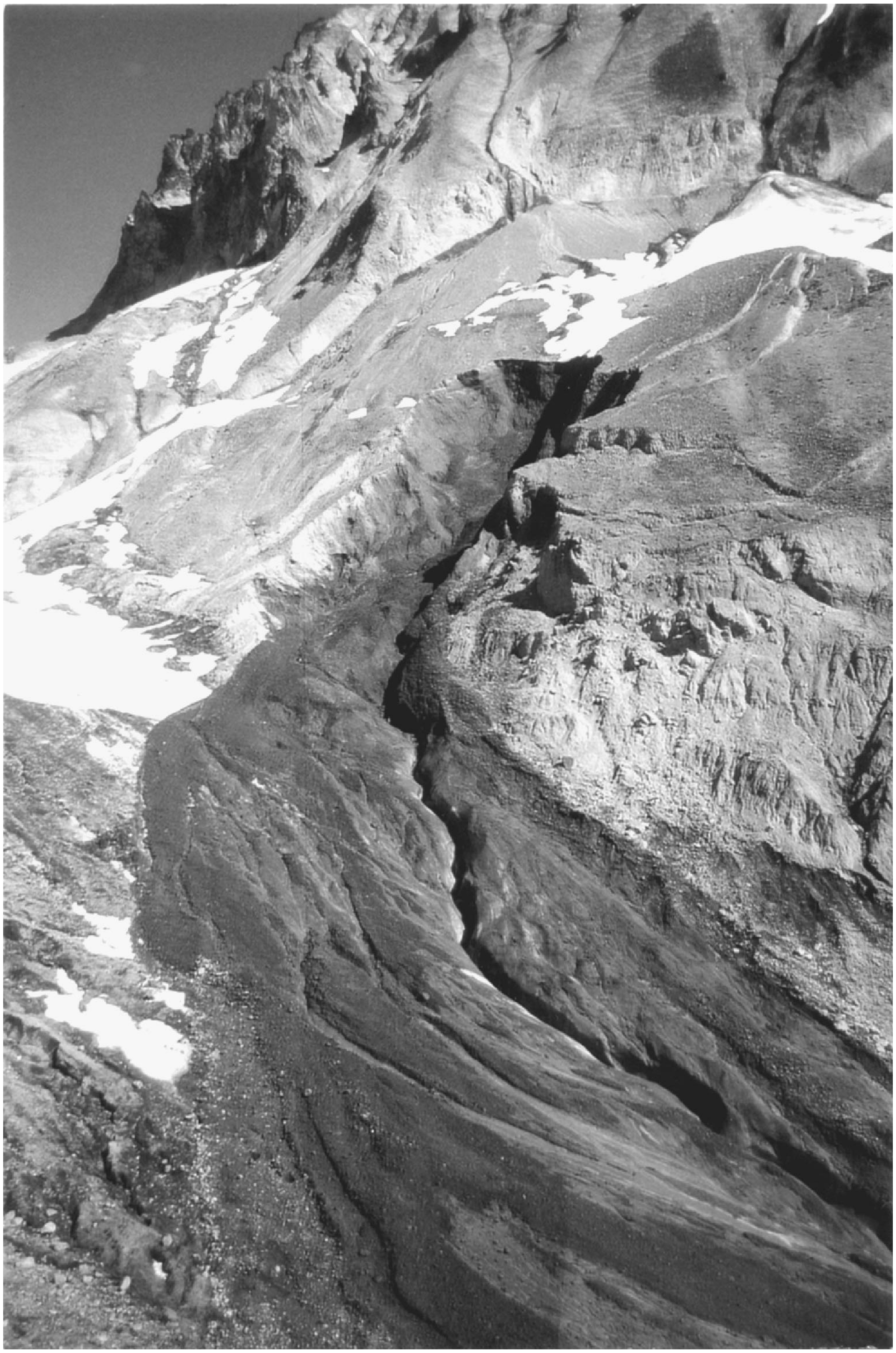


Fig. 3. Detachment zone of the 1998 debris flow on the south flank of Mount Meager. Note tension cracks and sackung features on the right side of detachment zone. Debris-covered Capricorn Glacier is in the foreground. The failure scarp is approximately 80 m across at its widest point. Photo taken August 2, 1998.



scribed in this paper). Entrainment of loose colluvial material adjacent to the channel accounts in part for the high magnitude of debris flow events in this basin.

Given the abundance of readily mobilizable material within Capricorn Creek basin, a relatively high frequency of mass movement events is expected. The basin is classed as transport-limited (Bovis and Jakob 1999), since debris supply is not a limitation on the frequency of events. Based on the tree-ring record, 13 major mass movement events have been documented within the basin over the past 330 years (Jakob 1996). Some of these events may have caused landslide impoundments of Meager Creek (Jordan 1987).

Fig. 4. Capricorn Creek confluence with Meager Creek showing the debris flow track, landslide dam, landslide-dam lake, and sediment loading by hyperconcentrated flows to lower Meager Creek. Photo taken August 2, 1998.

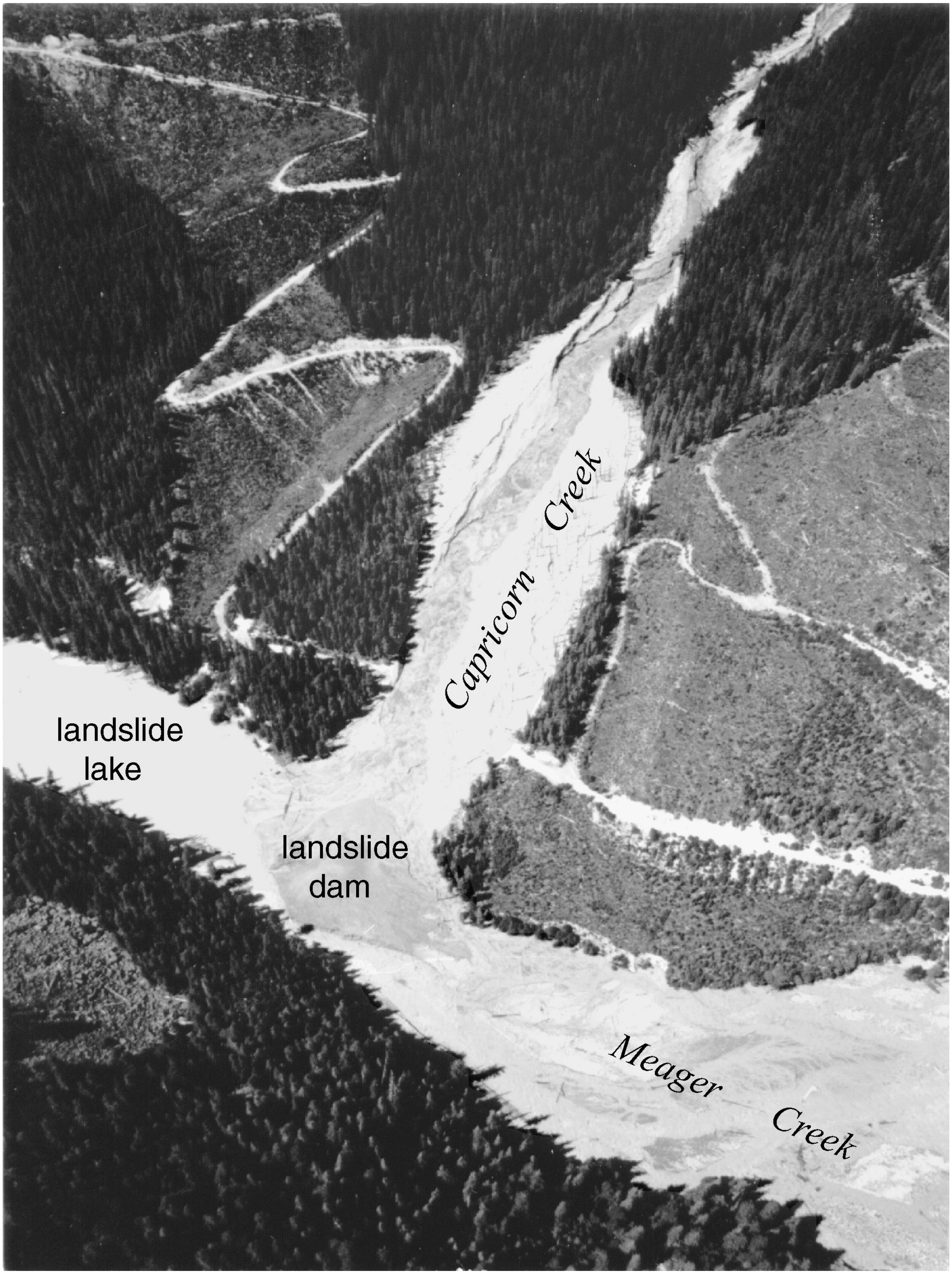
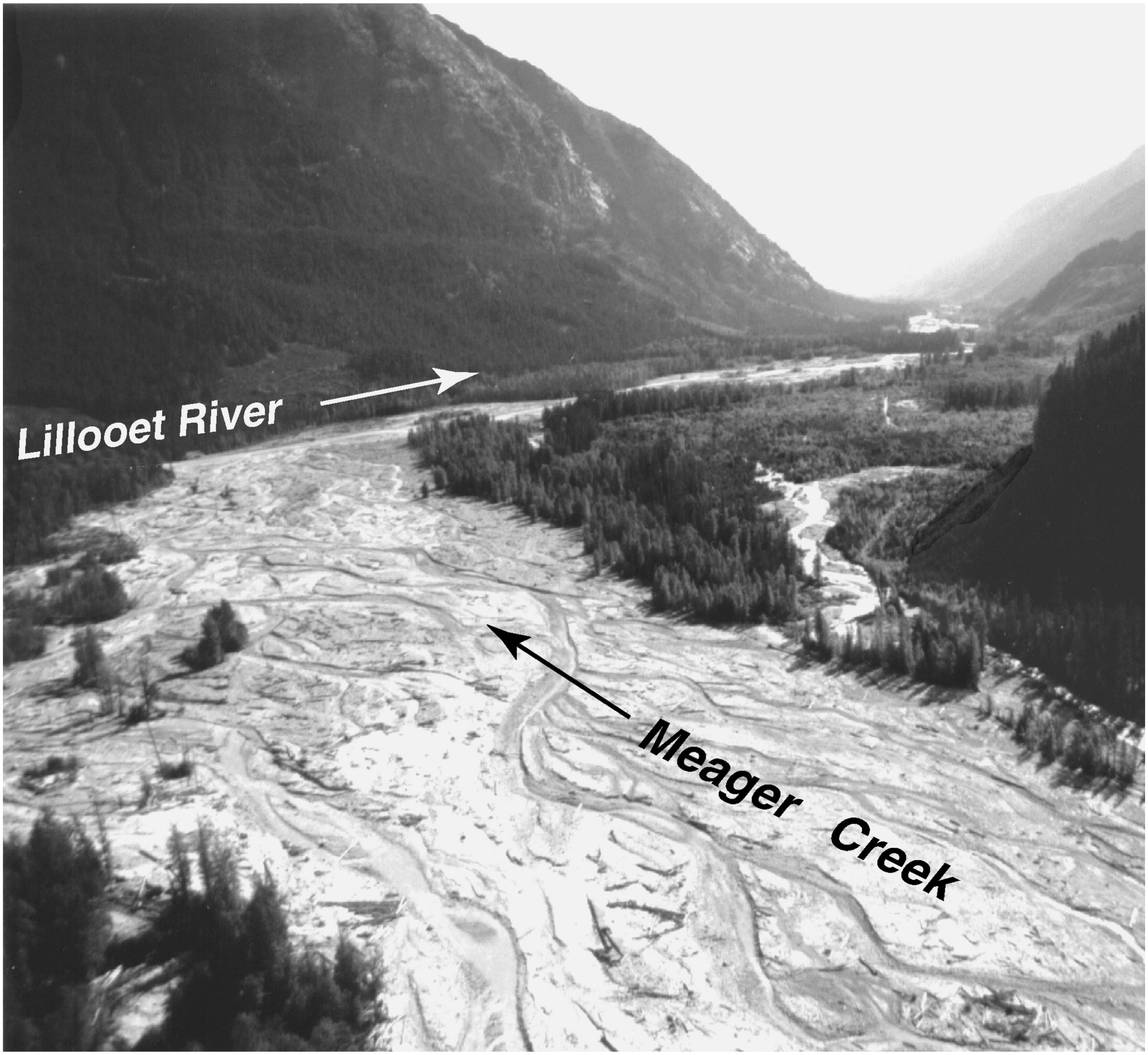


Fig. 5. Lower Meager Creek flood plain downstream of Capricorn Creek, showing extensive recent aggradation from hyperconcentrated flows and fluvial reworking of the July 1998 debris flow deposits. Lillooet River is at the foot of the steep slope in the background. Photo taken August 2, 1998.



The 1998 failure and debris flow event

Detachment zone conditions

The 1998 debris flow was triggered by a debris slide detachment of approximately 5.5×10^5 m^3 of colluvium from a 30–35° slope on the southwest flank of Mount Meager (Figs. 3, 7). The debris slide fell 200 m to the debris-covered surface of Capricorn Glacier, where large amounts of supraglacial debris, and probably water, were entrained. It is likely that the mass was fully developed as a debris flow within upper Capricorn Creek. The volume of the initial debris slide (length 240 m, depth 30 m, width 70 m) was determined by a hand-held laser rangefinder survey of the detachment zone. Ground inspection of the detachment zone walls revealed a crudely stratified deposit with a clast-supported, talus-like structure, consisting of rubble layers with relatively few fines sandwiched between blocky diamicton layers with matrix-supported structure (Fig. 8). The surface layer was a loose talus deposit, comprising volcanic clasts (porphyritic felsic to intermediate lavas and felsic tuffs) derived from the weathering of Mount Meager. This stratigraphy suggests a composite colluvial blanket composed of rockfall material, interspersed with debris flow diamictons.

The colluvial blanket adjacent to the 1998 failure zone is traversed by numerous tension cracks and antislope scarps (Figs. 2, 6). These features are commonly seen on steep bedrock and colluvial slopes in the Meager Creek area and have

Fig. 6. Double stereogram of upper Capricorn Creek based on 1994 air photographs (BCC 94102: 83–85) showing location of the 1998 detachment zone. Compare with Fig. 2. Prominent antislope scarps and tension cracks are accentuated with black toothed lines. Note cracks and scarps, and late-lying avalanche snow adjacent to the 1998 detachment, and debris flow gully descending from couloir C on the south flank of Mount Meager. The significance of this gully is discussed in the text. Areas R1 and R2 are rock avalanche detachment zones. Rock avalanche deposit D probably dates from 1933.

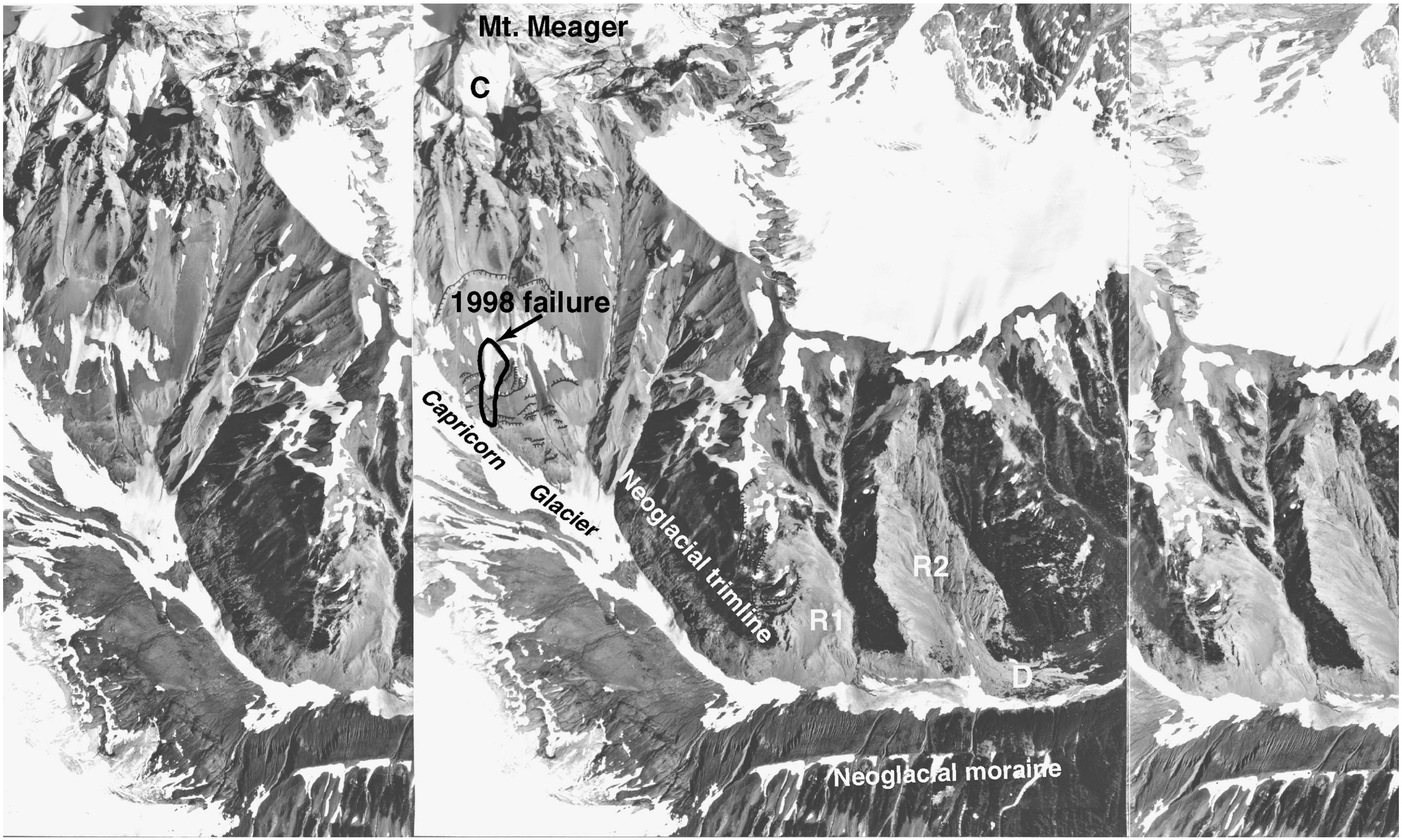
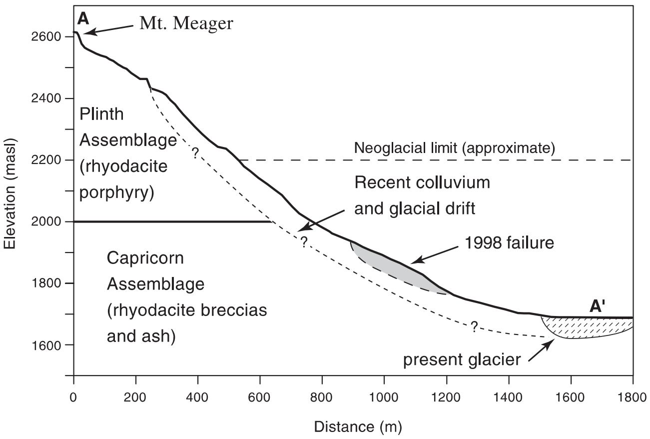


Fig. 7. Longitudinal profile of the 1998 landslide detachment zone showing bedrock and surficial geology and position of the failure relative to present and past glacial limits.



been attributed to slow, progressive slope movements of the “sackung” type (Bovis 1982, 1990; Bovis and Evans 1996). Many other debris slide, rock avalanche, and debris avalanche detachment zones in the region are flanked by similar sackung features, implying that progressive slope movements in both bedrock and colluvial materials are likely precursors to catastrophic failure. The available air photograph record indicates a progressive development of tension cracks and antislope scarps in the vicinity of the 1998 debris detachment zone. The earliest photographs from 1948 (BC 684: 79–80) show few obvious cracks adjacent to the failure site. By 1962 (BC 4085: 170–171), some cracks are visible, but the photographs are small scale and detailed features are not easily resolved. By 1973 (BC 7551: 56–58), many cracks and scarps had assumed approximately their present dimensions. These observations suggest that a 50 year period of progressive slope movements preceded the 1998 failure. The much lesser apparent development of scarps on the 1948 air photographs suggests that a prolonged period of negligible slope movements followed the commencement of glacial downwasting.

Climatic antecedent conditions

The July 29th debris flow was initiated at the peak of a prolonged heat wave that affected most of southern and central British Columbia in late July 1998. At Pemberton, a valley bottom site located 60 km southeast of Capricorn Creek, daily maximum temperatures were above 30°C in the period July 20–30, and just exceeded 40°C on July 26 and 27 (Fig. 9). Also shown in Fig. 9 is the temperature record from a rock slope monitoring site in upper Affliction Creek basin, at an elevation of 1700 m, 8 km northwest of the debris detachment zone. The single daily temperature readings at noon from this site are probably similar to the maximum daily temperatures prevailing in upper Capricorn Creek in the detachment zone (1800–1950 m elevation).

Given the relatively high temperatures at high elevation (Fig. 9, Affliction Creek record), snow melt would have contributed to groundwater recharge in the area of the failure. At the time of our August 2, 1998 field visit, snow covered about 30% of the upper basin area to a depth of approximately 50 cm. Although we have no on-site climatic records in upper Capricorn Creek, it is reasonable to conclude that groundwater recharge from accelerated snowmelt provided the final water pressure trigger for the failure.

It is probably not coincidental that the 1998 debris slide detachment zone lies within an area of late-lying avalanche snow (Fig. 6) and is directly downslope of a steep couloir basin on the south flank of Mount Meager (area C in Fig. 6). The 1998 detachment zone therefore lies within an area of natural runoff concentration, rendering it more prone than adjacent areas to the attainment of critical pore pressures.

Weather conditions similar to those of July 1998 also preceded the catastrophic July 1975 debris avalanche at Devastation Creek (Fig. 1), which claimed four lives. Figure 9 shows the striking similarity in temperature trends prior to each event. In 1975, a heat wave in early July probably caused extensive snowmelt in upper Devastation Creek basin. The failure occurred on July 24 during a second heat wave that had commenced on July 20, 1975.

Sedimentological characteristics of the deposit

We sampled the landslide dam deposit created by the debris flow at the Meager Creek confluence (Fig. 3) within two days of the debris flow’s occurrence, while the material was still in the undrained state and impossible to traverse on foot. Accordingly, sampling was conducted on the north margin of the debris flow deposit, in an area relatively unaffected by subsequent hyperconcentrated flows. The sedimentary characteristics of the deposit sampled at the time of our first site visit are, therefore, considered to be representative of material properties at the time of deposition. The material had physical properties similar to those of many other debris flow deposits (Table 1).

The main debris flow was followed by hyperconcentrated flows that were observed on August 2, 1998. These exhibited discharges estimated to have varied between 5 and 10 $m^3 \cdot s^{-1}$ over periods as short as one minute. Reconnaissance of upper Capricorn Creek basin showed that the hyperconcentrated flow surges were caused by debris flows originating from the newly formed landslide scar. A grab sample of hyperconcentrated flow, taken close to the peak of one of the surges in lower Capricorn Creek, yielded a suspended sediment concentration of 36% by volume. This value is typical of the transition between hyperconcentrated flow and debris flow (Pierson and Costa 1987).

Debris flow volume and peak discharge

An estimate of the debris flow volume was obtained from a detailed ground survey of the landslide dam and adjacent fan materials using a Geodimeter laser EDM system. A digital terrain model derived from this survey was compared with elevation data from 1994 air photography. Elevation differences between these two models provide an initial estimate of the volume of the 1998 event. However, this value is considered a minimum since the 1994 stereo model makes no allowance for post-1994 erosion by Capricorn Creek. (The well-incised channel through the fan was completely filled in and overtopped by the 1998 event). Because we have no topographic datum points for lower Capricorn Creek immediately prior to the 1998 event, an estimate of the pre-event fan morphology was obtained by computing an average annual rate of channel erosion by comparing terrain

Fig. 8. Section through stratified colluvium on the east flank of the 1998 landslide detachment zone. Person standing (indicated by arrow) gives scale. Photo taken August 2, 1998.

Fig. 9. Temperature trends prior to the 1998 Capricorn Creek and 1975 Devastation Creek landslide events.

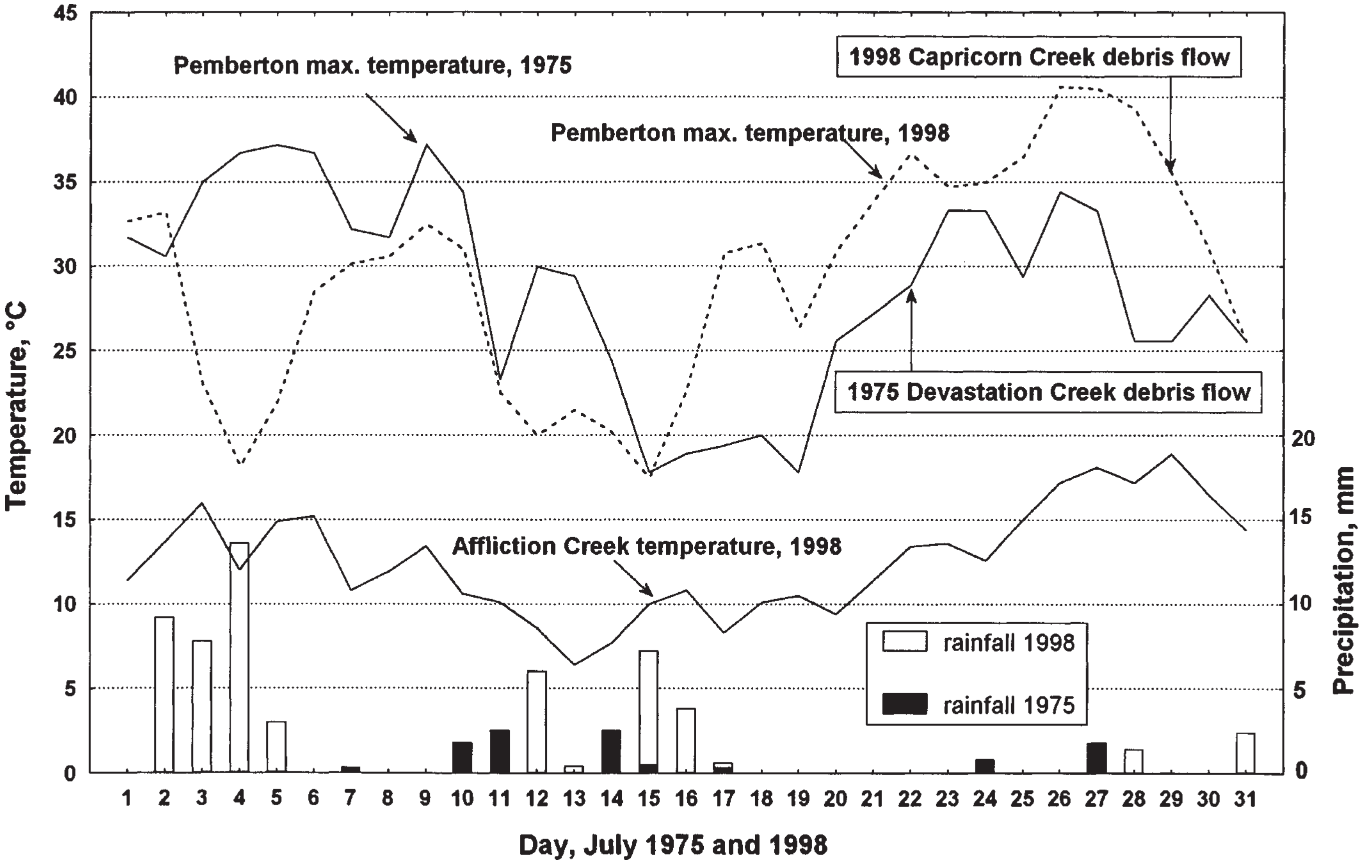


Table 1. Material properties of the 1998 debris flow deposit.

Volume conc. of solids (%)	Unit weight ($kN \cdot m^{-3}$)	% >8 mm	% 2–8 mm	% sand	% silt	% clay	Void ratio	Water %
70.1	20.5	8.3	24.3	52.1	12.5	2.8	0.43	12.6

Table 2. Channel yield rates for debris flows in southern British Columbia.

Location	Yield rate ($m^3 \cdot m^{-1}$)	Source
Capricorn Creek 1998	110	This paper
Hope Creek 1995	50	Jakob et al. (1997)
Hummingbird Creek 1997	28	Jakob et al. (In press)
Pierce Creek 1995	23	Jakob et al. (1997)
Mackay Creek 1995	10	KWL–EBA (1996)
Hope Creek 1984	8	Thurber Consultants Ltd. (1985)

Note: KWL–EBA, Kerr Wood Leidal Associates Ltd. and EBA Engineering Consultants Ltd.

models from 1990 and 1994 air photography. The net loss of 4×10^5 m^3 by channel erosion over this period represents 100 000 $m^3 \cdot a^{-1}$. Assuming a continuation of this rate in 1994–1998, the revised volume for the 1998 event would be 7.5×10^5 m^3 + 4×10^5 m^3 = 1.15×10^6 m^3. To this must be added the estimated 5×10^5 m^3 eroded from the landslide dam soon after its emplacement across Meager Creek, a figure derived from a laser rangefinder survey of the natural spillway cut through the dam. The total event volume is therefore estimated to be 1.2×10^6 m^3.

Estimates of the detachment zone volume, the total event volume, and the traveled distance of the flow permit calculation of a debris entrainment rate, or debris yield rate, along the channel ($m^3 \cdot m^{-1}$) (Hungr et al. 1984) (Table 2). Yield rates have been computed for numerous small gullies in the coastal belt of British Columbia for the purposes of estimating the impacts of timber harvesting on debris flow magnitude (Fannin and Rollerson 1993). However, relatively few such calculations have been made for large events in the Canadian Cordillera because of uncertainties about both the detachment zone and total event volumes (Hungr et al. 1984; Jakob et al. 1997, In press). The Capricorn Creek yield rate exceeds the previously measured highest rate by a factor of two (Table 2). The difference may be attributed to the large cross-sectional area of the 1998 Capricorn Creek debris flow and its relatively long travel distance. The longer the travel distance, the larger the wetted perimeter of the flow and the more material can be entrained. Our calculations for the Capricorn Creek event show that the entrained volume slightly exceeds the initial failure volume, an important ob-

Table 3. Peak discharge calculations for the 1988 debris flow.

Equation	Source	Velocity ($m\cdot s^{-1}$)	Cross-sectional area of flow (m^2)	Peak discharge ($m^3\cdot s^{-1}$)
$v = (1.21g\Delta H)^{0.5}$	Wigmosta (1983)	7	300	2100
$v = (R\ g\ \cos\beta\ \tan\alpha)^{0.5}$	Johnson (1984)	8	300	2400

Note: v, average flow velocity; g, gravitational acceleration; ΔH, super-elevation height; R, radius of channel curvature of flow at flow centre line; β, longitudinal channel slope; α, flow banking angle.

Table 4. Back-calculated peak discharges of debris flows in southern B.C.

Site	Event date	Calculated peak discharge ($m^3\cdot s^{-1}$)	Source
Meager Creek	1931	70 000	Jordan (1994)
Turbid Creek	1984	4 000	Jordan (1994)
Capricorn Creek	1998	2 300	This paper
Hummingbird Creek	1997	1 000	Jakob et al. (In press)
Pierce Creek	1995	740	Jakob et al. (1997)
Hope Creek	1995	640	Jakob et al. (1997)
Canyon Creek	1990	600	Jordan (1994)
Wahleach Creek	1984	570	Evans and Lister (1984)
No Good Creek	1992	500	Jordan (1994)
Mount Currie	1994	380	Jakob (1996)
Charles Creek	1983	340	Thurber (1983)
McLeod Creek	?	340	Jakob (1996)
Two Mile Creek	?	330	Jakob (1996)
Turbid Creek	1993	270	Jakob (1996)
Victor Creek	?	230	EBA (1999)
Tonkawatla Creek	?	230	EBA (1999)
M. Creek	1983	210	Thurber (1983)
Ferguson Creek	1995	180	Jakob (1996)
Clanwilliam Creek	?	160	EBA (1999)
Eagle Summit Creek	?	160	EBA (1999)
Eagle Pass #2 Creek	?	120	EBA (1999)
Charles Creek	1969	120	Thurber (1983)
Mackay Creek	1995	115	KWL–EBA (1996)
Charles Creek	1981	100	Thurber (1983)
Eagle Pass #1 Creek	?	90	EBA (1999)
Mica Sawmill Creek	?	90	EBA (1999)
Burner Creek	?	90	EBA (1999)
Newman Creek	?	85	Thurber (1985)

Note: EBA, EBA Engineering Consultants Ltd.; KWL–EBA, Kerr Wood Leidal Associates Ltd. and EBA Engineering Consultants Ltd.; Thurber, Thurber Consultants Ltd.

servation when considering likely volumes of future similar events.

The peak discharge of the main surge of the 1998 event was estimated by surveying debris flow lateral deposits along lower Capricorn Creek. The cross-sectional area of flow was adjusted for incision caused by hyperconcentrated flows subsequent to passage of the debris flow. Flow velocity was estimated from the banked super-elevation profile of the frontal surge as it deflected off the right bank. Flow radius of curvature and super-elevation were determined from a ground survey of lateral deposits on both sides of the flow (Table 3). The two discharge values (2100 and 2400 $m^3\cdot s^{-1}$), obtained from the two equations in this table, are in reasonably close agreement. The mean peak discharge of 2300 $m^3\cdot s^{-1}$ is among the largest values recorded in British Columbia (Table 4), being exceeded only by the 1931 Devastation Creek and 1984 Turbid Creek events (Jordan 1987). It is notable that the three largest events in terms of discharge are all derived from Quaternary volcanic complexes. These comprise relatively weak volcanic assemblages that are prone to deep-seated, high-magnitude failures. Such failures establish the high initial discharge rate required for entrainment of a large debris volume downstream of a detachment zone.

Record of historic and prehistoric debris flows in Capricorn Creek basin

Catastrophic mass movements of similar magnitude to the 1998 debris flow have occurred in the Meager Creek area several times in the past 70 years. Catalogues of these historic events, and even larger prehistoric events, have been compiled by Jordan (1994) and Jakob (1996). Other recent catastrophic events producing landslide dams in a wider Coast Mountains area are summarized in Clague and Evans

(1994). At Capricorn Creek, debris flows estimated to have exceeded 100 000 m^3 in total volume occurred in 1998, 1972, 1944–1945, and 1933–1934, yielding a remarkably short return period of 17 years for such large events (Jakob 1996).

The tree-ring record of debris impacts indicates that other large mass movements of unknown total magnitude occurred in 1909, 1903, 1873, 1850, 1841, and 1669 (Jakob 1996). To document such events, trees scarred by debris impact were sampled by cutting wedges or entire discs, which were then sanded and examined under a binocular microscope to determine the precise date of impact (Jakob 1996). Other events were inferred from coring trees that had suffered stress and growth reduction due to partial burial by debris. The same procedures were repeated with several trees of the same species to confirm the date of inundation. Comparisons were made with ring-width patterns in nearby control stands of trees unaffected by debris inundation. With these methods, it was possible to identify a total of 13 large events at Capricorn Creek over a period of 330 years, or one event per 25 years. Not all documented events are necessarily debris flows, since high-discharge debris floods (hyperconcentrated flows) may be partly responsible for both burial and scarring of trees.

It is worth noting that there is no general correlation between recent mass movement events from Capricorn Creek and the 100 year record of varved lake sedimentation in Lillooet Lake (located 80 river kilometres downstream of Meager Creek) (Gilbert 1975; Desloges and Gilbert 1994). This indicates that although Meager Creek and its tributaries probably dominate the delivery of coarse sediment to Lillooet River, the production of finer material from landslide point-sources apparently is not usually high enough to influence the basinwide sediment flux associated with autumn rainstorms and nival runoff.

A possible exception to this pattern is the 1932 lake sedimentation pulse identified by Desloges and Gilbert (1994, their Fig. 7*a*). This may be a delayed response to the very large 1931 debris flow event from Devastation Creek, which ran several kilometres along Meager Creek (Jordan 1987). Discharge of Lillooet River was anomalously low in 1932, which reduces the likelihood that the sediment peak was related to a basinwide runoff event. Since granitic materials underlie most of Lillooet River basin, detailed mineralogical analyses of Lillooet Lake sediments would help establish material provenance, in particular temporal variations in the flux of landslide-related volcanic materials from the Meager Creek area.

Glacial retreat as a factor in debris flow initiation

A well documented recession of temperate mountain glaciers has taken place in many mountain areas since the peak of the Little Ice Age readvance (Grove 1988). In the southern Coast Mountains of British Columbia, this is considered to have culminated in the mid- to late nineteenth century (Ryder and Thomson 1986; Ryder 1998). In the Mount Meager Volcanic Complex, glacial limits at the Neoglacial maximum can be traced from lateral moraines and distinct trimlines, the latter produced by glacial scouring of valley side slopes. Limit moraines and glacial trimlines indicate that approximately 44% of the Capricorn Creek basin was ice covered at the Neoglacial maximum, compared with only 20% in 1994.

Figure 2 indicates that the Little Ice Age Capricorn Glacier covered the area of the July 29, 1998 landslide scar. The landslide and subsequent debris flow could not have occurred until the area had become ice free several decades later (Fig. 6). Glacial retreat over the last 100 years has uncovered large areas of poorly consolidated thick colluvium and volcanic talus, and has also debuttressed many slopes along its retreat path. This effect has been noted previously in the region by Bovis (1982, 1990) and Evans and Clague (1994).

Little is known about the triggering mechanisms for older debris flow events within the Capricorn Creek basin. However, two large failures are clearly visible on the east flank of the basin (areas R1, R2, Figs. 2, 6) and represent detachment zones for rock avalanches within intrusive basement materials (Croft 1983; Jordan 1994). The most recent rock avalanche deposit (area D, Figs. 2, 6) probably dates from the early 1930s and may have triggered the 1933–1934 debris flow. Air photographs from 1948 (BC 684: 79–80) clearly show the poorly vegetated path of a large failure descending from zone R2. (The apparent freshness of the deposit D in Fig. 6 is caused by much more recent debris flow deposits derived from zone R2). The position of the Neoglacial trimline (Figs. 2, 6) indicates that the toes of zones R1 and R2 had previously been undercut by Capricorn Glacier. Thus, the R2 rock avalanche must postdate the Neoglacial retreat. Judging from the position of the glacier terminus on 1948 air photographs, it is reasonable to propose that both slopes had been glacially debuttressed well before the R1 rock avalanche event. This suggests a further connection between glacial retreat and large slope failures in Capricorn Creek basin. Both R1 and R2 are flanked by extensive systems of tension cracks and uphill-facing scarps, implying that future large failures are likely to detach from this highly deformed slope (Figs. 2, 6).

Within the Devastation Creek basin (Fig. 1), a similar pattern of catastrophic slope collapse has occurred over the past 70 years, involving steep glacially debuttressed slopes underlain by relatively weak volcanic rocks and unstable colluvium (Jordan 1987, 1994). As the Capricorn and Devastation glaciers continue to recede, increasingly large areas of unstable volcanic debris will be uncovered and rendered prone to landsliding. An increase in the frequency of catastrophic mass movements might therefore be expected over the next few decades.

There is some historical evidence of notable changes in river channel character in response to accelerated sediment production from basins tributary to Meager Creek. Jack Ronayne, a long-time resident of the Lillooet Valley near Pemberton, whose father took up residence there in 1900, reported that upper Lillooet River near the Meager Creek confluence was relatively stable and that Meager Creek was well confined between large stands of veteran cedars until about 1920. A cycle of channel instability then ensued causing significant aggradation along the Meager Creek flood plain. Although this information is anecdotal and cannot be fully relied upon, the apparent increase in sediment production from the Mount Meager complex after about 1920 could be accounted for by an increase in the rate of mass movement activity.

Conclusions

Catastrophic events such as the 1998 debris flow at Capricorn Creek have occurred several times in the past century, some causing landslide dams across Meager Creek. The high frequency of catastrophic landslides in the Meager Creek area can be attributed primarily to steep, glacially debuttressed slopes underlain by relatively weak volcanic formations and colluvial blankets. These factors render the Meager Creek area one of the most geomorphically unstable in Canada. At least two of the recent catastrophic events are known to have taken place during heat waves in midsummer, indicating that water pressure build up from snowmelt may be the most important contributory cause of failure.

Many detachment zones of recent large landslides in the Meager Creek area are flanked by systems of tension cracks and antislope scarps, suggesting long, premonitory phases of creep-type deformation that culminate in catastrophic detachment. Similar systems of cracks and scarps occur on many steep slopes in the Meager Creek area, indicating a potential for future catastrophic failures. As glacial retreat continues into the 21st century, perhaps at an accelerating pace, events of magnitude similar to the 1998 Capricorn Creek failure are likely to reoccur. This likelihood should be factored into ongoing plans to improve recreational facilities in the area, including the Meager Creek hot springs, which presently are accessible only via a gravel road across Capricorn Creek.

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