Large Holocene landslides from Pylon Peak, southwestern British Columbia

Pierre A. Friele and John J. Clague

Abstract: Mount Meager massif, the northernmost volcano of the Cascade volcanic belt, has been the site of very large (>10^7 m^3) landslides in the Holocene Epoch. We document two complex landslides at Pylon Peak, one of the peaks of the Mount Meager massif, about 7900 ^14C and 3900 ^14C years ago (about 8700 and 4400 calendar years ago). Together, the two landslides displaced ~ 6 x 10^8 m^3 of volcanic rock from the south flank of Pylon Peak into nearby Meager Creek valley. Each landslide consisted of at least two phases, an early debris flow resulting from failure of hydrothermally altered pyroclastic rock at mid levels on the mountain and a later rock avalanche from a higher source. Both debris flows likely traveled down Meager Creek, and preliminary evidence from drilling indicates the 4400-year-old event traveled down Lillooet River into areas that are now settled and where population density is increasing rapidly. The mobility of the debris flows was due to the high content of fine, weathered volcanic sediment and the availability of sufficient water. The causes of the landslides are a wet climate and the presence of weak, hydrothermally altered volcanic rock containing abundant phreatic water on glacially oversteepened slopes. The landslides may have been triggered by earthquakes or by upwelling of magma to shallow depths within the volcano. However, they may also have occurred without specific triggers following extended periods of progressive weakening of the volcanic rocks.

Résumé : Le massif du mont Meager, le volcan le plus septentrional de la ceinture volcanique de Cascade, a été le site de très gros (>10^7 m^3) glissements de terrain à l’Holocène. Nous documentons deux glissements complexes au sommet Pylon, l’un des deux sommets du massif du mont Meager, il y a environ 7900 ^14C et 3900 ^14C années (soit environ 8700 et 4400 années civiles). Ensemble, les deux glissements de terrain ont déplacé environ 6 x 10^8 m^3 de roches volcaniques du flanc sud du sommet Pylon dans la vallée du ruisseau Meager abovosinat. Chaque glissement de terrain comprenait au moins deux phases; en premier, une coulée de débris résultant de la défaillance, à mi-pente sur la montagne, de roches pyroclastiques ayant subi une altération phréatique, puis une avalanche de pierre d’une source plus élevée. Les deux coulées de débris ont probablement dévalé le ruisseau Meager; des évidences préliminaires de forages indiquent que l’évènement datant de 4400 ans a descendu la rivière Lillooet jusqu’à des endroits qui sont maintenant peuplés et où la densité de la population s’accroît rapidement. La mobilité des coulées de débris était due à la haute teneur en sédiments volcaniques, altérés et fins, et à la disponibilité d’une quantité d’eau suffisante. Les causes des glissements sont un climat humide et la présence, sur les pentes surraidées par la glaciation, de roches volcaniques, incompétentes, qui ont subi une altération hydrothermale et qui contenaient une grande quantité d’eau phréatique. Les glissements de terrain peuvent avoir été déclenchés par des tremblements de terre ou par des remontées magmatiques jusqu’à de faibles profondeurs à l’intérieur du volcan. Ils peuvent toutefois aussi avoir eu lieu sans déclencheurs spécifiques à la suite de longues périodes d’affaiblissement progressif des roches volcaniques.

[Traduit par la Rédaction]

Introduction

A chain of active and dormant stratovolcanoes marks the western fringe of the Cascadia subduction zone in the Pacific Northwest of the United States and Canada. These volcanoes represent a significant regional hazard because of their eruptive potential and because they are underlain by weak, hydrothermally altered volcanic rocks that are susceptible to failure (Finn et al. 2001). Many large, long-runout landslides originating on Cascade volcanoes have inundated valleys tens of kilometres from their sources, and some of the inundated areas now support large populations (Pierson 1985; Pierson and Scott 1985; Vallance and Scott 1997).

The Cascade volcanic chain in southwestern British Columbia includes three main volcanic centres: Mount Cayley, Mount Garibaldi, and Mount Meager (Fig. 1a; Green et al. 1988). Mountain valleys adjacent to these volcanoes are accessible by roads and are intensively used for forestry and recreation.


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Several large landslides have occurred on the western flank of Mount Cayley in historic time (Clague and Souther 1982; Cruden and Lu 1992; Evans et al. 2001), and small debris flows (<5 × 10^5 m^3) occur there regularly, disrupting access to the area. At least nine large landslides from Mount Cayley blocked Squamish River during the Holocene (Brooks and Hickin 1991; Evans and Brooks 1991). Floods caused by failure of the landslide dams, and recurrent, late Holocene landslides are responsible for channel instability downstream (Hickin and Sichingabula 1988, 1989; Cruden and Lu 1989).

Mount Garibaldi volcano and nearby vents were active at the end of the Pleistocene (Mathews 1952; Brooks and Friele 1992). The western flank of Mount Garibaldi erupted partly on ice and collapsed about 10,600 14C years BP during glacial retreat (Mathews 1958; Friele and Clague 2002a, 2002b). Pyroclastic deposits and lavas exposed on the deeply eroded flanks of the volcano periodically fail, generating large rock avalanches and debris flows (Moore and Mathews 1978; Clague et al. 2003).

Mount Meager volcano last erupted about 2400 years ago (Clague et al. 1995), blanketing nearby areas in pumice and sending ash as far east as Alberta (Nasmith et al. 1967).
Pyroclastic flows dammed upper Lillooet River, impounding a lake that later drained catastrophically (Evans 1992; Stasiuk et al. 1996). A large lahar associated with the eruption traveled at least 50 km downvalley along Lillooet River (Friele 2002; Simpson et al. 2003). Numerous large landslides have also occurred at Mount Meager in the historic period (Carter 1932; Mokievsky-Zubok 1977; Croft 1983; Evans 1987; Jordan 1987, 1994; Jakob 1996; Bovis and Jakob 2000). The high frequency of landslides in this area led Read (1981) to state that the Mount Meager massif may be the most active landslide area in the Canadian Cordillera.

Although much work has been done on modern debris flow processes at Mount Meager (Jordan 1994; Jakob 1996), no one has reconstructed the history of prehistoric landslide activity in the area. This paper describes deposits of two large postglacial landslides in Meager Creek valley (Fig. 1b) on the south side of the Mount Meager massif. The deposits were recognized by Read (1978, 1981) and Jordan (1994), but they did not accurately map, date, differentiate, or describe them. In this paper, we describe two distinct landslide deposits and reconstruct the events that produced them. Our study contributes to the growing body of literature on geologic hazards associated with volcanoes in British Columbia and elsewhere, and provides valuable data on geologic hazards for land-use decision makers.

**Study area**

Mount Meager (2650 m above sea level (asl)) is a dissected Quaternary stratovolcano with up to 2000 m of local relief (Fig. 1b). It was covered by the Cordilleran ice sheet for several thousand years at the end of the Pleistocene Epoch until the ice sheet disappeared about 10 00014C years ago (Friele and Clague 2002a, 2002b).

The study area is characterized by a coastal montane climate with warm summers and cool winters. Temperatures reach 25–35 °C during late July and early August when glacier and snow melt is greatest. Fall storms produce heavy and often prolonged rainfall. Precipitation in winter is dominated by snow, with average snow depths in April of 2–3 m at mid-elevation sites.

Intrusive rock of the Coast Plutonic Complex and pendants of metasedimentary rock underlie Quaternary volcanic rocks at Mount Meager (Woodsworth 1977; Read 1978, 1990). The basement rocks are extensively jointed and altered (Read 1990). The Devastator Assemblage contains abundant smectite (Table 1) and underlies most of the sites where landslides have occurred and where potential instabilities exist (Read 1978, 1990).

The oldest volcanic rocks include a basal breccia unit (PL1, Fig. 1b) and a porphyritic dacite unit (PL2, Fig. 1b), both of Pliocene age. The basal breccia unit is up to 300 m thick and consists of blocks of granitic, volcanic, and metamorphic rocks up to 20 m long in a tuffaceous matrix (Read 1978). The porphyritic dacite unit has a maximum thickness of 200 m and comprises subhorizontal lava flows.

The Pleistocene Devastator Assemblage (P1, Fig. 1b) overlies the Pliocene rocks. It is a yellow-ochre-weathering unit up to 500 m thick comprising intensively hydrothermally altered rhyodacite tuff, breccia, lava flows, and shallow intrusive rocks (Read 1980). The Devastator Assemblage contains abundant smectite (Table 1) and underlies most of the sites where landslides have occurred and where potential instabilities exist (Read 1978, 1990).

The Pylon Assemblage (P3, Fig. 1b) overlies the Pliocene rocks. It is a yellow-ochre-weathering unit up to 500 m thick comprising intensively hydrothermally altered rhyodacite tuff, breccia, lava flows, and shallow intrusive rocks (Read 1990). The Pylon Assemblage contains abundant smectite (Table 1) and underlies most of the sites where landslides have occurred and where potential instabilities exist (Read 1978, 1990).

The exhumed vent near Pylon Peak is drained by Angel Creek, which heads in a 1500-m-wide, hemispherical, south-facing scarp (Fig. 2). The scarp crest forms an ârête, with ice-filled cirques to the north and unglaciated landslide.

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Note: a, abundant; m, minor, tr, trace.

**Table 1.** Clay mineralogy of basal units of the two landslide deposits (M3 and M7) and Devastator Assemblage rock (DA-4, DA-5).

**Fig. 2.** Oblique view north to The Devastator and Pylon Peak, showing the Devastator Assemblage (P1) and lava flows of the Pylon Assemblage (P3).
basins to the east and west. Pylon Peak (2481 m asl) and The Devastator (2327 m asl) form high points on the arête.

**Methods**

The extent and surface expression of the landslide deposits in Meager Creek valley were determined through airphoto analysis and ground traverses. Geologic units were identified and then plotted on a 1:20000-scale topographic base map with 20-m contours. Most river and road-cut exposures in the valley were examined and recorded. Texture, colour, lithology, and clast angularity were logged for each geologic unit, and unit contacts were described. Samples were collected and analyzed for matrix texture (sand:silt:clay ratio), clay mineralogy, and age (14C and 36Cl). Clast lithology counts were made at some sites.

**Geology and geomorphology of the Angel Creek basin**

The landslide deposits described in this paper are derived from the Angel Creek basin (Figs. 2, 3). The basin has an area of 2.6 km² and is underlain by the basal breccia unit and the Devastator and Pylon assemblages. The volume of
rock missing from the basin is about $4.5 \times 10^8$ m$^3$, estimated by projecting contours across the basin from smooth slopes at its sides. About 70% (3.2 $\times 10^8$ m$^3$) of this volume are Pylon Assemblage rocks, 20% (9 $\times 10^7$ m$^3$) are Devastator Assemblage rocks, and 10% (4.5 $\times 10^7$ m$^3$) are the basal breccia. The Angel Creek basin is unglaciated, but it supports a small Neoglacial moraine, demonstrating that no significant landslides have occurred at the head of the basin since the end of the Little Ice Age in the late 1800s.

Hotsprings issuing from near 800 m asl in the Angel Creek basin (Figs. 1b, 3a) indicate the presence of a very high geothermal gradient in this area. Drilling results suggest that a geothermal plume is situated directly beneath the vent (Fig. 3); GeothermEx Inc. 2001). This plume is probably responsible for the intense hydrothermal alteration of the Devastator Assemblage rocks.

**Distribution and morphology of landslide deposits**

Landslide deposits derived from the Angel Creek basin extend along Meager Creek valley from 2 km above the confluence of Meager and South Meager creeks to at least Lillooet River (Fig. 1b). The full downstream extent of the deposits is unknown, as Lillooet River has aggraded its floodplain during the Holocene (Jordan and Slaymaker 1991), burying landslide materials derived from the Meager Creek basin.

The Angel basin landslide materials comprise two morphologically distinct deposits. Each deposit appears to consist of two distinct units, which we term the basal and surface units. The basal units are similar in character, although different in age. The surface units are lithologically similar but sedimentologically distinct.

The older landslide deposit (unit A8; Figs. 1b, 3) has an undulating to hummocky, inclined surface sloping, on average, 7° to the northwest. Individual hummocks are steep-sided with up to 20 m of local relief. At the southeast edge of the deposit, a thin layer of volcanic landslide debris extends 75 m up the slope separating Barr and Hot Springs creeks to a prominent, 300-m-long, 10-m-wide bench at 910 m asl (Fig. 3). To the northwest, Meager Creek has deeply incised the deposit, forming bluffs 100–140 m high. The deposit can be traced upstream to near Angel Creek. It may have extended farther upstream but was eroded or is covered by more recent fan deposits of No Good and Boundary creeks. The deposit has also been dissected by Hot Springs Creek, and only two remnant ridges of landslide debris rise above the surface of the Hot Springs Creek fan. No deposits of the older landslide have been found east of Hotsprings Creek. The landslide probably flowed into this area, but its deposits have been eroded by Meager Creek.

The second large landslide deposit (unit A4; Figs. 1b, 3) is inset in a stream-cut channel eroded into the older deposit. It extends from the lower reach of South Meager Creek to Lillooet River. At the confluence of Meager and South Meager creeks, the deposit forms smooth, paired terraces at about 720 m asl, which slope 1°–3° downstream (Figs. 4, 5). The terrace on the north side of Meager Creek grades into the rising slope of the Angel Creek fan, whereas the terrace on the south side of the creek abuts the higher, hummocky surface of the older landslide deposit. The terraces extend 2 km upstream along South Meager Creek from its mouth. They stand about 10 m above South Meager Creek just upstream of Barr Creek, but are 70 m above the creek at its confluence with Meager Creek. The terraces drop in elevation downvalley along Meager Creek (Fig. 4). Below Canyon Creek, they delineate a smooth surface 10–20 m above Meager Creek that can be traced downstream to Lillooet River. The surface gradient of the terraces is slightly steeper than that of the modern channel along this reach, resulting in a progressively lower scarp downstream.

**The older landslide deposit: instability 8700 years ago**

**Stratigraphy and sedimentology**

A slump at location M3 (Fig. 6) provides the best exposure of the older landslide deposit. Other river cuts (M5, M6, and M9) and road cuts on the surface of the deposit provide supporting detail.

**Meager Creek section 3 (M3)**

A slump 800 m downstream from the confluence of Meager and South Meager creeks (Fig. 6) has created a 135-m-high section through the older landslide deposit (Figs. 7, 8). Seventeen metres of compact, matrix-supported, polymictic diamicton (basal unit, Figs. 7b, 9a) are exposed at the base of the section. Particle-size analysis of the matrix of the diamicton yielded sand:silt:clay ratios of 53:45:2 and 63:25:12. The clay-size fraction contains abundant chlorite, kaolinite, and smectite, and minor illite (Table 1). Clasts range from pebble to boulder size and are angular to rounded. About 70% of the stones are volcanic and 30% are derived from basement rocks. The unit also contains abundant comminuted wood. Three wood samples yielded radiocarbon ages of 7920 ± 100 (GSC-6511), 7940 ± 90 (GSC-6598), and 8480 ± 80 14C years BP (TO-9559; Table 2).

The basal diamicton is overlain by 118 m of lithologically banded (Figs. 7, 9b), matrix-supported, sandy diamicton consisting entirely of volcanic detritus (source rock units P1 and P3). Clasts range from pebble to mega-gravel size (see Blair and McPherson 1998 for expanded textural classification) and are angular in shape. The lowest 27 m of the unit has a yellow- to cream-coloured matrix and contains zones of finely brecciated, granular to pebbly granitic debris and thinner
bands of red and grey, porphyritic andesite debris. A sample of the diamicton matrix yielded a sand:silt:clay ratio of 74:21:5. The upper 91 m of the unit consists of alternating bands of red and grey, porphyritic andesite debris with a few bands of yellowish debris. Samples of matrix yielded sand:silt:clay ratios of 84:15:1 and 78:21:1. Two large, grey andesite blocks on a hummock at the surface of the deposit gave ^{36}Cl surface exposure ages of 6 and 7.5 ka (Terry Swanson, personal communication, 2002).

The contact between the two units is not well exposed at section M3, but was observed in a gully 50 m upstream (Fig. 10). At the gully site, the compact polymictic diamicton is overlain successively by andesitic debris, yellow debris, and a sliver of polymictic diamicton. The sequence is the reverse of that at the base of section M3. The yellow debris has a steeply inclined, sharp contact with the underlying andesitic debris, which we interpret to be a thrust fault. Deformed bands within the yellow material also suggest shear.

**Other sections**

The basal unit at section M3 is also exposed at section M5 at the confluence of Meager and South Meager creeks (Fig. 6). At section M5, compact, matrix-supported polymictic diamicton contains comminuted wood and a large log. Outer rings of the log yielded a radiocarbon age of 8120 ± 70 14C years BP (GSC-6474), and a wood fragment gave an age of 8020 ± 70 14C years BP (TO-8837; Table 2).

Sections M6, M8, and M9 (Fig. 6) provide exposures of lithologically banded debris of the older landslide. Section M6 is the largest of these exposures, with about 60 m of...
cream-coloured volcanic debris unconformably overlain by 10 m of andesitic debris of the younger landslide deposit (Fig. 11).

**Landslide volume and surge velocity**

We estimate that the older landslide deposit covered an area of about 5.5 km$^2$ prior to incision and erosion. We base this estimate on the mapped distribution of the deposit, both on surface and stream-cut exposures. The deposit is more than 140 m thick along Meager Creek between South Meager and Hotsprings creeks. It thins toward the valley sides, as seen in exposures along Barr Creek. The average thickness of the deposit is probably 50–80 m, which gives a volume of 3–4 \times 10^8$ m$^3$.

As previously noted, a veneer of andesitic landslide debris extends upslope 75 m from the main debris surface to a prominent bench on the Barr Creek – Hotsprings Creek divide (Fig. 3c). Above the bench, the hillslope is mantled by till. The debris veneer and bench are a surge deposit (Hewitt 1999). Total run-up is about 100 m, measured from the base of the debris exposed along Barr Creek. Application of the velocity head equation, \( V = (2gh)^{0.5} \), where \( g \) is gravitational acceleration and \( h \) is run-up (Chow 1959, p. 152), suggests a surge velocity of 44 m s$^{-1}$, consistent with velocities reported for other rock avalanches in the region (e.g., Clague and Souther 1982).

**Interpretation**

The clay mineralogy, matrix texture, ratio of non-volcanic and volcanic lithologies, and presence of matrix-poor, fragmental lenses suggest that the basal unit of the older landslide deposit is a mixture of the basal breccia (PL1) and Devastator Assemblage (P1). The overlying lithologically banded unit comprises angular, sandy rhyodacitic and andesitic debris. Altered, light green, cream, and yellow-banded debris at the base of the lithologically banded unit is derived from the basal breccia (PL1) and Devastator Assemblage (P1). This debris is overlain by red- and grey-banded, porphyritic andesite debris of the Pylon Assemblage (P3). The vertical sequence of lithologies in the older landslide deposit thus is the same as the sequence of rock units in the Angel Creek basin (Fig. 3).

The basal unit is matrix-supported and contains mainly subangular to subrounded clasts, some rounded clasts (Fig. 9a), and abundant comminuted wood. These observations suggest that the debris flowed, rounding clast edges, incorporating and grinding vegetation, and entraining channel gravel. The source of the unit is hydrothermally altered, vent-filling rocks in the lower part of the Angel Creek basin.

Overlying the basal flow unit is a wedge of Devastator Assemblage debris that thickens towards Angel Creek (it is at least 60 m at sites M6, M8, and M9 versus 27 m at M3). Between sites M3 and M6, the top of the debris wedge has an apparent slope of 2.5°. This is a minimum estimate because...
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*Laboratories: GSC, Geological Survey of Canada, Ottawa, Ontario; TO, IsoTrace Laboratory, University of Toronto, Toronto, Ontario.

*bLaboratory-reported uncertainties are 1σ for TO ages and 2σ for GSC ages. Ages are normalized to δ13C = −25.0‰ PDB (PeeDee Belemnite).

cDetermined from atmospheric decadal dataset of Stuiver et al. (1998) using the program CALIB 4.1. The range represents the 95% confidence limit calculated with an error multiplier of 2.
the debris was eroded during formation of the Angel Creek fan. Thickening of the debris towards Angel Creek suggests that a block of Devastator Assemblage rocks slid into the valley.

In contrast, overlying debris derived from Pylon Assemblage rocks appears to thicken away from the source (0 m at M6, 90 m at M3). Distal thickening, lithologic banding, preservation of source rock stratigraphy, and the angular shape of most of the clasts suggest movement as a rock avalanche. This interpretation is supported by evidence of shear at the contact between the basal and surface units at sites M3 and M5, the hummocky surface morphology, and the run-up between Hot Springs and Barr creeks.

The basal breccia and Devastator Assemblage are implicated in the initial failure (Read 1978; Finn et al. 2001). Because of the presence of the hydrothermal plume at shallow depth beneath the Angel Creek basin, the rock mass probably had a high phreatic water content. The saturated rock mass may have liquefied at the narrow mouth of the basin, allowing it to flow shortly after movement commenced (Iverson et al. 1997). Alternatively, it may have transformed into a flow after it slid into the valley of Meager Creek. A portion of the 300-m-thick Devastator Assemblage slid en masse into the valley on the heels of the flow. This material was then overridden by avalanching debris from the destabilized summit. The rock avalanche achieved a velocity of up to 44 m s⁻¹ and surged 100 m up the valley wall opposite the source area. Thus, we infer a complex landslide event (terminology after Turner and Schuster 1996, p. 53), involving flow of the stratigraphically lowest rocks, followed by sliding of the middle unit, and rock avalanching at the end.

Five radiocarbon ages on wood fragments collected from the basal unit of the older landslide deposit range from 7920 to 8480 ¹⁴C years BP (Table 2). Because all five ages are wood fragments, they do not necessarily record the time of death of the shrub or tree and should be viewed as maximum ages for the landslide. Thus, the youngest of the ages, 7900 ¹⁴C years BP (ca. 8700 calendar [cal.] years ago), is closest to the time of the landslide.

The apparent surface exposure age of the deposit is 6000–7500 years old. We regard the ³⁶Cl ages as minima because post-depositional weathering of the dated volcanic blocks would render the ages younger than they should be. The lack of evidence for pedogenic weathering or fluvial reworking of the top of the basal unit suggest that the basal unit and the overlying lithologically banded debris are close in age and probably were deposited during one large, multiphased landslide.

The younger landslide deposit: instability 4400 years ago

Stratigraphy and sedimentology

Key exposures of the younger landslide deposit are located near the confluence of South Meager and Meager creeks (SM3, SM4, and M7) and in lower Meager Creek Valley (M1 and M2) (Fig. 6). These sections and a section at Hot Springs Creek are described in the following sub-sections.
South Meager Creek sections 3 and 4 (SM3 and SM4)

The section at site SM4 (Fig. 8), located 120 m upstream of the confluence of Meager and South Meager creeks, is about 60 m high. The lowest 3 m of exposed sediment is matrix-supported, polymictic diamict containing comminuted wood fragments and lenses of matrix-poor granitic fragments. Clasts are dominantly subangular to subrounded and pebble to small boulder in size. A wood fragment from this unit yielded a radiocarbon age of 4060 ± 50 14C years BP (TO-9561; Table 2). The basal unit is sharply overlain by 4.5 m of normally graded sand and silt. Wood fragments from the upper part of the sand–silt unit yielded an age of 4160 ± 50 14C years BP (GSC-6445). The graded sand–silt unit is overlain across an erosional contact by 1.2 m of normally graded, medium to coarse sand containing rip-up clasts of silt. The uppermost unit at SM4 is 40 m of matrix- to clast-supported, angular to subangular debris. It extends to the terrace surface at 718 m asl. Clasts in the debris are up to 10 m across and are composed of about 80% andesite and 20% non-volcanic lithologies.

At site SM3, which is on the opposite side of South Meager Creek from SM4, wood from a silt rip-up within a normally graded, medium to coarse sand bed yielded a radiocarbon age of 4120 ± 80 14C years BP (GSC-6453; Table 2). The sand is overlain by about 50 m of rubbly and blocky debris (Fig. 9c) consisting of about 90% andesite and 10% non-volcanic clasts. Particle-size analysis of the matrix yielded a sand:silt:clay proportion of 77:19:4.

Meager Creek section 7 (M7)

Site M7 is next to Meager Creek, 500–600 m upstream of the mouth of South Meager Creek (Fig. 6). Three slumps at this site provide additional exposure of the sediments underlying the terrace at the Meager – South Meager confluence (Figs. 8, 12a).

The lowest unit at site M7 consists of 5 m of hydrothermally altered, yellow debris. Its upper contact is sharp and irregular, with up to 10 m of relief. This unit is overlain by 24 m of compact, clast- to matrix-supported, polymictic diamict containing wood fragments, branches, and large logs. The outer rings of a log yielded a radiocarbon age of 4090 ± 60 14C years BP (GSC-6476), and a wood fragment was dated at 4080 ± 60 14C years BP (GSC-6466; Table 2). Clasts are subangular to subrounded and are about 81% volcanic and 19% non-volcanic lithologies. A sample of the matrix had a sand:silt:clay ratio of 57:39:4. Clay mineral analysis indicates the presence of abundant illite, chlorite, kaolinite, and smectite (Table 1).

The diamicton is overlain by 1–2 m of gravel, consisting of granitic pebbles, cobbles, and small boulders. This gravel bed is sharply overlain by 5 m of fining-upward, horizontally stratified, pebble–cobble–boulder gravel of dominantly volcanic
provenance (Fig. 12b). Above this is about 18 m of weakly stratified, clast-supported, cobble–boulder gravel with sand interbeds.

**Hotsprings Creek section 1 (H1)**

Section H1 is a road cut adjacent to the river bank at the forestry bridge over Hotsprings Creek. Up to 2 m of laminated and bedded silt and sand fill depressions on a surface underlain by angular to subangular, andesitic landslide debris. A sample of charcoal collected from a 1-cm-thick, charcoal-rich bed 20 cm above the base of the silt–sand unit yielded a radiocarbon age of 3440 ± 70 14C years BP (T0–8364; Table 2).

**Meager Creek sections 1 and 2 (M1 and M2)**

The sections at sites M1 and M2 expose sediments underlying paired terraces that extend downstream from Canyon Creek to Lillooet River. The lowest exposed unit at site M2, near the mouth of Canyon Creek, consists of 13 m of compact, matrix-supported, polymictic diamicton with a silt–sand matrix and abundant wood (Fig. 8). A sample of the wood yielded a radiocarbon age of 4320 ± 60 14C years BP (TO-8836; Table 2). The basal diamicton is overlain by 6 m of massive, poorly sorted, matrix-supported diamicton. This upper diamicton has a higher clast content and a sandier matrix than the basal diamicton. The outer rings of two logs in the upper diamicton were radiocarbon dated at 3930 ± 70 (GSC-4211) and 4080 ± 70 14C years BP (GSC-4207; Table 2). The upper diamicton is conformably overlain by a 2-m-thick, upward-coarsening unit of laminated silt, cross-stratified sand, and horizontally bedded gravel. Charcoal from a silt bed at the base of this unit was radiocarbon dated at 4040 ± 70 14C years BP (T0–8354; Table 2).
upward-coarsening unit yielded a radiocarbon age of 4760 ± 100 14C years BP (TO-8365; Table 2).

The section at site M1, which is 1 km west of the mouth of Capricorn Creek, has the same basal, polymictic diamicton as the section at site M2. Wood from the basal diamicton at site M1 yielded a radiocarbon age of 4050 ± 70 14C years BP (TO-8364) is a minimum age for the event. Thus, the landslide happened sometime between 3400 and 3900 14C years BP, most likely about 3900 14C years BP (4400 cal. years ago).

The closest radiocarbon ages from the two units of the younger landslide are statistically the same, thus the two units may have been deposited in quick succession. At several sites, however, stratified sediments separate the two units. At site SM4, for example, about 6 m of sand and silt separate the basal and surface units, and at site M1, stratified gravel separates the basal landslide unit from andesitic debris interpreted to be the surface unit. Similarly, at site M7, sand and well bedded, pebble–cobble gravel lie between the basal unit and a weakly bedded, poorly sorted boulder gravel. The gravels at sites M1 and M7 are interpreted to be fluvial sediments deposited when the basal unit was reworked by Meager Creek immediately after it was deposited. The stratigraphy implies that some time elapsed between deposition of the two landslide units, although how much is unknown. The interval, however, is too short to be resolved through radiocarbon dating; it could be hours to decades.

The sediments just described were deposited by a complex landslide about 4400 years ago. Like the landslide that occurred 4000 years earlier, it began as a failure of the basal, vent-filling rocks in the Angel Creek basin. The initial failure rapidly transformed into a large debris flow that reached the mouth of Meager Creek and traveled down Lillooet River valley (see Discussion). After the initial failure, silt and sand accumulated in local ponds on the debris, and the debris flow deposits were reworked by Meager Creek. Within hours to decades, part of Pylon Peak collapsed, producing a rock avalanche that filled the area at the confluence of Meager and South Meager creeks with up to 50 m of debris. The rock avalanche transformed into a debris flow that moved up South Meager Creek and down Meager Creek past Canyon Creek.

The younger landslide deposit, prior to incision and erosion, covered an area of at least 4.4 km². The base of the deposit is exposed at only a few sites, and its full downstream extent is unknown, consequently it is difficult to obtain a reliable estimate of the volume of the deposit. A minimum volume of $2 \times 10^8$ m³ is obtained by multiplying a conservative average thickness of 45 m by the minimum area of 4.4 km².

## Discussion

The rocks underlying The Devastator and Pylon Peak are the source of at least two, very large, complex landslides during the Holocene. The landslides produced the Angel Creek basin,
a cirque-like amphitheatre extending from 1600 m asl to the summit of Pylon Peak at 2286 m asl.

Using stratigraphic, sedimentologic, and morphologic evidence, we argue that each landslide was a multiphase event, involving a huge debris flow followed by a rock avalanche (Fig. 14). The debris flow phase of the first and larger landslide occurred about 7900 \(^{14}\)C years BP (8700 cal. years ago). Exposure ages on boulders on the surface of the rock avalanche provide a minimum age of 7500 \(^{14}\)C years BP for that phase. No evidence exists for a hiatus between the debris flow and rock avalanche phases, and we tentatively conclude that they occurred in rapid succession. The initial failure of hydrothermally altered rock at the middle level of the mountain likely destabilized the flow-layered rocks forming the summit cone, inducing an immediate collapse.

The debris flow and rock avalanche phases of the younger landslide occurred about 3900 \(^{14}\)C years BP (ca. 4400 cal. years ago). Stratified gravel and laminated silt locally separate the deposits of the debris flow and rock avalanche phases, indicating that some time elapsed between them. However, the two phases are not resolved by radiocarbon dating, suggesting that the hiatus was short, on the order of hours to decades. Although we recognize that this event comprises two discrete phases, we prefer to view the two phases as a single complex event. Again, it is logical to infer that initial failure of hydrothermally altered materials at mid-mountain level debuttressed higher slopes, thus triggering a rock avalanche. The Hope Slide (Mathews and McTaggart 1978) is an historical example of a landslide involving two closely spaced collapses, the second of which was triggered by the first (Weichert et al. 1994).

The downstream extent of these two landslides is presently poorly understood, but we have preliminary data that suggest the 4400-year-old debris flow traveled at least 40 km downstream from the confluence of Meager Creek and Lillooet River (Friele 2002; Simpson et al. 2003). Given the large area of the Mount Meager massif underlain by hydrothermally altered rock, similar large landslides may be expected in the future. The causes, triggering mechanisms, volumes, and rheology of landslides contribute to the severity of the downstream hazard and are discussed in the following sub-sections.

Potential causes and triggers

A number of factors may have contributed to the failures at Pylon Peak: climate-mediated phenomena (Church and Ryder 1972; Bovis and Jones 1992; Evans and Clague 1999); earthquakes (Mathews 1979; Clague and Shilts 1996); volcanism (Mokievsky-Zubok 1977; Bovis and Jakob 2000; see also Chleborad 1997). Increased soil pore-water pressures associated with rainstorms or snowmelt may have triggered these failures, but the cause of recent instability is a combination of weak rocks (Read 1978, 1990; Finn et al. 2001) and glacial debuttressing (Evans and Clague 1999; Holm et al. 2004). Some prehistoric landslides on the north side of the Mount Meager massif were triggered by the 2400-year-old eruption (Evans 1992; Stasiuk et al. 1996). However, no landslide deposits of this age have been found in Meager Creek valley and no other eruptions are known to have occurred during the Holocene. However, magma may have moved to shallower depths beneath the Meager massif prior to the landslides ca. 4400 and 8700 years ago, causing increased circulation of hot fluids in the vent area beneath Pylon Peak and triggering earthquakes. Alternatively, the landslide ca. 4400 years ago may have resulted from increased precipitation following the onset of Neoglaciation (Bovis and Jones 1992). The landslides may have occurred, however, without any specific trigger in response to progressive weathering and gradual weakening of the altered rock mass.

Volume estimates

The volume of missing rock from the Angel Creek basin is estimated to be 4.5 \(\times 10^8\) m\(^3\). A small amount of the missing rock may have been excavated by cirque glaciers and flushed out of the basin by small debris flows, but most of the material has been removed by large landslides. The missing volume is a maximum for the combined volume of the two complex landslides derived from the Angel Creek basin. Dilation of a rock mass due to fragmentation during a landslide can increase the volume of debris by 30%–60% (Turner and Schuster 1996, p. 42). Taking dilation into account, we estimate the volume of the debris to be 6–7 \(\times 10^8\) m\(^3\). This estimate compares favourably with our estimate of the volume of landslide deposits in Meager Creek valley of about 6 \(\times 10^8\) m\(^3\). This last estimate, however, may be a minimum, because the base of the landslide deposits is not exposed and the downstream extent of the deposits along Meager Creek is unknown. The older landslide appears to have been approximately twice the size of the younger one. Considering the proportions of basal breccia and Devastator Assemblage rocks in the basin, it is possible that the debris flow phase of each event involved roughly 1 \(\times 10^8\) m\(^3\) of debris.

Rheology of the basal debris flow units

The mobility of debris flows is partly determined by their clay content (Pierson 1985; Jordan 1994). Jordan (1994) suggests that a matrix clay content of 5% by weight separates coarse-grained debris flows from more mobile, fine-grained ones. Particle-size analysis shows that the clay contents of the basal debris flow units and the overlying rock avalanche deposits are similar, typically 3%–10% (Fig. 13). However, the proportion of silt and sand differs, with the basal debris flow units containing 25%–45% silt and 50%–65% sand, and the rock avalanche units containing 15%–25% silt and 70%–85% sand. The debris flow units, while generally having sufficient clay for high mobility, are silt-rich rather than clay-rich.

A water content of 10%–20% by weight or as little as 25% by volume is required for debris to maintain sufficiently low viscosity to flow over long distances (Pierson 1985; Costa 1988; Jordan 1994). Large debris flows may incorporate their water from phreatic sources (Vallance and Scott 1997), from snow and ice melt during eruptions (Pierson and Scott 1985), or by impounding streams (Carter 1932). The water source for the basal debris flow units described in this paper is unknown. Since each of the basal debris flows may have had a volume of 1 \(\times 10^8\) m\(^3\) or more, at least 2.5 \(\times 10^7\) m\(^3\) of water would be required for mobilization. Glacier ice is not
a probable source of the water because glaciers would have been present only at high elevations 8700 and 4400 years ago and would have been incorporated into the rock avalanche debris, not the debris derived from altered volcanic rocks lower on the slope. Although there is no direct evidence for it, a reservoir impounded by a landslide dam may have provided some of the required water. However, given the presence of a hydrothermal plume, phreatic waters may have been the source of much of the water that mobilized the debris flows 4400 and 8700 years ago.

**Downstream hazards**

Debris flows like those documented in this paper may pose a hazard to people living in the Lillooet River valley as far away as Pemberton. Examples from other areas illustrate this hazard. The Osceola Mudflow flowed at least 120 km from its source on Mount Rainier volcano in Washington state about 5600 years ago (Vallance and Scott 1997), filling valleys in Puget Lowland and greatly extending the deltas of the Puyallup and Green rivers into Puget Sound. Numerous lahars were triggered by the eruptions of Mount St. Helens in May 18, 1980 (Pierson 1985) and March 19, 1982 (Pierson and Scott 1985). The Pine Creek and Muddy River lahars (Pierson 1985) were unconfined flows at distances up to 10 km from the crater; farther downstream they were channelized and flowed 25 km to the Swift Creek Reservoir. The Toutle River lahar, triggered by a breach of the crater lake during the 1982 eruption, flowed 27 km before transforming into a hyperconcentrated flow that ran 83 km downstream from the crater (Pierson and Scott 1985).

The debris flows described in this paper, although not triggered by eruptions, were sufficiently large and mobile to travel many kilometres. Iverson et al. (1998) established a relationship between deposit volume (V) and the planimetric area (B) of the deposit outside the proximal hazard zone:

\[ B = 200V^{2/3} \]

Applying eq. [1], to a lahar of volume 1 \( \times 10^8 \) m\(^3\) yields an inundation area of between 10\(^2\) and 10\(^3\) m\(^2\) at the 95% confidence limits of the prediction (Iverson et al. 1998, Fig. 6). If we assume the downstream limit of the 8700-year-old rock avalanche deposit is the limit of the proximal hazard zone, Lillooet River valley might have been inundated 12–65 km downstream from Mount Meager by a 1 \( \times 10^3 \) m\(^3\) debris flow (Fig. 14) originating from near Pylon Peak. Preliminary evidence from extensive drilling along Lillooet River valley indicates that at least three lahars originating from somewhere in the Mount Meager volcanic complex did reach the now-settled portion of the valley during the Holocene (Friele 2002; Simpson et al. 2003). One of these lahars has been tentatively correlated with the 4400-year-old event (Simpson et al. 2003).

**Conclusion**

Volcanoes at the eastern margin of the Cascadia subduction zone, which extends from northern California to southern British Columbia, have been sites of numerous large landslides during the recent geologic past. The Mount Meager massif may be one of the least stable areas in British Columbia, the site of at least three landslides larger than one million cubic metres in the last century alone.

We have documented two landslides from the Mount Meager massif that are two orders of magnitude larger than any of the historic events, one about 4400 years ago and the other about 8700 years ago. The landslides occurred in weak, hydrothermally altered, Pliocene–Pleistocene volcanic rocks on the south side of Pylon Peak. Together, the landslides deposited about 6 \( \times 10^8 \) m\(^3\) of debris in the valley of Meager Creek adjacent to, and downstream from, Angel Creek. The deposits of each of the two landslides are similar, consisting of a basal silt-rich diamicton deposited by a debris flow and an overlying, more sandy, blocky diamicton deposited by a rockslide or rock avalanche. Lithologic analysis suggests that the debris flows originated in brecciated and hydrothermally altered volcanic rocks within the vent of Pylon Peak. In contrast, the source of the rock avalanche deposits is the less altered, flow-layered rocks forming the mountain peak. The debris flows may have traveled tens of kilometres from their source due to their relatively high water content and fine matrix. The source of the water is not certain, but may have been phreatic in origin.

Neither landslide was triggered by a volcanic eruption, despite an eruption about 2400 years ago. Perhaps movements of magma at shallow depth, accompanied by earthquakes, caused the failures. Alternatively, the landslides may have climatic causes or may simply have occurred due to progressive deterioration of slopes under the influence of gravity without a specific triggering event. Flank collapses like those 4400 and 8700 years ago, although rare, may pose a hazard to people and property in the Lillooet River valley 32–74 km downstream from Mount Meager.

Eruption-triggered lahars can be predicted by monitoring the volcano, but lahars that are not caused by eruptions probably cannot be forecast. Continued retreat of glaciers will further debuttress altered volcanic rock slopes, increasing the potential for mass failure. Given the rapid expansion of the town of
Fig. 14. Schematic depiction of the debris flow and rock avalanche phases of the two large Pylon Peak landslides. The extent of the rock avalanche deposit defines the proximal hazard zone. The debris flows reached Lillooet Lake at times when the delta front was much farther upvalley, and thus closer to the mouth of Meager Creek, than today (Friele 2002). A similar debris flow today would likely extend into the settled portion of the Lillooet River valley.

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