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Influence of a large debris flow fan on the late Holocene evolution of Squamish River, southwest British Columbia, Canada

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Abstract

Cheekye Fan is a large paraglacial debris flow fan in southwest British Columbia. It owes its origin to the collapse of Mount Garibaldi, a volcano that erupted in contact with glacier ice near the end of the Pleistocene Epoch. The fan extended across Howe Sound, isolating a freshwater lake upstream of the fan from a fjord downstream of it. Squamish River built a delta into this lake during the Holocene. We use 28 radiocarbon ages to describe the final infilling of the lake and the subsequent evolution of the Squamish River floodplain over the past 3300 years. These events are recorded in fine-grained lacustrine, wetland, river channel and overbank sediments exposed in the banks of Squamish River over a distance of more than 10 km upstream of the fan. We link these deposits to construction, persistence, and eventual degradation of the dam formed by Cheekye Fan and a smaller inset fan formed by Cheakamus River, into which Cheekye River flows. The coupled Cheekye Fan – Squamish River floodplain system is similar to other low-gradient valley floors upstream of fans such as at Tulare Lake, California, and Alexandra River in the Canadian Rocky Mountains. Future debris flows and landslides in the headwaters of Cheekye River are likely to continue to affect base level on lower Squamish River. We speculate that future aggradation of Cheekye Fan would cause increased flooding and sediment deposition upstream of this barrier. These landscape linkages should be included in future land-use planning in lower Squamish River valley.

Key words: Quaternary geology, alluvial fans, fan-impounded lakes, fluvial geomorphology, base level, Squamish River, Cheekye Fan

1 **Introduction**

2 The form and type of valley fill deposits in formerly glaciated regions are strongly influenced
3 by external forcing factors such as sediment supply and local base level change caused by
4 catastrophic impoundment or alluvial fan aggradation. These factors influence hazards faced
5 by people living in mountain valleys, and they also drive hypotheses about the origins of
6 montane valley fills. Alluvial fans in mountainous regions can have a substantial influence on
7 upstream deposits, causing gradient reduction; in extreme cases, they may impound lakes
8 upstream. In the Canadian Rocky Mountains, reaches of Alexandra and Columbia rivers
9 upstream of large alluvial fans have low-gradient anastomosing channels with floodplains
10 dominated by fine-grained sediments (Smith and Smith 1980; Smith 1983; Makaske et al.
11 2002, 2009). Smith (1972) noted that vertical accretion of the floodplain of Alexandra River
12 is related to recent aggradation on a downstream alluvial fan. Atwater et al. (1986) examined
13 a sequence of alternating lacustrine and floodplain sediments in Tulare Lake in California in
14 relation to activity on the alluvial fan that impounds the lake. They concluded that changes in
15 the height of the dam at the lake outlet were responsible for the alternation of lacustrine and
16 fluvial facies, and that sediment delivery to the fan controlled the dam height and was itself
17 controlled by Pleistocene glacier activity in the nearby Sierra Nevada. Alluvial fan control on
18 base level forcing upstream lake formation has also been described in the Andes (Colombo
19 2005), and is clearly a global, if little described, phenomenon. Alluvial fans in formerly
20 glaciated regions are commonly paraglacial landforms and therefore record a changing pattern
21 of sediment delivery from formerly glaciated watersheds.

This paper describes the stratigraphy and sedimentology of late Holocene sediment exposed on the banks of Squamish River, upstream of Cheekye Fan, the largest debris flow fan in southwestern British Columbia. We interpret these sediments in relation to the construction of Cheekye Fan in the early Holocene and incision by Squamish River during mid- and late Holocene time. We argue that infilling of a lake upstream of the fan and incision of the barrier at the toe of Cheekye Fan are controlled by a balance between sediment supply to the fan, upstream sediment supply to the lake, and the ability of Squamish River to erode the barrier. The level of the fan barrier is therefore related to the paraglacial history of the fan and the magnitude of sediment delivery from the Cheekye River watershed. Because alluvial fans are common features in other glaciated valleys, this study is relevant to understanding the history of valleys in formerly glaciated landscapes and the likely response of upstream fluvial environments to continued fan activity.

Geographic and geologic context

Squamish Valley

Squamish River drains an area of 3600 km² in the southern Coast Mountains of British Columbia (Figure 1). Discharge is highly seasonal, driven by precipitation and snowmelt. Annual precipitation in the Squamish River watershed is more than 2000 mm, and much of it falls during winter as snow at higher elevations. Snowmelt-driven freshet flows during late spring and early summer are 400–700 m³/s at the Water Survey of Canada gauging station near Brackendale (08GA022); low flows from January to March are 30–80 m³/s. The highest peak discharges, between 1000 and 3000 m³/s, are associated with rain-on-snow cyclonic

1 storms, most commonly in the fall (Figure 2). Approximately 11% of the watershed is
2 covered by snow and glacier ice (Brooks 1994).

3 Squamish River occupies a broad, steep-walled glaciated valley incised into Cretaceous
4 granodiorite and older metavolcanic and metasedimentary rocks (Monger and Journeay 1994).

5 The watershed contains two large Plio-Pleistocene stratovolcanoes: Mount Cayley near the
6 confluence of Squamish and Elaho rivers, and Mount Garibaldi just northeast of Squamish
7 (Figure 1). The Garibaldi volcanic complex shows extensive evidence of ice-contact
8 eruptions, as do several eruptive centres in the Mt. Cayley complex (Hickson 2000; Kelman et
9 al. 2002). The west cone of Mt. Garibaldi is formed of pyroclastic deposits that were erupted
10 onto the surface of the downwasting Cordilleran ice sheet (Mathews 1952; Green et al. 1988).

11 The upper reaches of Mamquam valley, east of Squamish were ice-free about 14,000 years
12 ago, and the Squamish Valley glacier had retreated to the present-day head of Howe Sound by
13 12,800 years ago (Friele and Clague 2002a). Glaciers briefly readvanced during the Younger
14 Dryas chronozone between 12,600 and 11,700 years ago (Friele and Clague 2002b) and had
15 retreated past the Cheakamus-Squamish confluence by 11,900 years ago (Friele and Clague,
16 2002a).

17 Ancestral Howe Sound extended far up-valley of its present head at the end of the Fraser
18 Glaciation, possibly to somewhere between Mt. Cayley and Ashlu Creek. Squamish River at
19 that time was a sediment-laden proglacial stream that was rapidly building a delta southward
20 into the fjord. Sediment was likely supplied by downwasting glaciers in the upper Squamish,
21 Elaho, and Ashlu Creek watersheds, and by later exhumation of valley fills left by these
22 glaciers (Brooks 1994). Hickin (1989) used records of suspended sediment in the Squamish

River to estimate that the delta front of Squamish River was about 30 km upstream of its present location near the mouth of Ashlu Creek 6000 years ago and had reached Cheekye Fan by about 3000 years ago.

Formation of Cheekye Fan

Cheekye Fan began to form as soon as lowermost Squamish Valley was deglaciated. Downwasting and retreat of the Squamish and Cheakamus valley glaciers destabilized pyroclastic deposits on the west side of Mt. Garibaldi volcano, causing them to collapse into the headwaters of Cheekye River east of Cheekye Fan and form kettled ice-contact benches between 12,800 and 11,500 years ago (Mathews 1952; Friele and Clague 2002b). The lowermost Cheekye River watershed was ice-free by about 11,900 years ago, allowing the river to rework the collapsed ice-contact deposits to the east and initiate construction of Cheekye Fan (Friele et al. 1999; Friele and Clague 2002a). Cheekye River began to build a fan-delta into Howe Sound at this time, forming foreset beds that are visible in ground-penetrating radar (GPR) profiles up to 45 m above present sea level (asl) (Friele et al. 1999). The delta continued to prograde across the fjord while the land rose due to glacio-isostatic rebound. By about 7500 years ago, the fan reached the west side of the fjord, isolating a lake upstream of the fan from the ocean to the south (Hickin 1989; Friele and Clague 2005). Relative sea level at this time was probably about 5–10 m lower than it is today (Clague et al. 1982; Shugar et al. 2014).

Base level of the lake upstream of Cheekye Fan was controlled by the depositional history of the fan and migration of the channel of Cheekye River, which supplied sediment to the west

margin of the fan. The bank of modern Squamish River in that area exposes a paleochannel that was buried by debris flow deposits after 7000 years ago (Eisbacher 1983; Friele and Clague 2005). At that site, the fan surface is at about 24–25 m asl, and the paleochannel is approximately 10–11 m below it at about 13–14 m asl. Debris flows travelling down this channel would have extended across the valley and impounded Squamish River. Once the channel reached the western valley wall, additional debris flows caused the channel to aggrade to the elevation of the present fan surface. A reasonable estimate of the elevation of the barrier is about 20–22 m asl, assuming a slight westward decline in elevation (Figure 3A).

Farther up the fan, at the site of the Squamish landfill, five debris flows (Ékes and Friele 2003; Friele and Clague 2005; location shown in Figure 4) filled a mid-Holocene paleochannel. The obstruction probably caused Cheekye River to avulse northward to its present confluence with Cheakamus River sometime after 5000 years ago (Friele and Clague 2005). Since that time, debris flows have routed into Cheakamus River just above its confluence with Squamish River. A flux of volcanic sediment from Rubble Creek, a tributary of Cheakamus River (Moore and Mathews 1978; Clague et al. 2003), together with sediment delivered by Cheekye River itself resulted in the building of a small fan-delta into the lake north of Cheekye Fan. A reconstruction of the land surface around the present Cheakamus-Squamish confluence indicates that this fan would also have impounded the river at about 20–22 m asl (Figure 3B).

Cheekye Fan contains about $1.6 \times 10^9 \text{ m}^3$ of sediment, of which about $1.4 \times 10^9 \text{ m}^3$ were deposited between 12,000 and 7500 years ago (average $3.3 \times 10^5 \text{ m}^3/\text{yr}$), and $2 \times 10^8 \text{ m}^3$ were deposited after 7500 years ago (average $3 \times 10^4 \text{ m}^3/\text{yr}$) (Friele et al. 1999; Friele and Clague

2009). Today, Cheekye River delivers about 1.8×10^4 m³/yr of sediment to Cheakamus River (Friele and Clague 2009). The exponential decline in sediment yield in the Cheekye basin through the Holocene fits the primary exhaustion model of sediment delivery in smaller paraglacial watersheds (Ballantyne 2002; Friele and Clague 2009).

Methods

The character and age of sediments exposed in the banks of Squamish River upstream of Cheekye Fan are based, respectively, on detailed descriptions of precisely mapped and georeferenced stratigraphic sections (locations shown in Figure 4) and radiocarbon ages. We measured elevations of the tops of stratigraphic sections using a dual-frequency differential GPS system in base station and rover configuration, and measured contacts and unit thicknesses with a survey tape, a laser rangefinder, and a clinometer. Ages of sedimentary strata are based on radiocarbon-dated in-situ roots, logs, sticks, stumps, and charcoal. The samples were dated at the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine. We calibrated raw radiocarbon ages using CALIB 7.0.4 and the IntCal13 calibration curve (Stuiver and Reimer 1993; Reimer et al. 2013; Stuiver et al. 2017). Radiocarbon samples are listed in Table 1 and are discussed throughout the text. As a convention, we refer to the calibrated two-sigma age range, species of the dated sample (if known), sample number, and elevation in the text. We interpreted depositional environments based on lithology (grain size, composition, and sorting), sedimentary structures, bed and unit contacts, colour, the presence or absence of organic matter, and types of plant macrofossils. Plant macrofossils were identified under a

stereoscopic dissecting microscope using commonly available keys for plants in the Pacific Northwest (Hitchcock et al. 1969; Taylor 1983; Robertson 1984; Pojar and MacKinnon 2004). We identified indicator species using the manuals of Klinka et al. (1989) and MacKenzie and Moran (2004).

Representative sediment samples were collected from several sections to validate field assignments of grain size. We measured the grain-size distribution of the samples using a Malvern Mastersizer 2000 laser particle-size analyser. The lateral extent of deposits on the floodplain was confirmed mostly by riverbank mapping, but was supplemented with several short GPR profiles collected using a pulseEKKO 100 system with 50 MHz and 100 MHz antennae. We collected GPR profiles with 0.5 m (50MHz) and 0.25 m (100MHz) spacings, and used common-offset transects to determine radar stratigraphy and common mid-point soundings to determine wave velocities through the sediments of interest.

Character and distribution of sediments

Sediments exposed on the banks of Squamish River were divided into six lithofacies based on sedimentology and preserved plant fossils. A general overview of the facies relative to modern high water river level is shown in Figure 5. The facies are briefly summarized below.

Facies 1: Organic-rich silt and peat (sections A, E, I, J, L, and M)

Facies 1 consists of olive grey silt interbedded with brown, mostly fibric, peat layers (Figure 6a). The unit is exposed on the banks of Squamish River near section A, on the west bank of the river from just south of section B to slightly south of section E, and continuously from section J past section L. Non-peaty organic-rich silt occurs at section M. An east-oriented

GPR profile near at this location reveals flat-lying beds underlain by high-impedance, low-resistivity sediment (Figure 7). Silt layers are typically 1–2 cm thick and rarely >5 cm thick; peat layers are up to 35 cm thick.

Where it is found, facies 1 extends to the waterline and is at least 2.0–4.5 m thick. Its lower contact is not exposed, although it may be underlain by thin-bedded organic poor silt (facies 2). It is overlain across a gradational contact by fine-grained sand (facies 4) or interbedded sand and silt (facies 6). Near fans, the unit may be incised and backfilled by channelized sand, pebble gravel, or diamicton (facies 4, 3, and 5 respectively). At sections E and L, peat and silt deposition is interrupted by channelized gravel and diamicton deposits. The unit extends up to 22.5 m asl at section A near the northern limit of its distribution, about 23.1 m at section E, and 19.0–20.0 m asl downstream at sections I, J, and L.

Macrofossil samples from sections L, E, and A include sedge seeds (*Carex livida*, *C. canescens*, *C. aquatilis*), *Comarum palustre* seeds, and herbaceous rhizomes and stems.

Nodular, woody roots from wetland trees are present at sections I and J. Samples from section A contained seeds of the wetland plant *Menyanthes trifoliata*. Samples from sections A and L contained trace conifer seeds and needles (*Thuja plicata* and *Picea sitchensis*).

Detrital wood collected near the low-water line has ages between 2746–2716 cal yr BP (*Thuja plicata*, sample L5, 15.9 m asl) and 2770–2746 cal yr BP (sample E6, 18.2 m asl). Wood collected below the waterline at section A was dated to 3227–3080 cal yr BP (18.8 m asl, *Taxus brevifolia*, sample A1). This sample may have come from facies 1 or from facies 2 below, as we were not able to directly observe the deposits. A rooted stump at section E returned an age of 2116–1997 cal yr BP (*Picea sitchensis*, sample E5, 19.7 m asl). The

youngest dated peat deposits are 1228–1067 cal yr BP at section J (sample J2, 19 m asl) and 961–927 cal yr BP at section A (sample A3, 23.5 m asl). Other radiocarbon ages from facies 1 range from about 2710 to 1190 cal yr BP and are listed in Table 1.

Facies 2: Thin-bedded to laminated organic-poor silt (sections N, R, T, W, and AK)

Mottled silt with some thin sand interbeds is exposed in riverbanks in the southern part of the study area (Figure 6b). Strata typically are 0.5–2.0 cm thick. Some strata are gently folded. The facies is exposed in a 2-km-long stretch of riverbank from about 700 m north of section T to section AK. An isolated exposure of similar sediment about 1.7 m thick is present at section R about 4 km up-valley.

Exposures of facies 2 generally extend to about 50 cm above the low-water level of Squamish River (about 15–16 m asl), although the facies is present up to approximately 20 m asl at section R. The base of the facies is everywhere below river level and thus not exposed. Facies 2 is typically overlain across a gradational contact by stratified fine-grained sand, which in turn grades into interbedded sand and silt. North of section T, facies 2 is overlain by blocky colluvium near the west valley wall.

The oldest dated deposits of facies 2 are located below the waterline at section T (3363–3247 cal yr BP, *Picea sitchensis*, sample T2, 13.6 m asl). Charcoal collected near an inferred contact between facies 4 and 2 yielded ages of 2101–1949 and 2037–1929 cal yr BP (sample W11, 16.9 m asl and sample T4, 17.8 m asl, respectively). A *Picea sitchensis* stump rooted in facies 2 at section T returned an age of 2282–2044 cal yr BP (sample T1, 15.5 m asl). Other radiocarbon ages from facies 2 range from about 2700 to 2120 cal yr BP (Table 1).

Facies 3: Coarse gravel (sections B, E, G, and Z)

Beds of crudely stratified, clast-supported gravel with a coarse sand matrix are the lowest exposed sediments in riverbank exposures in most riverbank exposures north of section A, and on the east bank of the river between sections B and G (Figure 8a). Clasts are pebble- to cobble-size, sub-rounded to well-rounded, and mainly of granitic composition. At section E, gravel with subangular clasts fills a channel incised into older sediments (Figure 8b). Cobble/boulder gravel of mainly volcanic lithologies (dacite and basalt) occurs up to about 17.2 m asl at section Z, and in a gravel pit on the floodplain about 1 km north of this section (Figure 8c). At section Z, Squamish River is constrained by this gravel on the east and by granitic bedrock with water-worn alcoves on the west. Some of these alcoves contain rounded volcanic boulders like those found on the east bank of Squamish River in this reach.

Facies 4: Stratified and massive fine to medium-grained sand (all sections except E, R, and L)

Facies 4 consists of horizontal (Figure 8a) to inclined (Figure 8d) beds of well-sorted, fine to medium sand. The beds are typically 10–20 cm thick, but some range up to 40 cm in thickness. In individual outcrops, the facies is commonly 1–2 m thick and overlies facies 1 or 2 across a gradational or erosional contact. Sedimentary structures include ripples, trough cross-beds, and inclined planar cross-stratification. Some beds contain rust-coloured mottles and root casts. A GPR profile near section B (Figure 9) shows an eroded channel filled with flat to gently-sloping sand beds.

Charcoal recovered from facies 4 at section W returned an age of 2101–1949 cal yr BP (sample W2, 16.9 m asl). Charcoal near the contact between facies 2 and 4 at section T yielded an age of 2037–1929 cal yr BP (sample T4 17.8 m asl). Sediments at the contact between facies 4 and interbedded silt and sand of facies 6 at section AK yielded an age of 2296–2042 cal yr BP (sample O3, 17.5 m asl). A log at the contact between facies 3 and facies 4 at section G is essentially modern (284–1 cal yr BP, sample G6, 21.1 m asl). We found a stone bowl in an anthropogenic hearth feature at section W; charcoal adjacent to the bowl returned an age of 1554–1415 cal yr BP. The bowl was located in the river bank about 3 m below the present floodplain surface (Figure 11b). Reimer et al. (2016) discuss the archaeological significance of the bowl.

Facies 5: Diamicton with coarse sand matrix (section L and several other areas on the west bank of the river)

Weakly stratified, matrix-supported diamicton with angular to subrounded granitic cobbles and boulders and abundant woody debris is exposed at section L (Figure 10). Similar boulder deposits overlie facies 2 silt at several unmapped sites on the west bank of the river. All exposures are associated with tributary valley fans. The diamicton matrix is mainly sand, but includes silt, granules, and small pebbles. The facies is up to 2 m thick in channels and at some sites forms a surficial veneer or blanket. Facies 5 has erosional basal contacts and sharp contacts with overlying units.

Facies 6: Horizontal, interbedded sand and silt (all sections)

Beds of fine to very fine sand separated by thin laminae and beds of silt and organic remains are the uppermost facies in the riverbank sections we studied (Figure 11a). Stratification in the sediments near the surface of the floodplain has been destroyed by the roots of conifers and deciduous trees. Facies 6 ranges from 3 to 5 m thick; sand beds are 2–20 cm thick, and silt beds are 0.5–4 cm thick.

Facies interpretation

The six facies described above represent four environments: shallow lake or ponds, low-lying lake-fringing wetlands, fluvial channel and overbank environments, and alluvial and colluvial fans, as explained below.

Shallow lake or ponds

The oldest and lowest sediment documented in this study is organic-poor silt of facies 2 exposed between sections T and AK. Facies 2 sediment at section R is higher than that between sections T and AK, but is undated. We infer that the silt of facies 2 was deposited in a shallow lake or ponds that were either deep enough or had sufficiently high inputs of silt that vascular plants could not become established. Folds in the strata are caused by syndepositional slumping and dewatering, which are common processes in a lacustrine prodelta environment. Because most exposures of facies 2 are near one another, they likely record a single former lake. Facies 2 at section R, farther upstream, may be an erosional remnant of sediment deposited in this lake when the outlet was higher (at least 20 m asl), or it

may record deposition in a separate channel-marginal pond on an aggrading delta or floodplain. No foreset beds were observed in facies 2 sediments, which suggests that the lake was too shallow to accommodate them (e.g., Eilertsen et al. 2011) at the time the sediments were deposited (3363–3247 cal yr BP). Flood-tolerant *Picea sitchensis* trees were growing on the former lake bed by about 2282–2044 cal yr BP. Younger silty sediments likely accumulated in shallow ponds or abandoned channels on a low-gradient floodplain; they are overlain conformably or disconformably by stratified sand, possibly deposited during levee breaches.

Our inferred age of final infilling of the lake is close to the earlier estimate provided by Hickin (1989) of 3000 ± 825 years ago. Assuming that infilling occurred simultaneously from Cheakamus River on the south and Squamish River on the north, the lake would likely have persisted longest in the reach between sections T and AK. In such a case, we infer that the deposits described in this paper record the very end of lacustrine deposition upstream of Cheekye Fan.

Deposits similar to facies 2 have been documented in inter-channel basins and backwater swamps of anastomosing river systems in eastern British Columbia and western Alberta (Smith 1972, 1983; Smith and Smith 1980; Makaske et al. 2002). These stream reaches are all upstream of alluvial fans.

Low-lying fringing wetlands

Interbedded peat and organic-rich silt of facies 1 are among the most common sediments exposed in the banks of Squamish River. The presence and excellent preservation of wetland

1 taxa such as *Menyanthes trifoliata*, *Carex livida*, *C. aquatilis*, *C. canescens*, and *Comarum*
2 *palustre* in the peat layers indicate that these sediments were laid down in an area with
3 persistent near-surface or surface water. The oldest deposits (3227–3080 cal yr) are found at
4 about 18.8 m asl, whereas those dating to about 2700–2300 years old lie between 18.2 m and
5 15.9 m asl (Table 1). This suggests that the sediments accumulated in low inter-channel
6 surfaces on a gently sloping floodplain or perhaps in an advancing, anabranching delta similar
7 to the Laitaure delta in Sweden (Axelsson 1967). The peaty portions of facies 1 may also
8 record marshes that existed at the fringes of the lake that was filling or was nearly infilled. Silt
9 beds and laminae likely represent flood-related crevasse splays in sedge-dominated fens.
10 Widespread peat deposition persisted on the Squamish River floodplain until about 1300–
11 1000 years ago. Similar deposits have been documented in the Pitt River marshes in the lower
12 Fraser Valley east of Vancouver (Styan and Bustin 1983). We interpret this facies as lake and
13 channel-marginal wetland sediment.

14 **Fluvial channel and overbank environments**

15 Facies 3, 4, and 6 are typical of channel and overbank sediments found on the floor of the
16 modern Squamish River valley. Sections B and G expose cobble gravel overlain by cross-
17 bedded and rippled fine to medium sand, and topped by interbedded very fine sand and
18 organic-rich silt. Brierley and Hickin (1991) record a similar succession of gravel, sand, and
19 silt exposed in Squamish River banks between Ashlu Creek and Pillchuck Creek, near section
20 B. They interpret the sediment architecturally as: channel framework gravel, bar platform
21 sand and gravel, chute channel scours, channel-marginal sand ridges, overbank sand wedges,
22 and distal floodplain deposits. Sections B and G are also sites where the modern river has

eroded older, fine-grained deposits of facies 1 and 2, suggesting that most existing fine-grained deposits in the Squamish River valley will eventually be removed by erosion. The present flood regime of Squamish River allows floods to inundate most of the floodplain (BC Ministry of Environment 1983). Ancient lake-bed features such as terraces and fine sediment, which are not directly threatened by lateral channel erosion, are being buried by successive flood inundation.

The oldest sandy fluvial sediment of facies 4 overlies laminated to thin-bedded silt (facies 2) at sections R and W. These sites were suitable for at least seasonal occupation by people, as hearth features with stone tool fragments dated to between 2305 and 1415 cal yr BP (Table 1) are present over a 50-m-long section of river bank. People were therefore using the floodplain at or shortly after the date of final lake infilling, about 2300–2100 years ago.

Alluvial and colluvial fans

Sediments deposited on alluvial or colluvial fans include: diamicton at section L; poorly sorted, blocky, granitic gravel overlying laminated to thin-bedded silt 0.6 km north of section T; and gravel channel fill at section E. This environmental assignment is based on the character and sorting of the sediments, their contact relations, and proximity to tributary valley fans extending into Squamish Valley from the Tantalus Range.

Cobble/boulder volcanic gravel found between section Z and the gravel pit 1.2 km to the north is likely sourced from Rubble Creek and Cheekye River, and distributed by Cheakamus River. The wide distribution of the gravel suggests that Cheakamus River floodplain adjacent to Cheekye Fan is a low-gradient inset fan. The constriction at section Z suggests that

Cheakamus River at one time controlled the level of the upstream river at about 17 m asl. Airphotos from 1948 and a floodplain map of Squamish River near Cheekye Fan drawn in 1893 (Author unknown 1893) show that the Cheakamus-Squamish confluence was oriented in a more eastward direction than today as late as the early 20th century (Figure 12).

Discussion

Time window of lacustrine deposition upstream of Cheekye Fan

Hickin (1989) estimated that the Squamish delta had prograded to Cheekye Fan sometime between 3825 and 2175 years ago. The distance from the north end of Cheekye Fan to Ashlu Creek is 16.7 km, such that the average progradation rate would have been between 4.4 and 7.7 km/ka. While we presume that the lake in lower Squamish Valley first formed before 7000 years ago due to damming of Squamish River by Cheekye Fan, no direct evidence has yet been found for its early phase. The oldest dated sediments in our study area, at sections A and T, are between 3400 and 3100 years old. By this time, Squamish River could have built a delta somewhere between 11.9 km and 20.8 km downstream of Ashlu Creek. Given the rapid rate of advance, the lake was likely filled less than 1000 years later, or by 2300–2100 years ago.

Evolution of base level through the late Holocene

Initial base level

Cheekye Fan formed a barrier that controlled base level on Squamish River at about 20–22 m from about 7000 to 5000 years ago. This period is recorded in the gentle gradient in the river

1 profile between sections B and G. This gently sloping reach of the river also contains section
2 R, which contains fine-grained facies 2 sediment up to about 20 m asl and more than 1 m
3 below a 2300–2150 year-old horizon. We do not know the exact age of the facies 2 sediments
4 at this site, but they are likely an erosional remnant of lacustrine sediments deposited in a lake
5 with a 20–22 m base level control (Figure 13A).

6 Base level decrease after 5000 to 3000 years ago

7 As sediment supply to Cheekye Fan and Cheakamus River diminished, Squamish River began
8 to erode the toe of the fan. As a result, base level at the fan barrier likely decreased to 17.2 m
9 asl, which is the level of fan gravel at section Z. At that time, a shallow lake fringed by sedge-
10 dominated wetlands likely covered the valley floor upstream of Cheekye Fan. Given the
11 elevation of gravel at section Z, the presence of a conifer root in growth position at section A,
12 and lake sediments at section T, the likely age of the 17–18 m asl lake stand is sometime
13 between 3400 and 3000 years BP. At that time, the lake may have extended as far north as
14 section R, about 7–9 km above the upstream end of Cheekye Fan (Figure 13B).

15 Continued base level fall and infilling of lake between 3000 and 2300 years ago

16 With the continued decrease in sediment yield, and in the absence of armouring by boulder
17 lag formation, base level at the fan continued to fall. The difference in elevation between the
18 lowest 2700-year-old deposits at section L, and 2700–2400 year-old wood in facies 2 deposits
19 at 15.1 m asl at section N (sample N3) is about 0.8 m. The dated wood sample at section L is
20 about 40 cm above a peat bed containing *Carex aquatilis*. We interpret the wood at section L
21 as having been deposited in a sedge marsh fringing the shore of a pond with a surface
22 elevation somewhat higher than 15.1 m asl. This suggests that base level decreased to

between 15 and 16 m asl after 3000 years ago, but before 2300 years ago (Figure 13C). As base level lowered, Squamish River advanced and rapidly filled in the remainder of the shallow lake. The oldest stumps on the Squamish River floodplain above Cheekye Fan are Sitka spruce at sections T (15.5 m asl) and E (19.7 m asl), both of which date to about 2300–2000 years ago. An analog for this scenario is the artificial lowering, by several metres, of the outlet of nearby Lillooet Lake in 1952. When the level of the lake fell, the delta at its north end rapidly advanced (Gilbert 1972; Jordan and Slaymaker 1991; Weatherly and Jakob 2014).

Present base level control

The Cheakamus River fan lies just upstream of Cheekye Fan and is confluent with Squamish River. The confluence is presently oriented sub-parallel to the west valley wall, although there is evidence that it has shifted several times in the past. A map from 1893 and airphotos flown in 1948 indicate that the Squamish-Cheakamus river confluence shifted 1.5 km southward from its former location near section Z sometime in the past century (Figure 3). Volcanic boulders in pools formed by water-worn alcoves on the west valley wall may mark the location of previous fan confluences. When the confluence is oriented more or less perpendicular to the west valley wall, Cheakamus Fan impounds Squamish River more effectively and base level is more likely to rise. The present configuration of the Cheekye Fan is such that local base level on Squamish River may continue to lower. Present base level is 13 m asl, about 4–5 m lower than when Squamish River was filling in the lake upstream of the fan (Figure 13D).

Relevance of previous research in the Squamish River watershed

Our research documents the late Holocene sediment fill in the lower meandering reach of Squamish River, but the riverbank exposures date only to the past 3300 years and therefore provide no information on the earlier history of the lake dammed upstream of Cheekye fan. Past research, however, has implications for this history. Impoundments of Squamish River by large debris avalanches from Mt. Cayley, dated to about 4800, 1100, and 500 radiocarbon years ago (Evans and Brooks 1991), trapped sediment in upper Squamish Valley and, upon erosion of the debris dams, generated large fluxes of coarse and fine sediment that were transported into our study area. The 4800-year-old landslide was the largest of the three, with a volume of $200\text{--}300 \times 10^6 \text{ m}^3$. The sediment flux resulting from breaching of this dam may have greatly reduced the size of the lake behind Cheekye Fan. It is noteworthy that widespread fen deposition on the Squamish River floodplain ceased about 1300–1000 years ago. It is possible that rapid aggradation on the floodplain during and following breaching of the 1100-year-old landslide dam buried the fens.

Changes in the paraglacial sediment flux also influenced events in lower Squamish Valley.

Brooks (1994) estimated that the Holocene paraglacial sediment contribution to the valley fill totals $415 \times 10^8 \text{ m}^3$, of which about $230 \times 10^8 \text{ m}^3$ was delivered by Squamish River upstream of Cheakamus River. The large early Holocene paraglacial sediment flux from upstream reduced the size of the lake trapped behind Cheekye Fan faster than would have been the case under reduced (late Holocene) conditions. The diminishing supply of sediment to the fan at the downstream end of the lake resulted in a lowering of base level, also allowing more rapid lake infilling and delta progradation.

1 Extrapolating present-day sediment yields back in time is thus confounded by the paraglacial
2 influence punctuated by large debris avalanche events (Friele and Clague 2009). Perhaps it is
3 more helpful to consider mountainous environments such as the Squamish River watershed as
4 inherently complex due to stochastic events that are unpredictable or that interact in an
5 unpredictable way. Landslide barriers both impound sediment and later contribute to the
6 downstream sediment load. Alpine glaciers currently cover about 11% of the watershed, but
7 the glacier cover was considerably greater in the Little Ice Age, further complicating
8 predictions of sediment yield and geomorphic change in lower Squamish Valley.

9 Although Cheekye Fan is much less active today than during the immediate postglacial
10 period, the Cheekye River watershed still has the potential to generate very large debris flows.
11 Collapse of the headwall in the upper part of the watershed would trigger a debris avalanche
12 or debris flow that might reach Squamish River (Friele and Clague 2005). Aside from danger
13 of such an event to the community of Brackendale, the sediment delivered to Cheekye and
14 Cheakamus Rivers would likely raise the level of the present barrier and increase the sediment
15 flux moving past Squamish. This would in turn elevate the risk of flooding both downstream
16 within Squamish Municipality and on the floodplain above the Squamish-Cheakamus river
17 confluence. Because, as documented herein, base level on Squamish River has changed in the
18 past and could change in the future, we advocate consideration of possible future large debris
19 flow and debris avalanche events, including redistributions of sediment from these events, in
20 hazard management in Squamish Valley.

Conclusion

This paper describes the stratigraphy, sedimentology, and age relations of late Holocene sediments exposed in the banks of Squamish River upstream of Cheekye Fan. The sediments span approximately the past 3300 years and record the later stages of infilling of a lake and the subsequent establishment of a floodplain upstream of the fan. Our paper is rare in the sedimentary literature, as it deals with the specific impact of an alluvial fan on the upstream sedimentary environment of the receiving river and provides a hypothesis of fan base-level control driven by fan geometry and Holocene sediment supply. It also shows that mass movement events on alluvial fans can have significant and long-lasting effects on upstream sedimentary environments. Lacustrine sediments older than 3300 years before present are likely present below present-day river level, but were not accessed in this study. Geophysical surveying coupled with drilling, however, may extend the record of the lake back to the early Holocene.

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References

Atwater, B.F., Adam, D.P., Bradbury, J.P., Forester, R.M., Mark, R.K., Lettis, W.R., Fisher, G.R., Gobalet, K.W., and Robinson, S.W. 1986. A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada. Geological Society of America Bulletin, **97**: 97–09.

Author unknown. 1893. Cheakamus No. 11 Reserve. 1893. Map provided by Eric Andersen (Squamish, BC resident), December 15, 2012.

Axelsson, V. 1967. The Laitaure Delta: A study of deltaic morphology and processes. Geografiska Annaler. Series A, Physical Geography, **49**(1): 1–127

Ballantyne, C.K. 2002. Paraglacial geomorphology. Quaternary Science Reviews, **21**: 1935–2017.

B.C. Ministry of Environment 1983. Floodplain mapping, Squamish River: Howe Sound – High Falls Creek. Sheets: 5461–1 to –10, at:

http://www.env.gov.bc.ca/wsd/data_searches/fpm/reports/region2.html, accessed: 2017–11–

10

- 1 Brierley, G.J., and Hickin, E.J. 1991. Channel planform as a non-controlling factor in fluvial
2 sedimentology: The case of Squamish River floodplain, British Columbia. *Sedimentary*
3 *Geology*, **75**: 67–83.
- 4 Brooks, G.R. 1994. The fluvial reworking of late Pleistocene drift, Squamish River drainage
5 basin, southwestern British Columbia. *Géographie physique et Quaternaire*, **48**: 51–68.
- 6 Brooks, G.R., and Hickin, E.J. 1991. Debris avalanche impoundments of Squamish River,
7 Mount Cayley area, southwestern British Columbia. *Canadian Journal of Earth Sciences*, **28**:
8 1375–1385.
- 9 Clague, J.J., Harper, J.R., Hebda, R.J., and Howes, D.E. 1982. Late Quaternary sea level and
10 crustal movements, coastal British Columbia. *Canadian Journal of Earth Sciences*, **19**: 597–
11 618.
- 12 Clague, J.J., Turner, R.J.W., and Reyes, A.V. 2003. Record of recent river channel instability,
13 Cheakamus Valley, British Columbia. *Geomorphology*, **53**: 317–332.
- 14 Eilertsen, R.S., Corner, G.D., Aasheim, O., and Hansen, L. 2011. Facies characteristics and
15 architecture related to palaeodepth of Holocene fjord-delta sediments. *Sedimentology*, **58**:
16 1784–1809.
- 17 Colombo, F. 2005. Quaternary telescopic-like alluvial fans, Andean Ranges, Argentina. *In*
18 *Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Edited by A.M. Harvey, A.E.*
19 *Mather and M. Stokes. Geological Society, London, Special Publication, 251: 69-84.*

- 1 Eisbacher, G.H. 1983. Slope stability and mountain torrents, Fraser Lowlands and southern
2 Coast Mountains, British Columbia. Geological Association of Canada, Mineralogical
3 Association of Canada, Canadian Geophysical Union, Joint Annual Meeting, Victoria, B.C.,
4 Field Trip Guidebook.
- 5 Ékes, C.S., and Friele, P.A. 2003. Sedimentary architecture and post-glacial evolution of
6 Cheekye fan, southwestern British Columbia, Canada. *In* Ground penetrating radar in
7 sediments. *Edited by* C.S. Bristow and H.M. Jol. Geological Society, London, Special
8 Publication, **211**: 87–98.
- 9 Evans, S.G., and Brooks, G.R. 1991, Prehistoric debris avalanches from Mount Cayley
10 volcano, British Columbia. Canadian Journal of Earth Sciences, **28**: 1365–1374
- 11 Friele, P.A., and Clague, J.J. 2002a. Readvance of glaciers in the British Columbia Coast
12 Mountains at the end of the last glaciation. Quaternary International, **87**: 45–58.
- 13 Friele, P.A., and Clague, J.J. 2002b. Younger Dryas readvance in Squamish River valley,
14 southern Coast Mountains, British Columbia. Quaternary Science Reviews, **21**: 1925–1933.
- 15 Friele, P.A., and Clague J.J. 2005. Multifaceted hazard assessment of Cheekye fan, a large
16 debris-flow fan in southwestern British Columbia. *In* Debris flow hazards and related
17 phenomena. *Edited by* M. Jakob and O. Hungr. Springer, Berlin, pp. 659–683.
- 18 Friele, P.A., and Clague, J.J. 2009. Paraglacial geomorphology of Quaternary volcanic
19 landscapes in the southern Coast Mountains, British Columbia. *In* Periglacial and paraglacial
20 processes and environments. *Edited by* J. Knight and S. Harrison. Geological Society,

- 1 London, Special Publication, **320**: 219–233.
- 2 Friele, P.A., Ekes, C., and Hickin, E.J. 1999. Evolution of Cheekye fan, Squamish, British
3 Columbia: Holocene sedimentation and implications for hazard assessment. Canadian Journal
4 of Earth Sciences, **36**: 2023–2031.
- 5 Gilbert, R. 1972. Observations on sedimentation at Lillooet Delta, British Columbia. *In*
6 Slaymaker, O.H., McPherson, H.J. (eds.), Mountain geomorphology: Geomorphological
7 processes in the Canadian Cordillera. *Edited by* O.H. Slaymaker and H.J. McPherson. BC
8 Geographical Series, No. 14. Tantalus Research Ltd., Vancouver, pp. 177–185.
- 9 Green, N.L., Armstrong, R.L., Harakal, J.E., Souther, J.G., and Read, P.B. 1988. Eruptive
10 history and K-Ar geochronology of the late Cenozoic Garibaldi volcanic belt, southwestern
11 British Columbia. Geological Society of America Bulletin, **100**: 563–579.
- 12 Hickin, E.J. 1989. Contemporary Squamish River sediment flux to Howe Sound, British
13 Columbia. Canadian Journal of Earth Sciences, **26**: 1953–1963.
- 14 Hickson, C J. 2000. Physical controls and resulting morphological forms of Quaternary ice-
15 contact volcanoes in western Canada. Geomorphology, **32**: 239–261.
- 16 Hitchcock, C.L., Cronquist, A., Ownbey, M., and Thompson, J.W. 1969. Vascular plants of
17 the Pacific Northwest, Part 1. Vascular cryptograms, gymnosperms, and monocotyledons.
18 University of Washington Press, Seattle, WA.
- 19 Jordan, P., and Slaymaker, O. 1991. Holocene sediment production in the Lillooet River

- 1 basin, British Columbia: A sediment budget approach. *Géographie physique et Quaternaire*,
2 **45**: 45-57.
- 3 Kelman, M.C., Russell, J.K., and Hickson, C.J. 2002. Effusive intermediate glaciovolcanism
4 in the Garibaldi volcanic belt, southwestern British Columbia, Canada. *In* Volcano-ice
5 interaction on Earth and Mars. *Edited by* J.J. Smellie. Geological Society Special Publication,
6 **202**: 195–211.
- 7 Klinka, K., Krajina, V.J., Ceska, A., and Scagel, A.M. 1989. Indicator plants of coastal British
8 Columbia. University of British Columbia Press, Vancouver, BC.
- 9 MacKenzie, W.H., and Moran, J.R. 2004. Wetlands of British Columbia: A guide to
10 identification. B.C. Ministry of Forests, Forest Science Program, Victoria, BC.
- 11 Makaske, B., Smith, D.G., and Berendsen, H.J.A. 2002. Avulsions, channel evolution and
12 floodplain sedimentation rates of the anastomosing upper Columbia River, British Columbia,
13 Canada. *Sedimentology*, **49**: 1049–1071.
- 14 Makaske, B., Smith, D.G., Berendsen, H.J.A., de Boer, A.G., van Nielen-Kiezebrink, M.F.,
15 and Locking, T. 2009. Hydraulic and sedimentary processes causing anastomosing
16 morphology of the upper Columbia River, British Columbia. *Geomorphology*, **111**: 194–205.
- 17 Mathews, W.H. 1952. Mount Garibaldi, a supraglacial Pleistocene volcano in southwestern
18 British Columbia. *American Journal of Science*, **250**: 81–103.

- 1 Monger, J.W.H., and Journeay, J.M. 1994. Guide to the geology and tectonic evolution of the
2 southern Coast Mountains. Geological Survey of Canada, Open File 2490.
- 3 Moore, D.P., and Mathews, W.H., 1978. The Rubble Creek landslide, southwestern British
4 Columbia. *Canadian Journal of Earth Sciences* **15**: 1039–1052.
- 5 Pojar, J., and Mackinnon, A. 2004. Plants of coastal British Columbia, including Washington,
6 Oregon, and Alaska, revised edition. Lone Pine Publishing, Vancouver, B.C.
- 7 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck,
8 C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason,
9 H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser,
10 K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M.,
11 Southon, J.R., Staff, R.A., Turney, C.S.M., and van der Plicht, J. 2013. IntCal13 and
12 Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, **55**(4):
13 1869–1887.
- 14 Reimer, R., Friele, P., Fath, K., and Clague, J. 2016. Tales from the river bank: An in-situ
15 stone bowl found along the shores of the Salish Sea on the southern northwest coast of British
16 Columbia. *Journal of Northwest Anthropology*, **49**: 1–26.
- 17 Robertson, A. 1984. *Carex of Newfoundland*. Canadian Forest Service, St. John's, NF.
- 18 Shugar, D.H., Walker, I.J., Lian, O.B., Eamer, J.B.R., Neudorf, C., McLaren, D., and Fedje,
19 D. 2014. Post-glacial sea-level rise along the Pacific coast of North America. *Quaternary*
20 *Science Reviews*, **97**: 170–192.

- 1 Smith, D.G. 1972. Aggradation and channel patterns of the Alexandra-North Saskatchewan
2 River, Banff National Park, Alberta, Canada. *In* Mountain geomorphology:
3 Geomorphological processes in the Canadian Cordillera. *Edited* O.H. Slaymaker and H.J.
4 McPherson. B.C. Geographical Series, No. 14. Tantalus Research Ltd., Vancouver, BC, pp.
5 177–185.
- 6 Smith, D.G. 1983. Anastomosed fluvial deposits: Modern examples from western Canada. *In*
7 Modern and ancient fluvial systems. *Edited by* J.D. Collinson and J. Lewin. Blackwell,
8 Oxford: 155–168.
- 9 Smith, D.G., and Smith, N.D. 1980. Sedimentation in anastomosed river systems: Examples
10 from alluvial valleys near Banff, Alberta. *Journal of Sedimentary Petrology*, **50**: 157–164.
- 11 Stuiver, M., and Reimer, P.J. 1993. Extended ^{14}C database and revised CALIB radiocarbon
12 calibration program. *Radiocarbon*, **35**: 215–230.
- 13 Stuiver, M., and Reimer, P.J. 2017. Calib 7.0.4 [radiocarbon calibration program], at
14 <http://calib.org/calib/>, accessed 2017–10–10.
- 15 Stylian, W.B., and Bustin, R.M. 1983. Petrography of some Fraser River delta peat deposits:
16 Coal maceral and microlithotype precursors in temperate-climate peats. *International Journal*
17 *of Coal Geology*, **2**: 321–370.
- 18 Taylor, T.M.C. 1983. The sedge family of British Columbia. B.C. Ministry of the Provincial
19 Secretary and Government Services, Provincial Museum Handbook, **43**.

- 1 Weatherly, H., and Jakob, M. 2014. Geomorphic response of Lillooet River, British
- 2 Columbia, to meander cutoffs and base level lowering. *Geomorphology*, **217**: 48–60.

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3 Table 1. Radiocarbon ages acquired during this study.

Field sample no.	UCIAMS #	Radiocarbon age (^{14}C yr BP)	2 σ cal age range	Dated Material	Elevation (m asl)	Facies ¹
A1	109466	2995 $\pm$ 15	3227–3080	<i>Taxus brevifolia</i> root	18.8	1
A3	109467	1030 $\pm$ 15	961–927	In-situ root	23.5	4/1
B2	109468	1450 $\pm$ 15	1369–1306	Charcoal	21.7	4
B3	109469	1595 $\pm$ 15	1536–1415	Charcoal	21.9	4
B10	109470	480 $\pm$ 20	534–505	Charcoal	26.0	6
E2	109471	85 $\pm$ 15	255–32	Log	23.5	6
E5	109472	2085 $\pm$ 15	2114–2000	<i>Picea sitchensis</i> stump	19.7	1
E6	109473	2640 $\pm$ 15	2770–2746	Bark	18.2	1
G6	109474	180 $\pm$ 15	284–1	Log	21.1	3
I1	115818	1320 $\pm$ 20	1293–1186	In-situ root	17.0	1
J1	115819	2470 $\pm$ 20	2713–2440	In-situ root	17.5	1
J2	115820	1215 $\pm$ 20	1228–1067	In-situ root	19.0	1
J3	115821	900 $\pm$ 20	908–744	Branch	19.7	4
L1	109475	890 $\pm$ 20	905–737	In-situ root	19.7	1
L3	109476	1740 $\pm$ 20	1708–1572	In-situ root	18.6	1
L5	109477	2560 $\pm$ 15	2746–2716	<i>Thuja plicata</i> log	15.9	1
M1	109478	1795 $\pm$ 15	1812–1630	<i>T. plicata</i> log	17.2	1
M2	109479	810 $\pm$ 15	738–688	<i>Picea sitchensis</i> stump	19.5	6/4
N1	109480	1140 $\pm$ 15	1170–978	Charcoal	19.0	6
N3	109481	2460 $\pm$ 15	2703–2383	<i>Malus fusca</i> log	15.1	2
O3 (AK)	115822	2135 $\pm$ 20	2296–2042	Charcoal	17.5	6/4
R1	109482	2230 $\pm$ 15	2322–2157	Charcoal	21.6	6/4
T1	109483	2130 $\pm$ 15	2282–2044	<i>Picea sitchensis</i> stump	15.5	2
T2	109484	3090 $\pm$ 15	3363–3247	<i>Picea sitchensis</i> log	13.6	2
T4	109485	2030 $\pm$ 15	2037–1929	Charcoal	17.8	4/2
W10	109486	2170 $\pm$ 20	2305–2116	Charcoal	15.8	2
W11	109487	2050 $\pm$ 15	2101–1949	Charcoal	16.9	4/2
Skw'emp' 4 Station W	109491	1610 $\pm$ 20	1554–1415	Charcoal	18.0	6/4

4 ¹ Numbered facies on the left overlies numbered facies on the right. For example 4/1 – facies 4 overlies facies 1.

5

6 **Figure captions**

7 Figure 1. Squamish River watershed showing the locations of Cheekye Fan and the study area.

8 Figure 2. Squamish River hydrograph (1958–2012) showing mean, minimum, and maximum
9 flood discharges.

10 Figure 3. Elevation profiles (see Figure 2 for locations). (A) P1 across Cheakamus Fan. (B) P2
11 across Cheekye Fan. Extrapolation of the profiles with a reduction in gradient at the bottom of
12 Squamish Valley would likely permit impoundments to perhaps 25 m asl in (A) and to 22 m asl
13 in (B).

14 Figure 4. Locations of measured sections described in the text.

15 Figure 5. Stratigraphic sections and Squamish River profile from site A to Cheekye Fan. The
16 spring 2012 water level represents a low-water level, and the September 1976 water level, which
17 is taken from floodplain mapping, likely represents the bankfull water elevation. Radiocarbon-
18 dated sample names are placed beside stratigraphic sections.

19 Figure 6. Fine-grained deposits in the banks of Squamish River. (A) Interlayered peat and silt
20 (facies 1). (B) Thin-bedded and laminated organic poor silt and clay (facies 2). Pit in (B) is about
21 50 cm deep.

22 Figure 7. GPR Profile 1 (location shown in Figure 4), showing high-impedance, low-resistivity
23 fine-grained floodplain sediment underlying well-drained, horizontally-bedded, overbank flood

deposits. Broken-up layers below the green line are electromagnetic reverberations from the contact between the two units (likely a water table reflection).

Figure 8. Sandy and gravelly deposits. (A) Pebble gravel with sand matrix overlain by horizontally bedded sand. (B) Gravel filling channel incised into facies 1 deposits. (C) Cobble/boulder volcanic gravel in borrow pit on the Squamish River floodplain. (D) Inclined fine sand beds overlying gravel bar deposits, which in turn overlie horizontally bedded sand. Cobble gravel crops out below the level of the shovel and is not visible in this photo.

Figure 9. GPR profile 2 showing evidence of lateral channel migration (location shown in Figure 4).

Figure 10. Matrix-supported boulder-rich diamicton underlying woody diamictic layer and organic-rich silt. Vegetated bank is underlain by horizontally bedded sand and silt.

Figure 11. (A) Horizontally bedded sand with intervening thin silt beds. The darker coloration of the silt beds is due to degraded forest litter. (B) Hearth with carved bowl at Station W. Hearth is defined by dark-colored charcoal bands and contains silty infill material and oxidized ochre-colored layers. Hearth was dug into floodplain sediments and buried by subsequent floods.

Figure 12. Historical images of the Cheakamus-Squamish confluence area. Airphoto on the left shows the confluence in 1947. Note northerly channel remnant. The map on the right is based on a survey completed in 1893 and depicts the confluence near the position of the abandoned channel in the photo on the left.

43 Figure 13. Schematic diagram showing progressive filling of the lake in Squamish Valley above
44 Cheekye Fan. Elevations are approximate barrier heights. (A) Cheekye Fan formed a barrier at
45 least 20–22 m asl. (B) Cheekye River avulsed northward allowing Squamish River to erode the
46 toe of Cheekye Fan sometime between 5000 and 3000 years ago. After this avulsion, base level
47 is controlled by Cheakamus Fan. (C) Squamish River has filled the lake by 2300 years ago and
48 base level is approximately 15–16 m asl. (D) The modern environment, in which minor changes
49 in base level are controlled by rare large debris flow that reach Cheakamus River. Present base
50 level is about 13 m asl.

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Figure 2. Squamish River hydrograph (1958-2012) showing mean, minimum, and maximum flood discharges

215x166mm (300 x 300 DPI)

Figure 3. Elevation profiles (see Figure 2 for locations). (A) P1 across Cheakamus Fan. (B) P2 across Cheekye Fan. Extrapolation of the profiles with a reduction in gradient at the bottom of Squamish Valley would likely permit impoundments to perhaps 25 m in (A) and to 22 m in (B).

190x107mm (300 x 300 DPI)

Figure 4. Locations of measured sections described in the text.

195x247mm (300 x 300 DPI)

Legend

Facies 1: Organic-rich silt and peat

Facies 2: Laminated and thin-bedded organic-poor silt

Facies 3: Crudely-stratified coarse gravel

Facies 4: Well-sorted, fine- to medium-grained sand

Facies 5: Diamicton

Facies 6: Interbedded sand and silt

Wood

Rooting traces

Charcoal

Lithics

Hearth

Stone bowl

Radiocarbon age (a BP)

Spring 2012 water surface

Sept 1976 water surface

Figure 6. Fine-grained deposits in the banks of Squamish River. (A) Interlayered peat and silt (facies 1). (B) Thin-bedded and laminated organic poor silt and clay (facies 2). Pit in (B) is about 50 cm deep.

102x54mm (300 x 300 DPI)

Figure 7. GPR Profile 1 (location shown in Figure 4), showing high-impedance, low-resistivity fine-grained floodplain sediment underlying well-drained, horizontally-bedded, overbank flood deposits. Broken-up layers below the green line are electromagnetic reverberations from the contact between the two units (likely a water table reflection).

54x15mm (300 x 300 DPI)

Draft

Figure 8. Sandy and gravelly deposits. (A) Pebble gravel with sand matrix overlain by horizontally bedded sand. (B) Gravel filling channel incised into facies 1 deposits. (C) Cobble/boulder volcanic gravel in borrow pit on the Squamish River floodplain. (D) Inclined fine sand beds overlying gravel bar deposits, which in turn overlie horizontally bedded sand. Cobble gravel crops out below the level of the shovel and is not visible in this photo.

240x222mm (300 x 300 DPI)

Figure 9. GPR profile 2 showing evidence of lateral channel migration (location shown in Figure 4).

178x56mm (300 x 300 DPI)

Draft

Figure 10. Matrix-supported boulder-rich diamicton underlying woody diamictic layer and organic-rich silt. Vegetated bank is underlain by horizontally bedded sand and silt.

119x89mm (300 x 300 DPI)

Figure 11. (A) Horizontally bedded sand with intervening thin silt beds. The darker coloration of the silt beds is due to degraded forest litter. (B) Hearth with carved bowl at Station W. Hearth is defined by dark-colored charcoal bands and contains silty infill material and oxidized ochre-colored layers. Hearth was dug into floodplain sediments and buried by subsequent floods.

141x93mm (300 x 300 DPI)

Figure 12. Historical images of the Cheakamus-Squamish confluence area. Airphoto on the left shows the confluence in 1947. Note northerly channel remnant. The map on the right is based on a survey completed in 1893 and depicts the confluence near the position of the abandoned channel in the photo on the left.

122x60mm (300 x 300 DPI)

Legend

- Alluvial Fans
- Cheekye Fan
- Floodplain
- Water Features

*Solid colours are used to convey local physiography and distance