Late Holocene history of Squamish River north of Brackendale, British Columbia

by

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Abstract

Laminated silt, organic-rich silt, and peat exposed in the banks of Squamish River north of Brackendale, British Columbia, provide evidence for a lake impounded behind Cheekye Fan during the late Holocene. The lake gradually filled with sediment as Squamish River advanced its delta and floodplain southward toward the fan. Radiocarbon ages on detrital and growth-position plant fossils provide evidence that the lake reached up to 9 km upstream of Cheekye Fan about 3400 years ago and persisted until about 2300 years ago. Geomorphic observations and the distribution of fine-grained facies indicate that both Cheakamus and Squamish rivers contributed sediment to the lake; consequently, different depositional environments existed near Cheekye Fan than farther upstream. Debris flows that travelled down Cheekye River to Cheakamus River provided fine-grained sediment that accumulated in the deepest part of the lake just north of the fan. Farther upstream, organic-rich silt was deposited in fens and marshes surrounding the lake. Squamish River is confined by steep banks of cobble-boulder gravel 1.5–2 km north of the present Cheakamus-Squamish confluence, suggesting that coarse sediment transported by Cheakamus River controlled the lake outlet and, accordingly, lake level. As sediment delivery from Cheakamus and Cheekye rivers declined through the late Holocene, the lake outlet was progressively lowered and the lake drained. Sedimentation in Squamish Valley upstream of Cheekye Fan is also influenced by landslides at Mt. Cayley, 45 km upstream. A large landslide at Mt. Cayley about 1100 years ago produced a sediment pulse that propagated downstream and caused the floodplain above Cheekye Fan to aggrade. Sand buried the remaining fens that covered part of the low-gradient floodplain, leading to their replacement by coniferous and riparian forest. The model that I use to interpret Squamish River sedimentary environments can be applied to other low-gradient floodplains influenced by alluvial fans.

Keywords: Fluvial geomorphology; Quaternary geology; lakes; flooding; rivers; Squamish; British Columbia

This thesis is dedicated to Len Hills, who will never read it. His influence and mentorship have helped me succeed as a geologist. He has touched the lives of many students over the years.

Rest well, friend.

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I extend my special thanks to Squamish Nation, which allowed me to work on their land, and to Randall Lewis, who accompanied me in the field a few times and was my liason and guide. I would also like to thank Eric Andersen, who provided valuable historical insight into the post-settlement history of Squamish River valley.

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1. Introduction

The equilibrium state, defined for rivers by Mackin (1948), is one in which "over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin." The two most important independent factors in this model are load and discharge, and changes in either alter the grade of the system: a stream brought out of equilibrium by a change in discharge or sediment load will alter its gradient by depositing sediment or eroding its channel to return to a state of equilibrium.

Hewitt (2006) used the term "disturbance regime landscapes" in reference to landscapes that are perennially prevented from reaching an equilibrium state by repeated mass movements on slopes, glacier fluctuations, or volcanism. Streams in disturbance regime landscapes do not attain a graded state because geomorphic disturbances repeatedly and persistently change their channels and sediment supply. The form of these streams and their sediments may "not be readily correlated with available relief, the vertical organization of climatic, geomorphic and hydrological environments, vegetation belts, or major geological and tectonic divisions" (Hewitt, 2006). A disturbance-regime stream may not behave like other streams in the same area.

Coastal rivers in British Columbia flow in deep, steep-walled, glacially eroded valleys. Their hydrology is controlled by the wet Pacific maritime climate; spring and summer snowpack melt causes sustained high summer freshet flows and occasional floods, and fall cyclonic storms from the North Pacific Ocean typically cause flooding. Landslides and debris flows are common on steep valley walls and supply large amounts of sediment to streams (Brooks and Hickin, 1991; Jakob and Friele, 2010; Guthrie et al., 2012). Glaciers in the headwaters of most coastal watersheds also produce large amounts of sediment (Church et al., 1989). Stream and river channels are typically floored with gravel, and fine-grained sediment generally is deposited only in overbank settings during floods.

This study documents an anomalous reach of Squamish River, a large river that flows into Howe Sound in the southern Coast Mountains of British Columbia. The 10-km reach of Squamish River north of Brackendale is anomalous in that it has a lower gradient than other parts of the river and its banks are dominated by several metres of laminated silt and peat of late Holocene age. In this thesis, I describe the uppermost, exposed part of the sediment sequence. I provide stratigraphic, sedimentological, and geomorphic observations, radiocarbon ages, plant macrofossil data, and ground penetrating radar (GPR) profiles. My observations are anchored in three-dimensional space with the aid of precise global navigation satellite system (GNSS) surveys. The results of the thesis are presented in two parts, as stand-alone papers. In Chapter 2, I show that the fine sediments exposed in riverbanks upstream of Cheekye Fan are remnants of a late Holocene shallow lake, and I relate the elevation of the lake outlet to patterns of sediment delivery to the fan. In Chapter 3, I attempt to construct a history of late Holocene flooding based on exposures of rhythmic overbank flood deposits along my study reach. In Chapter 4, I relate landform development in Squamish River to concepts of disturbance regime land systems and paraglacial sedimentation, and discuss another stream that might provide related, additional information in a similar study to mine.

2. Fan-controlled base-level change on Squamish River, British Columbia

2.1. Abstract

Squamish River has prograded a delta into Howe Sound in southwestern British Columbia since the end of the last glaciation. When the glacier in Squamish Valley retreated at the end of the Pleistocene, Howe Sound reached more than 30 km upvalley of its present head at Squamish. A lake formed in Squamish Valley upstream of what are now the northern suburbs of Squamish during the early Holocene. The lake was impounded behind Cheekye Fan, which had spread across and blocked the valley. Over the remainder of the Holocene, the lake gradually filled as Squamish River advanced its delta and floodplain southward toward the fan. Exposures of organic and inorganic silts in the banks of Squamish River north of Brackendale provide evidence for persistence of a shallow lake that reached up to 9 km upstream of Cheekye Fan from before 3400 years ago to 2300 years ago. Geomorphic observations and the distribution of fine-grained facies indicate that both Cheakamus and Squamish rivers contributed sediment to the lake, and, consequently, different depositional environments existed closer to Cheekye Fan than farther upstream. Cheakamus River deposited fine-grained sediment derived from debris flows that travelled down Cheekye River in the deepest part of the lake, just north of the fan. Farther upstream, organic-rich silts were deposited in fens and marshes surrounding the lake. Steep banks of cobble-boulder gravel confine Squamish River 1.5–2 km north of the present Cheakamus-Squamish confluence, suggesting that coarse sediment transported by Cheakamus River was important in controlling the lake outlet. As sediment delivery from Cheakamus and Cheekye rivers declined, the lake outlet was progressively lowered and the lake drained.

2.2. Introduction

Large mass movements in mountainous regions may leave deposits on valley floors that persist for centuries to millennia. Hewitt (2001, 2006, 2009), in particular, has described infilled lakes, spillways, terraces, and epigenetic gorges related to such barriers in the Karakoram Himalaya. He refers to the evolution of rivers that are repeatedly affected by large landslides as the "interrupted valley epicycle," and, because of their dominant influence on river systems in mountains has suggested that they represent a disturbance regime landscape model (Hewitt, 2006). Alluvial fans in mountainous regions are also a product of mass movements and are particularly active during periods of paraglacial activity (Church and Ryder, 1972; Ballantyne, 2002). Atwater et al. (1986) examined a sequence of alternating lacustrine and floodplain sediments in Tulare Lake in California in relation to activity on the alluvial fan that impounds the lake. They concluded that changes in the height of the dam at the lake outlet were responsible for the alternation of lacustrine and fluvial facies, and further that sediment delivery to the fan controlled the dam height and was itself controlled by fluctuations of glaciers in the nearby Sierra Nevada. Alexandra and Columbia rivers, upstream of large paraglacial alluvial fans in the Canadian Rocky Mountains, have low-gradient anastomosing channels with floodplains dominated by fine-grained sediments (Smith and Smith, 1980; Smith, 1983; Makaske et al., 2002, 2009). Smith (1972) noted that vertical accretion on Alexandra River is related to recent aggradation on a downstream alluvial fan.

Organic-rich silt and peaty layers and finely laminated silts dominate bank exposures along Squamish River upstream of Cheekye fan in southwestern British Columbia (Figure 2.1). These sediments are unusual because, in the reach where they are found, the river has a gravel bed and sandy washload. Presently, the river only deposits fine-grained sediments in levee and backswamp settings. Such deposits are laterally restricted, typically overlie channel sand and gravel deposits, and are in turn incised by younger channel deposits (Brierley and Hickin, 1991). In contrast, the sediments discussed in this study make up the lowermost exposed stratigraphic units, and form continuous beds for hundreds of metres in riverbank exposures.

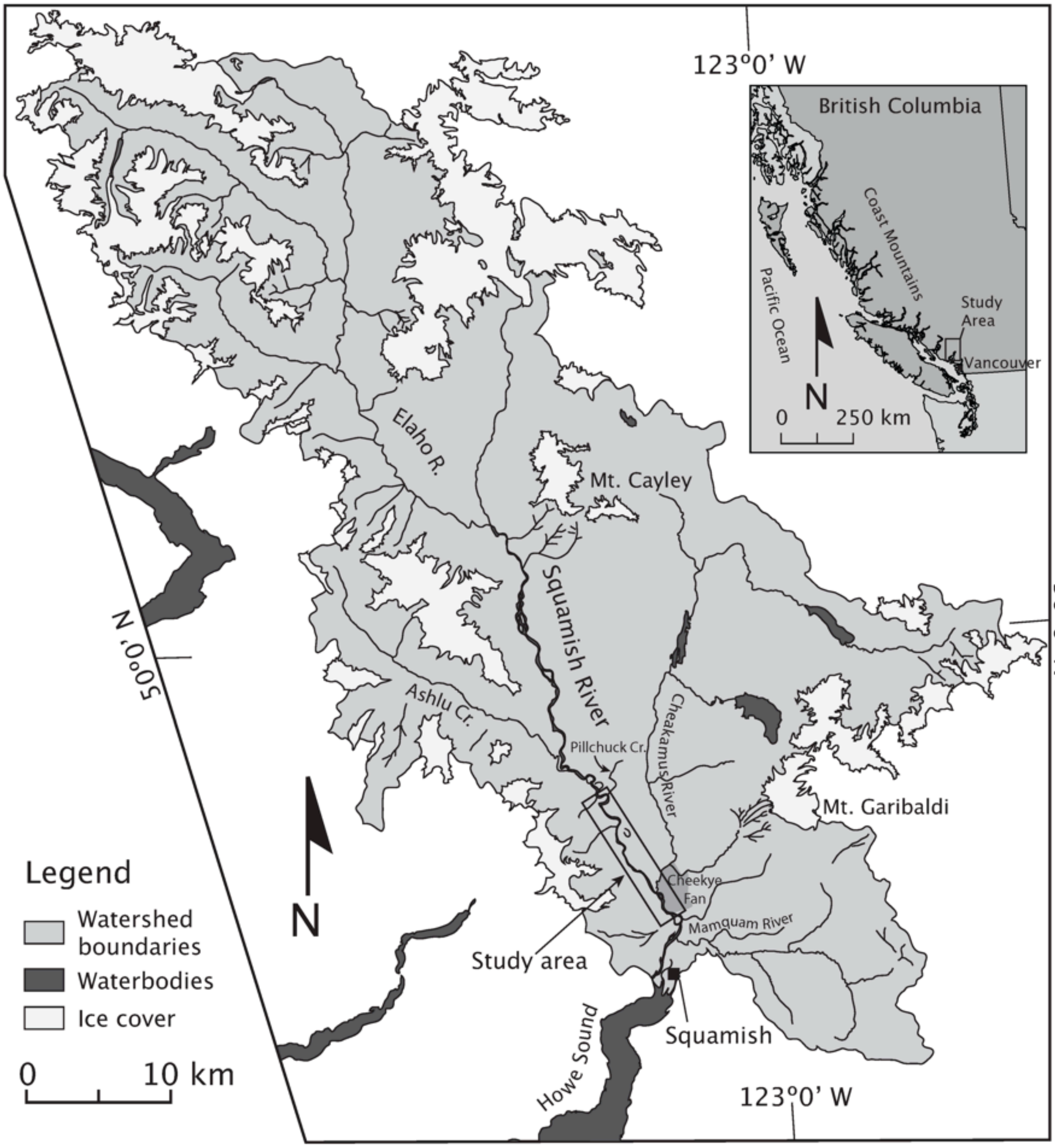

Figure 2.1. Squamish River watershed (medium-gray area of the main map). Glaciers are white areas; water bodies are dark grey.

In this chapter, I focus on the sedimentology and stratigraphy of these fine-grained sediments and their association with other, coarser sediments over a 10-km reach of the river upstream of Cheekye Fan. I describe the physical and biotic characteristics of the sediments, and their stratigraphic context, elevations, and ages. I then discuss the stratigraphy in relation to development and maintenance of a downstream alluvial fan dam. Because Cheekeye Fan is a paraglacial feature, I also discuss the sediments in relation to the concepts of disturbance regimes and paraglacial land systems.

2.2.1. Geomorphology and glacial history

Squamish River drains an area of 3600 km^2 in the southern Coast Mountains of British Columbia (Figure 2.1). Discharge is highly seasonal, driven by precipitation and snowmelt patterns. Annual precipitation in the Squamish River watershed is more than 2000 mm, and much of it falls during the winter as snow at higher elevations. Snowmelt-driven freshet flows during late spring and early summer are 400–700 m^3/s at the Water Survey of Canada gauging station near Brackendale (08GA022); low flows from January to March are 30–80 m^3/s. The highest peak discharges, between 1000 and 3000 m^3/s, are associated with rain-on-snow cyclonic storms, most commonly in the fall (Figure 2.2). Approximately 11% of the watershed is covered by snow and glacier ice (Brooks, 1994).

Squamish River occupies a steep-walled glacially modified valley incised into granodiorite and older metavolcanic and metasedimentary rocks of the Coast Plutonic Complex (Monger and Journeay, 1994). The watershed contains two large, Plio-Pleistocene stratovolcanoes: Mount Cayley near the confluence of Squamish and Elaho rivers, and Mount Garibaldi just northeast of Squamish (Figure 2.1). The study area was last covered by glacier ice during the late Pleistocene Fraser Glaciation, which began about 30,000 years ago and ended about 11,000 years ago (Clague, 1981). Volcanic eruptions at Mt. Garibaldi and Mt. Cayley appear to be coeval with glacial periods; many lava flows and volcanic necks show evidence of having erupted in contact with glacier ice, and several lava flows date to the end of the Fraser Glaciation (Mathews, 1958; Green et al., 1988). Pyroclastic deposits were erupted from Mt. Garibaldi onto the surface of the downwasting Cordilleran ice sheet about 14,000 years ago (Mathews, 1952; Green et al., 1988). The upper reaches of Mamquam valley, east of Squamish, were ice-free about 14,000 years ago, and the Squamish Valley glacier had retreated to the present-day head of Howe Sound by 12,800 years ago (Friele and Clague, 2002a). Glaciers readvanced briefly during the Younger Dryas Chronozone between 12,600 and 11,700, years ago (Friele and Clague, 2002b), and had retreated past the Cheakamus-Squamish confluence by 11,900 yr BP (Friele and Clague, 2002a).

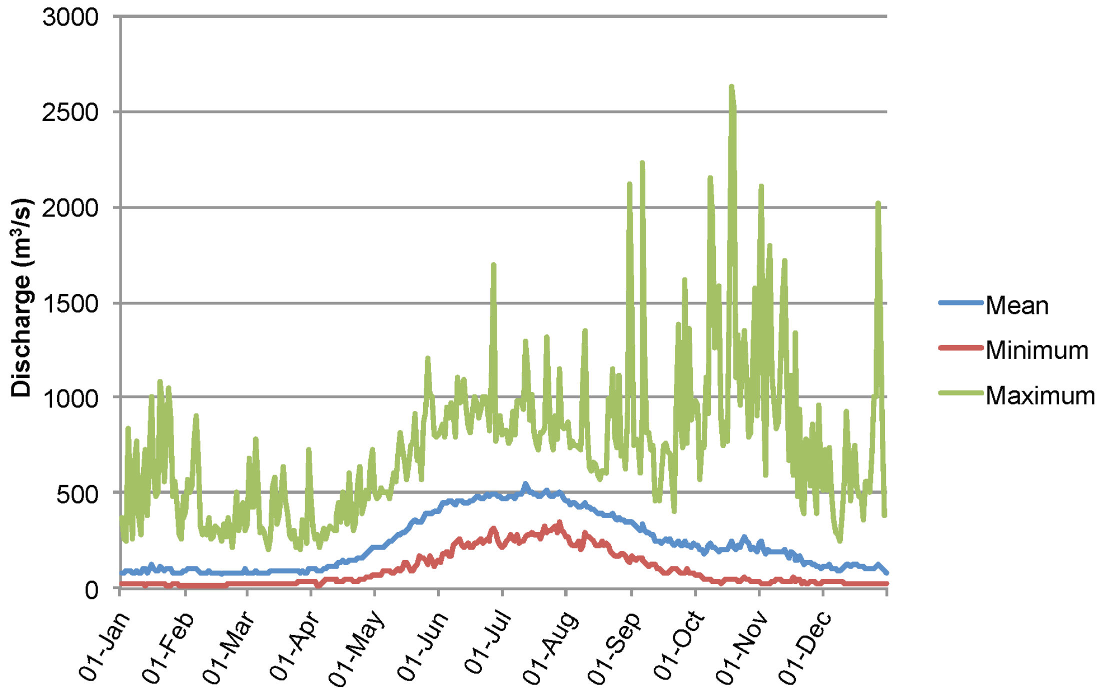

Figure 2.2. Hydrograph of Squamish River from 1922 to 2011 (data from Water Survey of Canada).

At the close of the Fraser Glaciation, Howe Sound extended far upvalley from its present head at Squamish, possibly to somewhere between Mt. Cayley and Ashlu Creek. Squamish River at that time was a sediment-laden proglacial stream that was rapidly building a delta southward into the fjord. The delta front was possibly located near the mouth of Ashlu Creek 6000 years ago, and reached Cheekye Fan by 3000 ± 825 years ago (Hickin, 1989). Throughout most of this period, the delta was being built into a lake dammed by Cheekye Fan, which blocked Squamish Valley just north of Squamish.

Cheekye Fan began to form as soon as lowermost Squamish Valley was deglaciated. Downwasting and retreat of the Squamish and Cheakamus valley glaciers destabilized the west flank of Mt. Garibaldi, causing it to collapse into the headwaters of the Cheekye River watershed east of the present fan between 12,800 and 11,500 years ago and forming what Mathews (1952) describes as hummocky, ice-contact terraces (Friele and Clague, 2002b). The lower portion of the Cheekye River watershed was ice-free by 11,900 years ago, allowing the river to rework the ice-contact deposits to the east and initiate construction of Cheekye Fan. Deltaic foreset beds are visible in GPR profiles along the axis of Cheekye Fan up to 45 m above sea level (Friele et al., 1999), indicating that Cheekye River was building a fan-delta into the fjord at this time. The delta continued to prograde across the valley while the land rose due to glacio-isostatic rebound. By about 7000 years ago, the fan extended to the west side of Squamish Valley, isolating a lake upstream of the fan from Howe Sound to the south (Friele and Clague, 2005).

Cheekye Fan contains about 1.6×10^9 m^3 of sediment, of which about 1.4×10^9 m^3 was deposited between 12,000 and 7500 years ago (average 3.3×10^5 m^3/yr), and 2×10^8 m^3 after 7500 years ago (average 3×10^4 m^3/yr) (Friele et al., 1999; Friele and Clague, 2009). Today, Cheekye River delivers about 1.8×10^4 m^3/yr of sediment to Cheakamus River (Friele et al., 1999).

The western part of Cheekye Fan became progressively less active after 5600 yr BP when a series of debris flows blocked off the main, westward-flowing channel of Cheekye River, finally forcing it to avulse to the north (Clague et al., 2003a; Friele and Clague, 2005). Debris flows, with the exception of the Garbage Dump debris flow event 800 years ago, have all been directed into lowermost Cheakamus River since then. The addition of debris-flow material from Cheekye River shifted the active fan barrier northward from Cheekye Fan to the Cheakamus-Squamish confluence. The Squamish-Cheakamus confluence and the toe of Cheekye Fan remain a barrier that reduces the gradient of Squamish River over a distance of more than 10 km upstream. Local gradient in the study reach is between 0.0005–0.00062[1], less than half the gradient upstream of Ashlu Creek (0.00019)[2]

2.2.2. Contemporary fluvial deposits in Squamish River valley

Squamish River displays many of the characteristics of a high-energy, braided-to-meandering river upstream of Cheekye Fan. During the Holocene, Squamish River

[1] Gradient based on elevations determined by real-time kinematic GPS measurements at sites just downstream of Pillchuck Creek and several kilometres above Cheekye Fan.

[2] Gradient based on estimated water surface elevations taken from BC Ministry of Environment floodplain maps between Ashlu Creek and High Falls Creek.

breached several large landslide barriers at Mount Cayley (Brooks and Hickin, 1991). The impact of these landslides on the river is significant: the river has not finished incising the first of the landslides, which occurred about 4800 years ago; and landslide debris from this and subsequent landslides is still being redistributed downstream. Because of the high sediment delivery from Mount Cayley, Squamish River has a braided planform over a distance of about 13 km downsteam of the volcano. Farther downstream, from 5 km north of the Squamish-Ashlu Creek confluence to about 1.5 km south of the confluence, the river has a wandering planform. The gradient of the river decreases markedly about 1.5 km below Ashlu Creek, coincident with a change from a wandering to a meandering planform. The river channel is much less sinuous where it flows over fine-grained silt that forms much of the floodplain over the lowest 6-7 km above Cheekye Fan.

Squamish River deposits sand and gravel by lateral accretion. Brierley and Hickin (1991) describe seven units of Squamish River sediment in or near the active channel and on the floodplain in the steeper braided and meandering reaches of the river between Mount Cayley and Pillchuck Creek, upstream of my study reach. They recognized four channel units: basal gravels; bar platform sands; laterally restricted chute channels; and ridge-shaped sand bodies dipping toward the main channel. The three overbank units that they recognized are: wedge-shaped sand bodies with erosional basal contacts; rhythmically bedded, sheet-like sand and silt bodies; and laterally extensive, dark grey to brown sands and silts. The laterally extensive, dark grey to brown sands and silts are remnants of floodplain swamps exposed by lateral river erosion.

Many riverbanks between Ashlu Creek and Pillchuck Creek consist of sediment less than 100 years old. Aerial photographs taken between 1947 and 2009 show that entire meander bends have formed, migrated, and been abandoned in this reach (Sichingabula and Hickin, 1988; Bauch, 2009). Lateral erosion has removed a large area of ancient floodplain south of an oxbow lake in my study reach, and further reworking of ancient fine-grained deposits is possible in the future.

2.3. Methods

The evidence for fan impoundment and the existence of a lake behind Cheekye Fan comes from detailed descriptions of riverbank sections, geomorphic interpretation, radiocarbon ages on fossils recovered from bank sediments, plant macrofossils taken from organic-rich bank sediments, and several ground-penetrating radar profiles on the floodplain. I completed fieldwork during the winter, spring, and summer of 2012, with additional site visits in the winter of 2013.

2.3.1. Riverbank stratigraphy

I described 11 stratigraphic sections bed-by-bed and three others at least to the facies level. I measured sections with a measuring tape, clinometer, and laser rangefinder. Field descriptions of sediments included observations of lithology (grain size, sorting), sedimentary structures, bed and unit contacts, colour, and the presence or absence of fossil plant material. I collected samples of representative units for laboratory grain-size analysis and processed them with a Malvern Mastersizer laser grain-size analyzer to calibrate field descriptions.

2.3.2. GPS stationing and vertical control

I determined bank-top elevations with a Topcon HiPer Lite+ dual frequency real-time kinetic GNSS system in base station and rover configuration. The rover unit was left for a miniumum of 10 minutes at surveyed sites in order to obtain centimetre-scale accuracy. At the end of each surveying session, I submitted base station logs to CSRS-PPP, an online post-processing service of Natural Resources Canada that provides three-dimensional base station coordinates accurate to 2 cm. I processed computed base-station coordinates with Topcon Tools 8.3 phase differential post-processing software to obtain precise rover coordinates.

2.3.3. Radiocarbon dating

I collected samples for radiocarbon dating from tree stumps in growth position, in-situ roots, detrital tree stems, branches, twigs, and soil charcoal layers. I sampled the outermost rings of trees, branches, and stumps because they most closely approximate the time of death of the plant and, therefore, the age of the enclosing sediments. Charcoal might be derived from inner rings of trees and thus charcoal ages could be significantly older than the age of the associated sediments. I submitted 28 samples of wood and charcoal to the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California in Irvine. I washed and air-dried the samples and isolated fresh, root-free wood and charcoal prior to submission. I calibrated the radiocarbon ages using Calib 6.1 and the IntCal09 calibration curve (Stuiver and Reimer, 1993, 2011; Reimer et al., 2009).

2.3.4. Macrofossil analysis

Organic-rich silt and peat layers in Squamish River bank sections contain abundant plant macrofossils. To assist with my palaeoenvironmental interpretation, I collected samples of peat and organic-rich silt ranging in mass from several hundred grams to 2 kg from bank exposures. I targeted horizons near the top and bottom of peat exposures to detect any major changes in macrofossil composition. I collected multiple samples from the bottom to the top of one, particularly organic-rich section (Section A). I sealed samples in plastic bags to prevent dessication, but some samples were not refrigerated for the entire period prior to analysis, and so some macrofossils degraded. Visual comparison of fresh, refrigerated, and unrefrigerated samples indicates that damage was limited mainly to green leaf tissues in preserved mosses. I wet-sieved 50 mL sub-samples of organic-rich material in the laboratory through 2 mm, 1 mm, and 250 µm nested sieves and examined fossils using a stereoscopic dissecting microscope.

I used the keys of Hitchcock et al. (1969), Taylor (1983), Robertson (1984), and Pojar and MacKinnon (2004) to identify indicator plant species. Special emphasis was put on identifying indicator species that might provide evidence of past inundation or of wetland conditions. I used Klinka et al. (1989) and MacKenzie and Moran (2004) to determine environment indicated by the identified fossils.

2.3.5. Ground-penetrating radar surveys

I obtained several ground-penetrating radar (GPR) profiles on Squamish River floodplain using a pulseEKKO 100 system with 50 MHz and 100 MHz antennae. I used 0.25 or 0.5 m step-sizes with 1 m antenna separation in the 100 MHz surveys, and 2 m antenna separation and 0.5 m step size for the 50 MHz surveys. I processed survey traces using EKKO_View Deluxe software (Sensors and Software) and edited profiles to remove duplicate traces, apply gain, and clip the time window to attenuation depth. Surveys were carried out on largely flat floodplain surfaces; however, two lines were surveyed using a rod and level and a differential GPS to document small changes in surface elevation. I applied elevation corrections in EKKO_View. Common midpoint (CMP) surveys were done using 0.5 m (50 MHz) and 0.25 m (100 MHz) step sizes. The CMP surveys showed that wave velocities in the shallow sediments beneath the floodplain are 0.065-0.09 m/ns. Wave penetration was poor in silty floodplain sediments, but good in sand and gravel sequences. Two of the profiles are discussed in the results section of this chapter.

2.3.6. Geomorphic mapping

I input data collected in the field into QGIS, a free and open-source geographic information system. Using vertical aerial photographs taken in 1947, 1964, and 2009 (Table 2.1), and stratigraphic information collected in the field, I created a geomorphic map of the Squamish River floodplain (Figure 2.3). I also used the photographs to document changes in the Squamish and Cheakamus river channels during the historical period.

Table 2.1. Historical airphotos used in this study.

Roll number	Photo numbers	Date	Scale
BC400	72, 74, 75, 76, 77	1947	1:20,000
BC5105	203, 204, 205, 215, 216	1964	1:20,000
92G [mapsheet]	65, 74, 75, 84, 85, 94,95	2009	1:20,000

I georeferenced old airphotos in QGIS by comparison with the digitally orthorectified and georeferenced 2009 airphotos. I stitched individual photos from 1947 and 1964 together using Adobe Photoshop CS5 and georeferenced the composite scans by tying them to bedrock outcrops at river channel margins, bridge crossings, and road intersections on the orthophoto base map. I projected the maps using third-order polynomial warping algorithms, for which average root mean square (RMS) errors in georeferencing are 15.6 m for the 1947 map and 17.8 m for the 1964 map.

2.4. Stratigraphy

2.4.1. Facies descriptions

I divided sediments exposed in riverbanks along the study reach into six facies. Representative examples of the six facies are shown in Figures 2.5, 2.7, 2.9, 2.12, and 2.13.

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

Facies 1 consists of fine-grained, olive-grey, organic-rich silt interlayered with thin, brown, mostly fibric, peaty layers that consist largely of sedge stems and rhizomes (Figures 2.4, 2.5, and 2.6). Most silt and peaty layers are 1–2 cm thick, but some silt layers are >5 cm thick and some peaty layers are up to 35 cm thick.

Facies 1 forms the lowermost exposed unit in sections where it is found. It is at least 2–4.5 m thick, with an undefined base, and typically has a gradational contact with overlying very fine-grained sand (facies 4) or with interbedded sand and silt (facies 6). Some occurrences, however, have a sharp erosional contact with overlying channelized sand, pebble gravel, or diamicton (facies 4, 3, and 5, respectively). At sections E and L, the channels filled with these coarse sediments are themselves overlain by facies 1. At section L, peaty beds within facies 1 are interbedded with thin layers of fine sand. Organic-rich silt at section M contains large woody debris and is overlain by facies 4.

Facies 1 extends up to about 22.5 m asl at section A and 23 m asl downstream at section E. At sections I, J, and L, the facies reaches up to between 19 and 20 m asl.

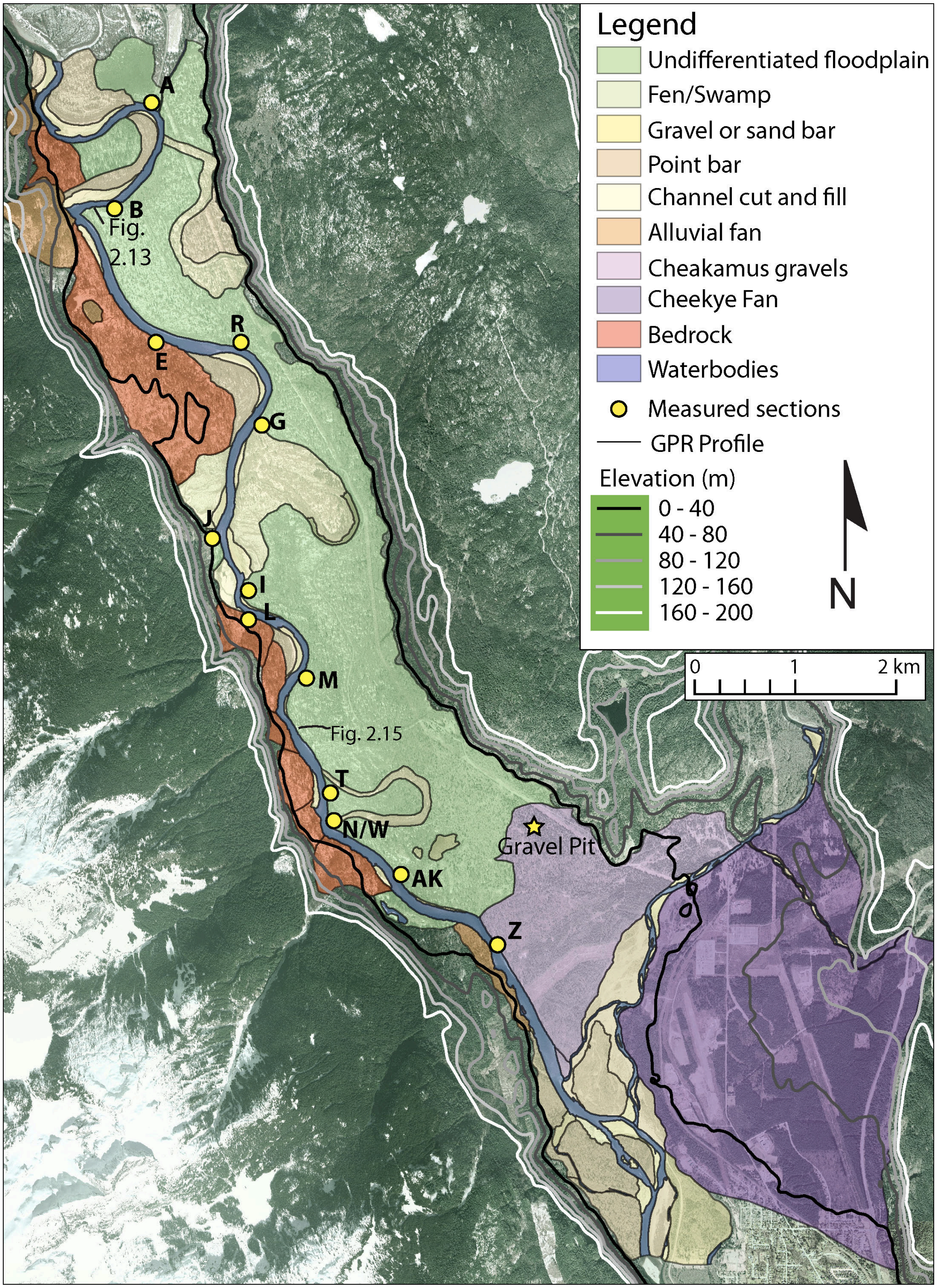

Figure 2.3. ***Geomorphic map of the study reach in Squamish Valley.***

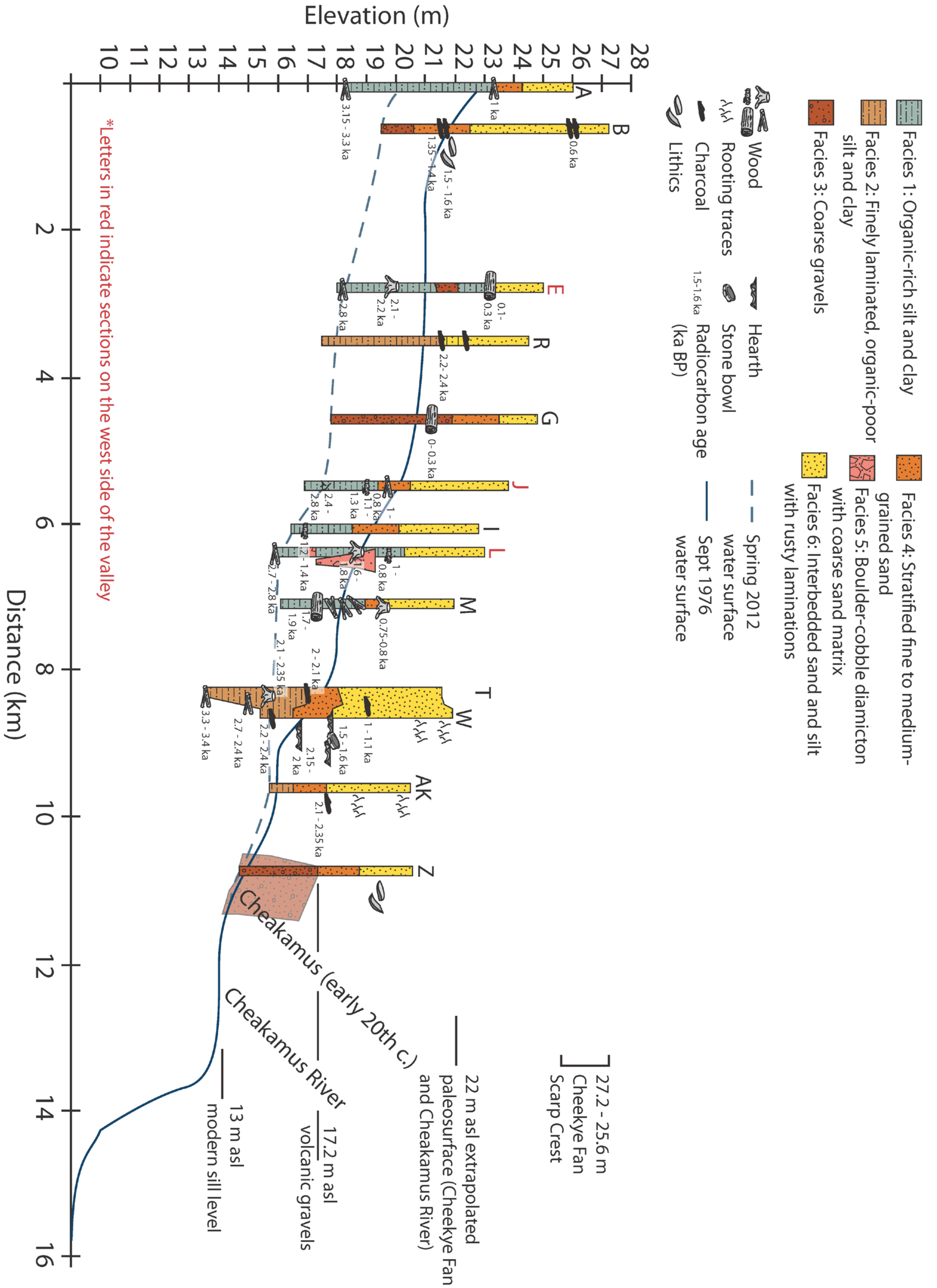

Figure 2.4. ***Stratigraphy of bank sediments at 14 study sites along Squamish River. Section N is included with sections T and W and thus is not shown separately.***

Macrofossil samples from facies 1 at the base of sections L and E comprise sedge seeds and herbaceous (probably sedge) rhizomes and stems. Mats of *Equisetum* occur in many sections, but cannot easily be identified to species, reducing their indicator value. Peaty deposits at sections I and J contain mats of 1-cm diameter woody stems or roots. Samples of peat from section A contain sedge seeds and seeds of *Menyanthes trifoliata*, a common pond plant. Samples collected at sections A, E, and L show an upward increase in either deciduous leaf litter, moss, woody twigs and cedar scales, or conifer needles and cones. The samples from section L contain many hemlock and spruce needles and a hemlock cone, but no deciduous leaf fossils.

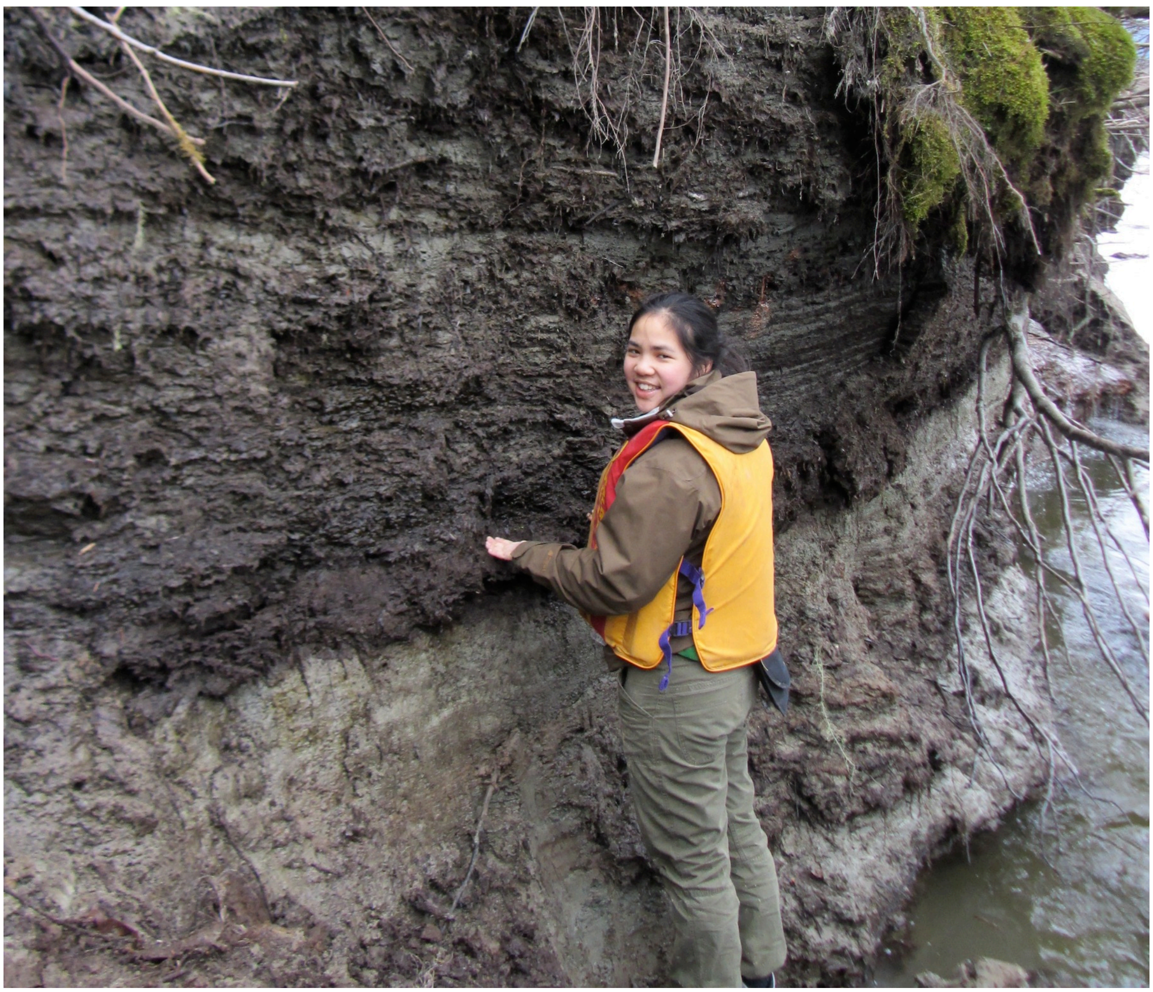

Figure 2.5. Organic-rich silt and peat at section J.

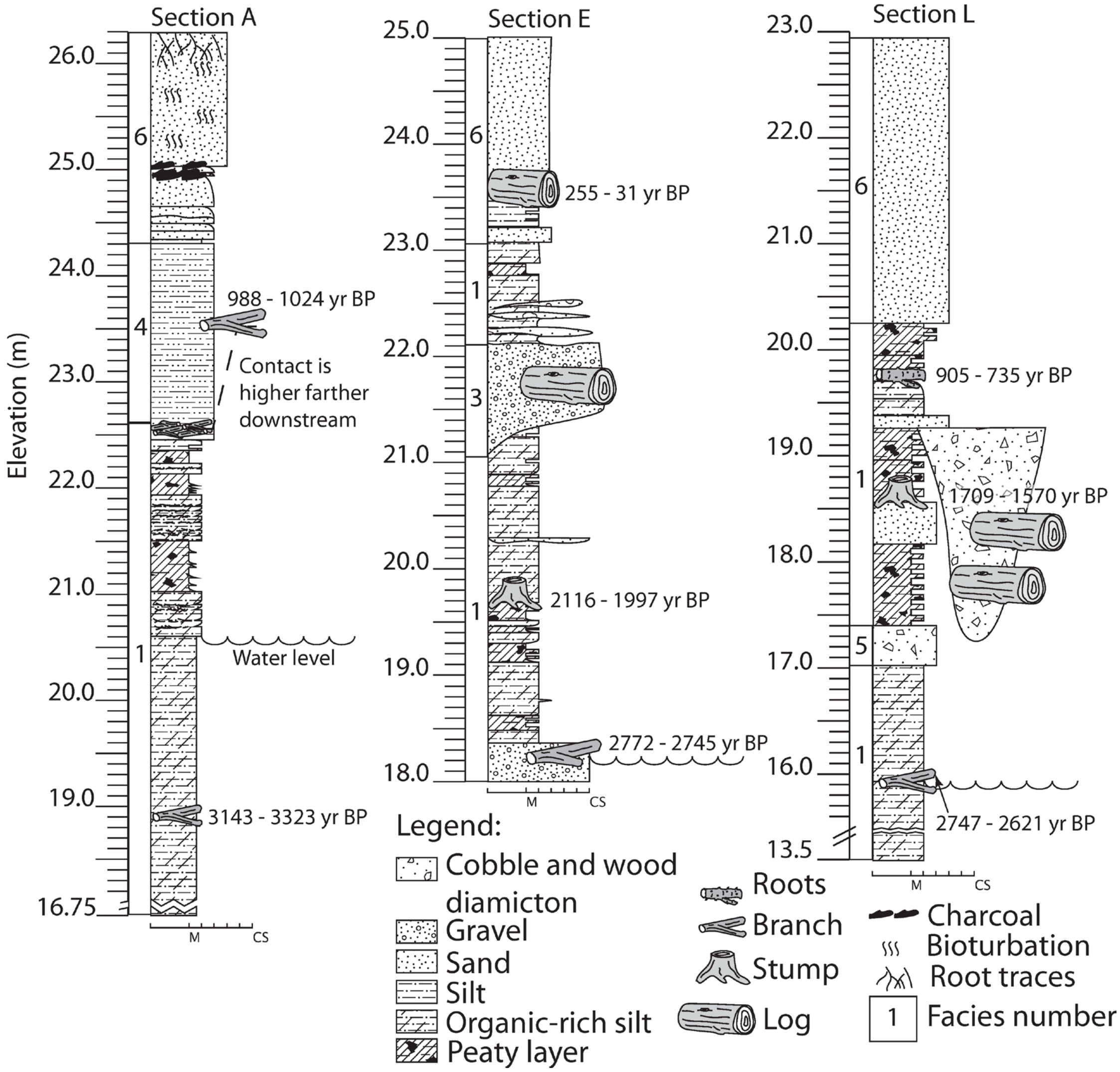

Figure 2.6. Stratigraphy of sections A, E, and L. Numbers to the left of stratigraphic columns refer to facies.

Interpretation

Styan and Bustin (1983) describe deposits similar to facies 1 in the Fraser River lowland east and south of Vancouver. They name these deposits: sedge-clays, sedge-grass peats, and sedge-wood peats. Sedge-clay deposits are dominated by layers of sedge, grass, and *Equisetum* stems, similar to deposits found in sections A, E, I, J, and L. Thin silt and fine sand layers are interpreted as distal crevasse splay deposits. Sedge-wood peats, which Styan and Bustin (1983) associate with natural levees, contain layers of horizontal birch stems and branches. Similar deposits occur at sections I and J in my study area.

Facies 1 records an aggrading, periodically inundated sedge fen on a floodplain or at the margin of a shallow lake. Influxes of sand and silt into fens periodically interrupted deposition of peaty layers. Fens adjacent to valley-side fans were channelized and then rapidly back-filled by debris flow deposits containing large woody debris (section L), sand (section J), or gravel (section E). In some cases, channels may have aggraded behind log jams. Fens may have formed at the margins of these fans where the river flowed around them or where the fans built deltas into standing water. Many of these fans have since been partly eroded by the river. Squamish River floods and periodic debris flows from the sidewall fans left sand, gravel, and diamicton lenses in the fine-grained silt and peat layers at these sections. Lenses of coarse-grained sediment are absent at sections on the east bank of the river; these sections display a gradual transition from periodically flooded sedge fens to riparian forest. The lithological signature of this transition is an increase in silt relative to peat and a short gradational contact between facies 1 and facies 4 above it. This contact records flooding of the sedge fens and deposition of fine-grained sand.

2. Laminated and thin-bedded, organic-poor silt (sections N, R, T, W, and AK)

Organic-poor silt of facies 2 is exposed in the banks of Squamish River up to 8 km upstream of Cheekye Fan. Facies 2 is dominated by laminated and thin-bedded, olive-brown to light tan silt (Figure 2.7). The sediments are typically mottled, and some strata are gently folded, perhaps due to dewatering during and following deposition. This facies lacks the peaty layers that are common in facies 1, but it does contain in-situ stumps and detrital wood, including large branches and tree stems.

Facies 2 is generally overlain across a gradational contact by stratified fine-grained sand (facies 4), which in turn grades up into facies 6 (Figure 2.8). In some sections near the west valley wall, debris-flow deposits (facies 5) overlie facies 2 (Figure 2.7). The typical upper limit of facies 2 (sections T, N, W, and AK) is 15-16 m asl. Section R has an unusually high occurrence (20 m asl) of the facies and is located several kilometres upstream of other sections with similar lithology.

Figure 2.7. ***Laminated silt 0.6 km upstream of section T. The pit is approximately 50 cm deep. Coarse gravel on top of the laminated silt is from a nearby alluvial fan.***

Interpretation

Sediments similar to facies 1 and 2 have been documented in interchannel basins and backswamps in anastomosing river systems in eastern British Columbia and western Alberta (Smith, 1972, 1983; Smith and Smith, 1980; Makaske et al., 2002, 2009). These river reaches are upstream of alluvial fans and are a good analog for a fan-dammed river.

I infer that sediments of facies 2 were deposited in one or more shallow lakes 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, folding, and dewatering, which are common processes in a lake prodelta environment. Many of these sections are close to one another and represent different parts of a since-vanished lake. Section R, farther upstream, may be an erosional remnant of the lake when the outlet of the lake was higher, or it may represent a shallow, channel-marginal pond in an aggrading delta system.

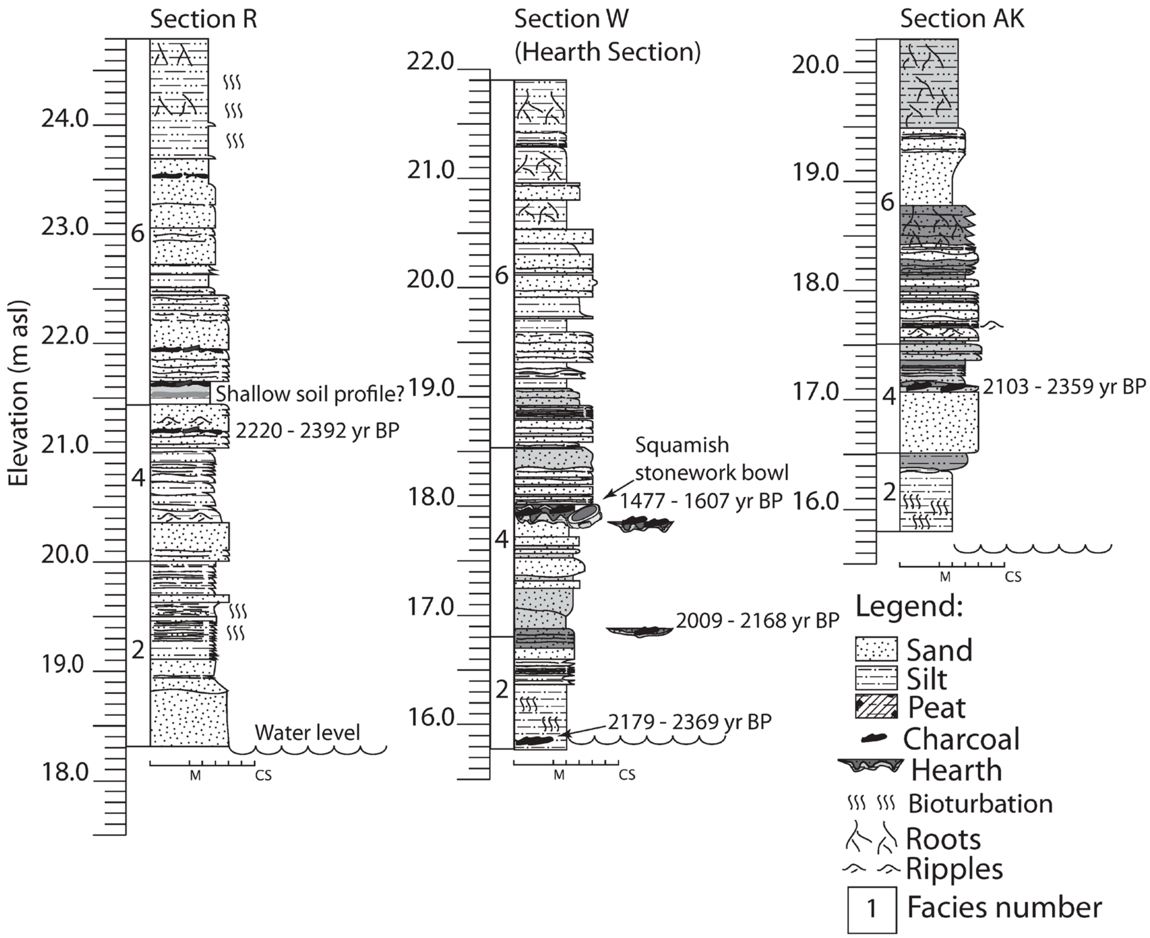

Figure 2.8. Sections R, W, and AK.

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

Gravel at sections B and G is crudely stratified and clast-supported, with a coarse sand matrix (Figure 2.9, 2.10). Clasts are pebble- to cobble-size and composed mostly of granitic rock. Section E contains a channel fill of pebble gravel with clasts that are less rounded and smaller than those at sections B and G (Figure 2.9A).

Figure 2.9. ***A – Pebble gravel (indicated by arrow) interbedded with medium sand at section G. Shovel is 1 m long. B – Fan gravel at gravel pit near the confluence of Squamish and Cheekye rivers (largest clasts are 20-30 cm long).***

Gravel in bank exposures near the confluence of Squamish and Cheakamus rivers is very coarse, up to boulder-size. Cobbles and boulders are well rounded to sub-rounded and consist mostly of dacite and basalt sourced from nearby lava flows in the Garibaldi volcanic complex; minor granitic and greenstone rocks are also present (Figure 2.9B).

Gravel between section Z and the Squamish-Cheakamus river confluence occurs up to 17.2 m asl, or 2 m above the low-water level of Squamish River along that reach. Facies 3 also occurs in a gravel pit on the north side of Squamish River valley (starred in Figure 2.3).

Interpretation

Coarse gravel at sections B and G resembles the modern channel and point bar deposits of Squamish River (Brierley and Hickin, 1991) and was likely deposited in these environments. Facies 3 includes younger channel deposits, for example those at section G, and older point bar deposits such as those at section B. The gravel at section E, given its location and geometry, is a fan deposit from an unnamed creek on the west side of the valley.

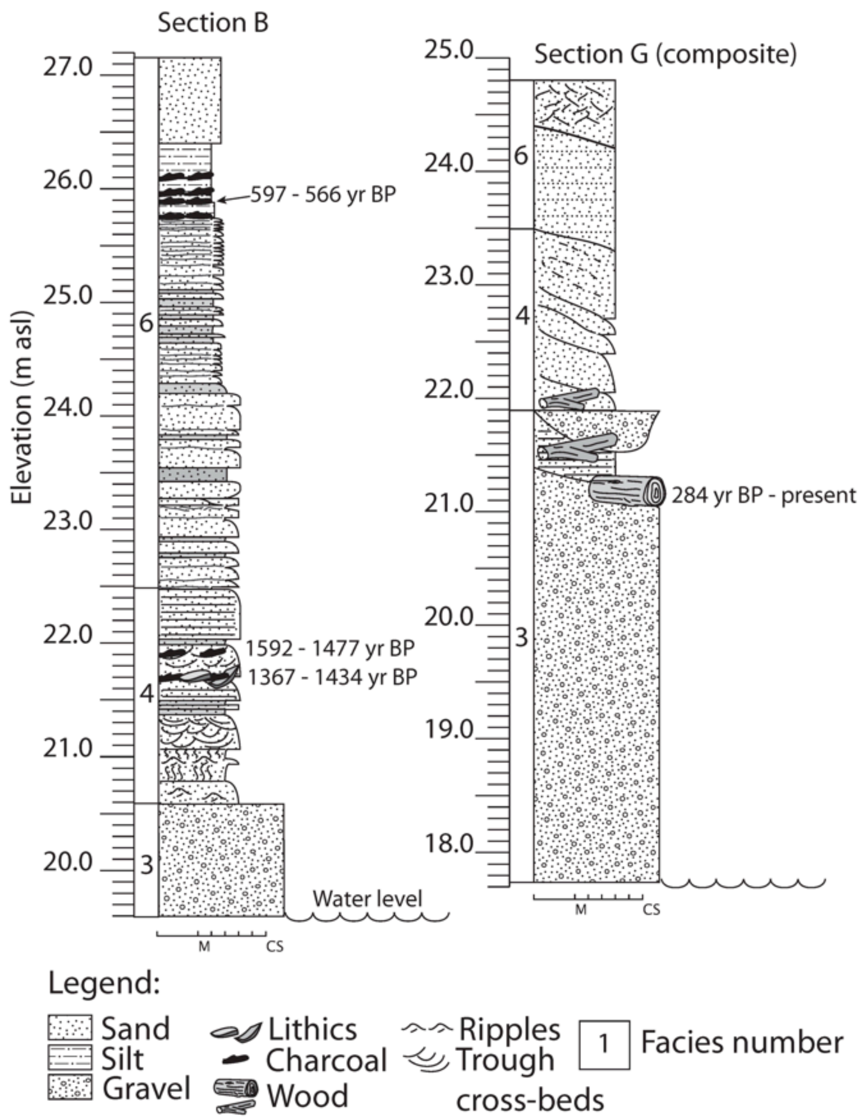

Figure 2.10. Stratigraphy of sections B and G.

Gravel in the vicinity of section Z is associated with a low-gradient alluvial fan marking the former confluence of Cheakamus and Squamish rivers. The location of the Cheakamus River channel on the fan must have changed, perhaps repeatedly, between Cheekye Fan and the north side of Cheakamus Valley for the gravel to have such a wide spatial distribution.

4. Stratified and massive fine to medium sand (all sections except E, R, and L)

Facies 4 consists of beds of well-sorted, fine- to medium-grained sand that are typically 10–20 cm thick, but may be up to 40 cm thick (Figures 2.9A, 2.10). Beds are horizontal or inclined. In logged bank exposures, the unit is commonly 1–2 m thick and overlies facies 1 or 2 across a gradational contact. Where it overlies facies 1 in sections A, I, and M, the sand is water-saturated, silty, poorly structured to massive, and liquefiable. Massive sand also occurs at several other locations. Facies 4 sharply overlies facies 3 gravel and is everywhere gradationally overlain by facies 6. Sedimentary structures include ripples, troughs, cross-beds, and planar tabular cross-stratification. Many beds also contain rust-coloured mottling and include evidence of rooting.

Facies 4 sand may have been deposited rapidly: 3 m of inclined, stratified sand beds were deposited on top of channel gravel at section G in less than 300 years, and sand completely fills an incised channel at section J. Planform changes visible on airphotos and historic maps reveal that many parts of the Squamish River floodplain upstream of the study area that are underlain by facies 4 sand are less than 100 years old. Several occurrences of facies 4 also appear to be associated with meander migration: GPR profiles reveal a buried channel and scroll bars near section B, indicating that channel migration played an important part in floodplain development about 1300 years ago (Figure 2.11).

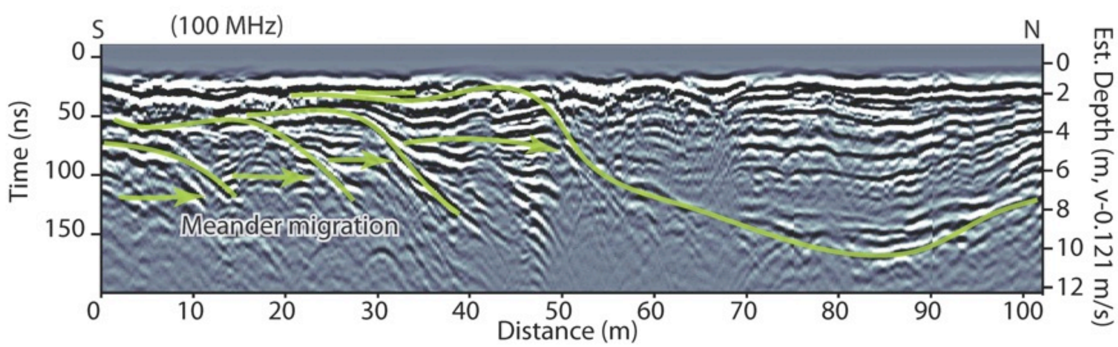

Figure 2.11. GPR profile near section B (see Figure 2.3 for location).

Interpretation

Brierley and Hickin (1991) describe several different Squamish River floodplain elements that contain stratified sand: their bar platform, chute channel, ridge, and sand wedge elements. All of these elements, except the sand wedges, are within-channel deposits. Thick, dipping beds of stratified sand, such as those at section G (Figures 2.10A, 2.11), and trough cross-bedded sand beds at the base of section B are probably bar platform deposits. Wavy- and horizontally bedded sands higher in sections are likely ridge deposits, which Brierley and Hickin (1991) ascribe to channel-marginal levees. Massive silty sand at facies 1-facies 4 contacts may represent distal overbank deposits (Brierley and Hickin, 1991), perhaps deposited as crevasse splays. The lack of stratification in these sands may result from root action or possibly rapid deposition from suspension. Massive sand at section J, however, lacks mottling commonly associated with rooting activity and, given that it fills a channel, probably is associated with a nearby alluvial fan.

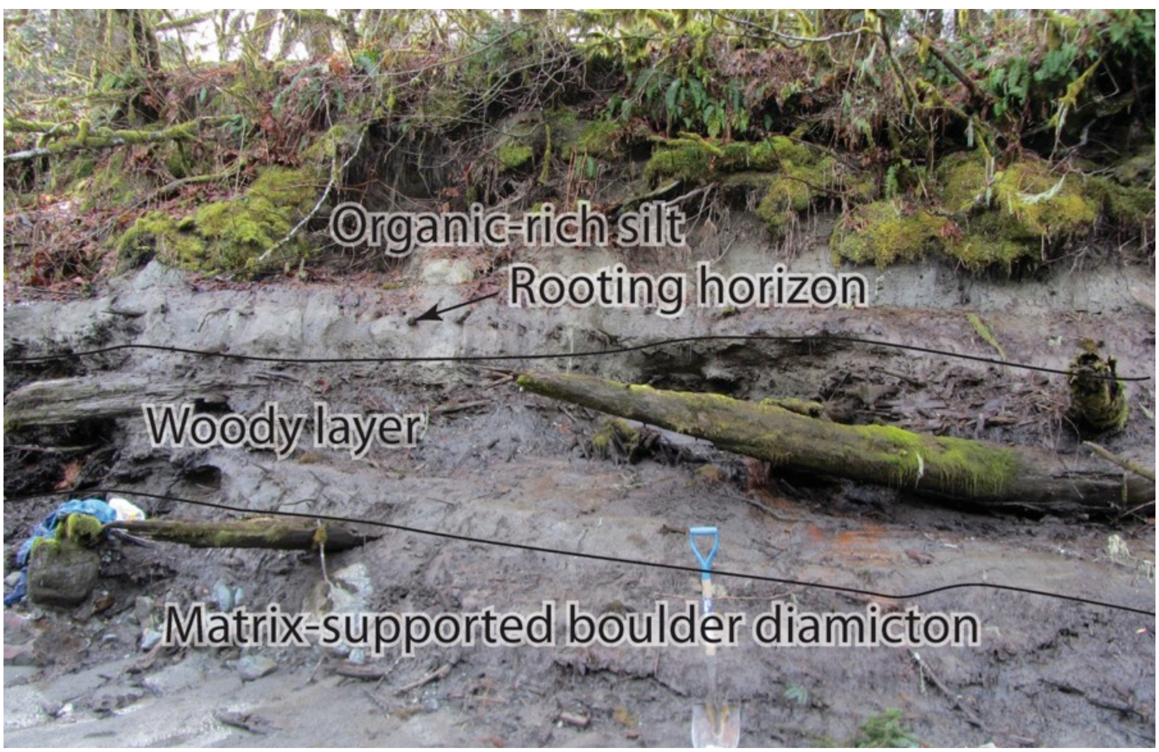

Figure 2.12. Woody diamicton at section L.

5. Diamicton with coarse sand matrix (section L)

Weakly stratified, matrix-supported diamicton with angular to subrounded granitic cobbles and boulders and abundant woody debris is exposed at section L (Figure 2.12). The matrix of the diamicton is mainly sand, but includes silt, granules, and small pebbles. At section L, facies 5 occupies a narrow channel within facies 1 and is also overlain by facies 1. In other bank exposures, facies 5 overlies facies 1 or 2.

Interpretation

I observed sediments similar to facies 5 in riverbank exposures at the margin of other fans on the west side of Squamish River. The abundance of large woody debris and locally derived granitic clasts, and an association with valley-side fans indicate that sediments of facies 5 are debris-flow deposits.

6. Horizontal, interbedded sand and silt (all sections)

Interbedded sand and silt are the dominant sediments in the upper part of bank exposures along the studied reach of Squamish River. This facies consists of beds of fine to very fine sand ranging from 2 to 20 cm thick, separated by thin (0.5–4 cm) laminae and beds of silt and organic silt (Figure 2.13). The dominant sedimentary structures in the sand beds are horizontal planar stratification and ripples. Where facies 6 extends to the surface of the floodplain, it is disturbed by numerous plant roots and contains root traces of riparian shrubs and herbs. Sedimentary structures within the rooting zone have been almost completely destroyed by bioturbation, making it impossible to determine the thickness of individual beds.

Interpretation

Brierley and Hickin (1991) described sediments similar to facies 6 in their study area as channel-marginal overbank sediments deposited during floods. The rhythmically alternating sand and silt layers of facies 6 are the product of repeated out-of-channel floods. The floods created natural levees that extend onto the floodplain away from the banks of Squamish River. Thin organic-rich silt layers separating the sand beds are incipient soils that developed on the floodplain between floods.

Figure 2.13. Interbedded sand and silt at section W.

2.4.2. Depositional environments

I assigned the six facies to four depositional environments: herbaceous wetlands, shallow basins, fans, and meandering channel and overbank deposits.

1. Herbaceous wetlands (sections E, J, L, A, I, and M)

Herbaceous wetlands are dominated by facies 1 (organic-rich silt and peaty layers). These sediments occur in riverbank sections in the northern part of the study area and extend over great distances along banks and into the floodplain. A GPR survey near section M reveals fine-grained beds with poor signal penetration several hundred metres away from the main river channel. Trough cross-bedded channel sands fill an incised channel near the riverbank (Figure 2.14). This record suggests that fine-grained sediments are laterally extensive; they are not limited to oxbow lakes or concave bank-bench deposits, nor are they interrupted by sand-filled channels. The length and continuity of fine-grained sediment exposures in riverbanks supports this interpretation.

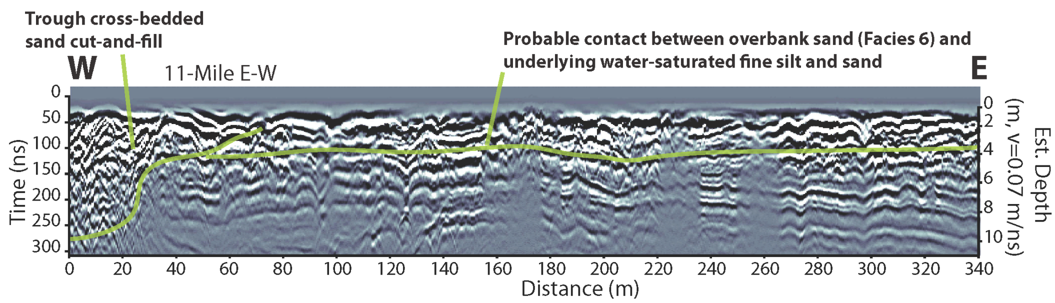

Figure 2.14. GPR profile in fine-grained sediments near section M (location shown in Figure 2.3).

Fens are considered transitional between marsh and bog environments (MacKenzie and Moran, 2004). When a ponded water body fills with sediment and peat begins to accumulate in the basin, acidic conditions support a community of mosses and ericaceous herbs. In sections in the study area, however, there is no evidence for an upward increase in mosses or ericaceous herbs. Instead, fens at sections E, L, and A were succeeded by floodplain forest. In stratigraphic terms, herbaceous wetland sediments were succeeded by alluvial fan deposits, stratified sand, and overbank fines, rather than by more peat. Floodplain aggradation possibly prevented bogs from forming on the Squamish River floodplain, although they have formed along other rivers in southwestern British Columbia, for example Fraser River (Styan and Bustin, 1983). Alternatively, the change in vegetation may reflect a lowering of local base level. If the elevation of the river channel was falling, even as the floodplain was aggrading, the widespread fen on the Squamish River floodplain might have been replaced immediately by a well-drained forest with scattered backswamps.

2. Shallow basins (sections R, T, N, W, and AK)

This depositional environment is dominated by facies 2 (laminated and thin-bedded, organic-poor silt), which occurs over a large area, mainly in the southern part of the study area within 4.5 km of the northern limit of Cheekye Fan. It records deposition in a long–lived, spatially extensive, although shallow lake. The gradational contact between facies 2 and overlying facies 4 indicates that the lake eventually filled and its deposits were covered with fluvial sand. The transition between the two environments may involve sediment bypass in channels within a shallow lake, where water depth was insufficient to accommodate delta foresets. Such bypass sediments have been documented in a fjord-fill sequence in Norway and are thought to have been deposited in water depths less than 2.5 m (Eilertsen et al., 2011). This interpretation is consistent with the idea that Squamish River filled a very shallow lake at the end of the Holocene. Cheakamus River may also have contributed sediment to the lake in this part of the valley (Figure 2.3). Facies 2 was partially covered by prograding fans along the western margin of the valley (Figure 2.7).

3. Fans (sections E, J, and L)

Diamicton (facies 5) and gravel (part of facies 3) fill channels cut into shallow lacustrine or wetland sediments at the margins of fans on the west side of Squamish Valley. Sheets of poorly sorted gravel with monolithic granitic, angular clasts overlie inorganic silt (facies 2) 0.6 km upstream of section T on the west side of the river (Figure 2.7). Stratified coarse gravel exposed near the confluence of Cheakamus and Squamish rivers (part of facies 3) is part of the low-gradient alluvial fan of Cheakamus River.

4. Channel and overbank environments (sections B and G; uppermost unit along most of the Squamish River study area)

Sediments of channel and overbank environments include coarse gravel (facies 3; sections B and G), stratified sand (facies 4), and interbedded fine sand and silt (facies 6). The main depositional environments are point bars (facies 3, 4, and 6 at sections B and G) and bank levees (transition between facies 1/2 and 4, sections I and M; and facies 6, sections R, T, N, W, and AK). GPR profiles reveal scrolls of point-bar deposits and infilled channels of this environment (Figure 2.14).

2.5. Development and evolution of a downstream dam on Squamish River

Fine-grained sediments exposed in riverbanks within the study area were deposited in a slackwater environment upstream of Cheekye and Cheakamus fans. Topographic profiles near the present-day Squamish-Cheakamus confluence indicate that the elevation of the barrier at one time was 20–22 m asl (Figure 2.15B). Elevation data from the incised portion of Cheekye Fan yield a similar barrier elevation (Figure 2.15A).

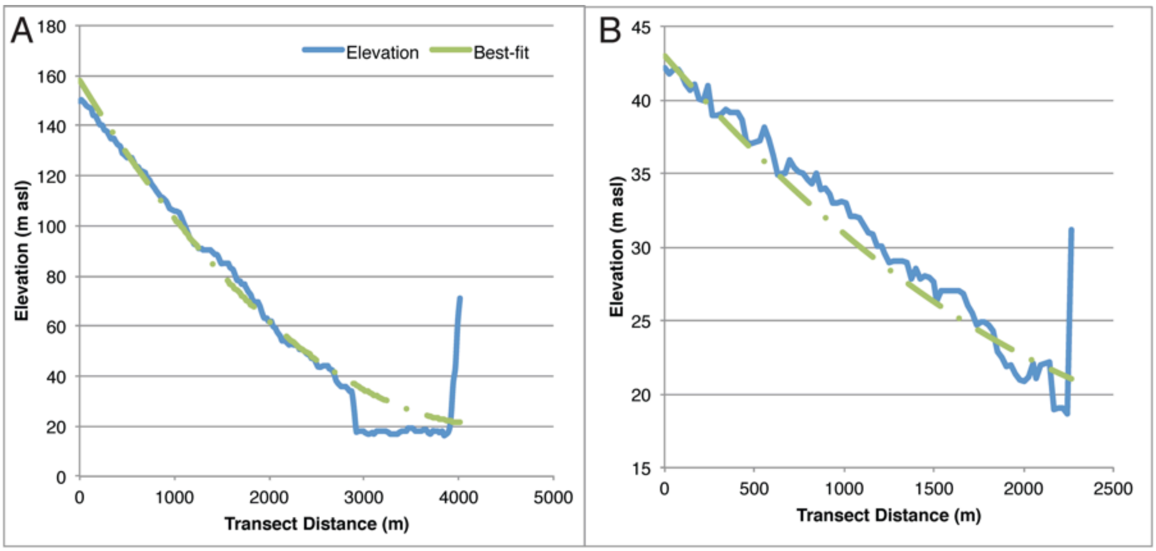

Figure 2.15. Topographic profiles across (A) Cheekye Fan and (B) Cheakamus River (see Figure 2.16 for locations).

Organic matter in silt at an elevation of about 13 m asl from the incised west margin of Cheekye Fan yielded a calibrated radiocarbon age of 6450-6950 years (5890 ± 100 ^{14}C yr BP; GSC-3256; Eisbacher, 1983). Charcoal from a debris flow unit 2 m lower in the same exposure yielded a calibrated radiocarbon age of 7400-7700 yr BP (6595 ± 90 ^{14}C yr BP, GX-17894; Thurber Engineering/Golder Associates, 1993). The dated materials underlie, respectively, 13 m and 15 m, of coarse fan gravel and debris flow deposits that extend to an elevation of about 25–26 m asl (Figure 2.16A). Based on these data, Cheekye Fan impounded Squamish River upvalley to an elevation of about 20–22 m asl after 6500 years ago.

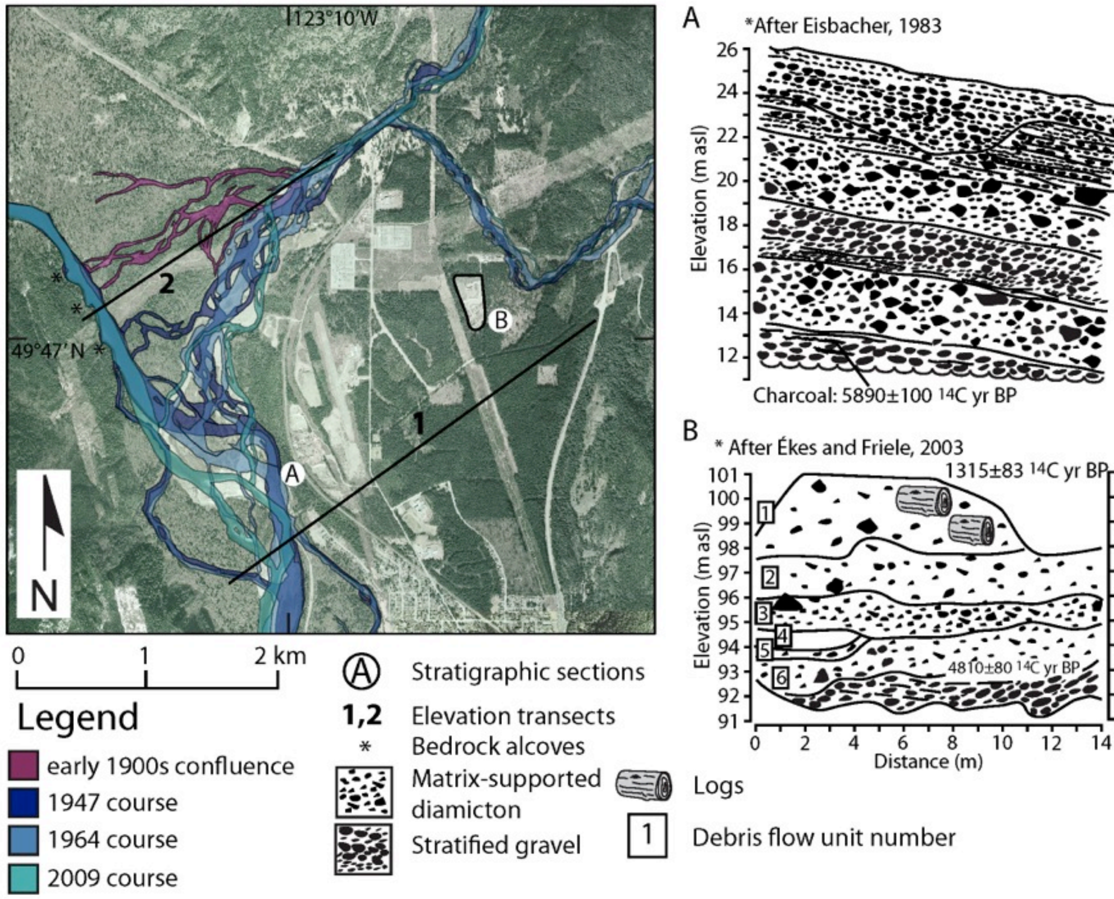

Figure 2.16. Southward shift of the confluence of Squamish and Cheakamus rivers during the twentieth century. A. Squamish River section on Cheekye Fan. B. Squamish Landfill section.

A section at Squamish Landfill shows six debris-flow units overlying 5500-5700-year-old stratified gravel (Figure 2.16B; 4810 ± 80 ^{14}C yr BP, GSC-6293; Ékes and Friele, 2003). Successive debris flows built up the surface of the fan and 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 been routed into Cheakamus River just above its confluence with Squamish River, contributing to maintenance of the barrier in that area. Fan gravel up to 17.2 m asl, or 2.8 m above present-day Squamish River low-water level at section Z, records progressive incision of the barrier from 20–22 m asl to the present level of about 14 m asl starting around 5500 years ago (Figures 2.4, 2.17).

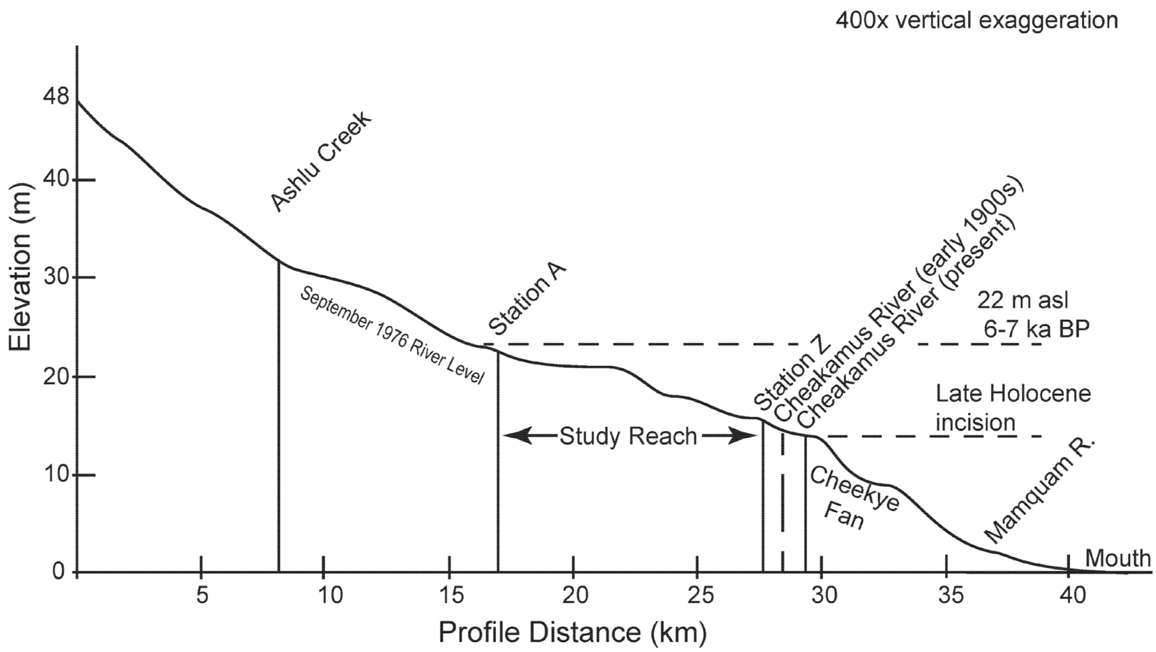

Figure 2.17. Longitudinal profile of lower Squamish River.

Maps from the 1890s (unknown author, 1893, "Cheakamus No. 11 Reserve [map]") and airphotos from 1948 indicate that the Squamish-Cheakamus confluence shifted 1.5 km southward from its former position near section Z sometime in the past century (Figure 2.16). Opposite section Z, and in several places downstream, there are alcoves carved into bedrock on the west side of Squamish River. The alcoves are set back about 10-50 m from the main river channel and are 100–200 m long in near-vertical bedrock cliffs. Small, high-gradient tributary streams flowing into Squamish River from the west have eroded the alcoves, and Cheakamus River has deposisted bouldery fan gravels against them. The notches indicate that the Cheakamus-Squamish confluence has shifted many times in the past and also show that Squamish River is constricted in this reach. Debris flows from Cheekye Fan continue to supply material to Cheakamus River. Cheakamus River transports that sediment to its confluence with Squamish River. A series of such debris flows in the future might plug the current channel of Cheakamus River, triggering another northward shift in the confluence.

Based on contours on the Squamish River floodplain map, I estimate that about 3 x 10^5 m^3 of sediment would be required to temporarily raise the level of Squamish River at the site of the old Squamish-Cheakamus confluence to 19 m asl. The approximate size of a Cheekye River debris flow with a 20-year return period is about 2 x 10^5 m^3 (Jakob et al., 2012). Debris flows of this size are large enough to temporarily dam Cheakamus River, although much of the sediment is fine and would be rapidly removed by the river. However, a series of such debris flows, or a larger debris flow with an average return period of 50–100 years (4-6 x 10^5 m^3), might overwhelm Cheakamus River and force it to aggrade the confluence area, elevating local base level over a period of decades or longer.

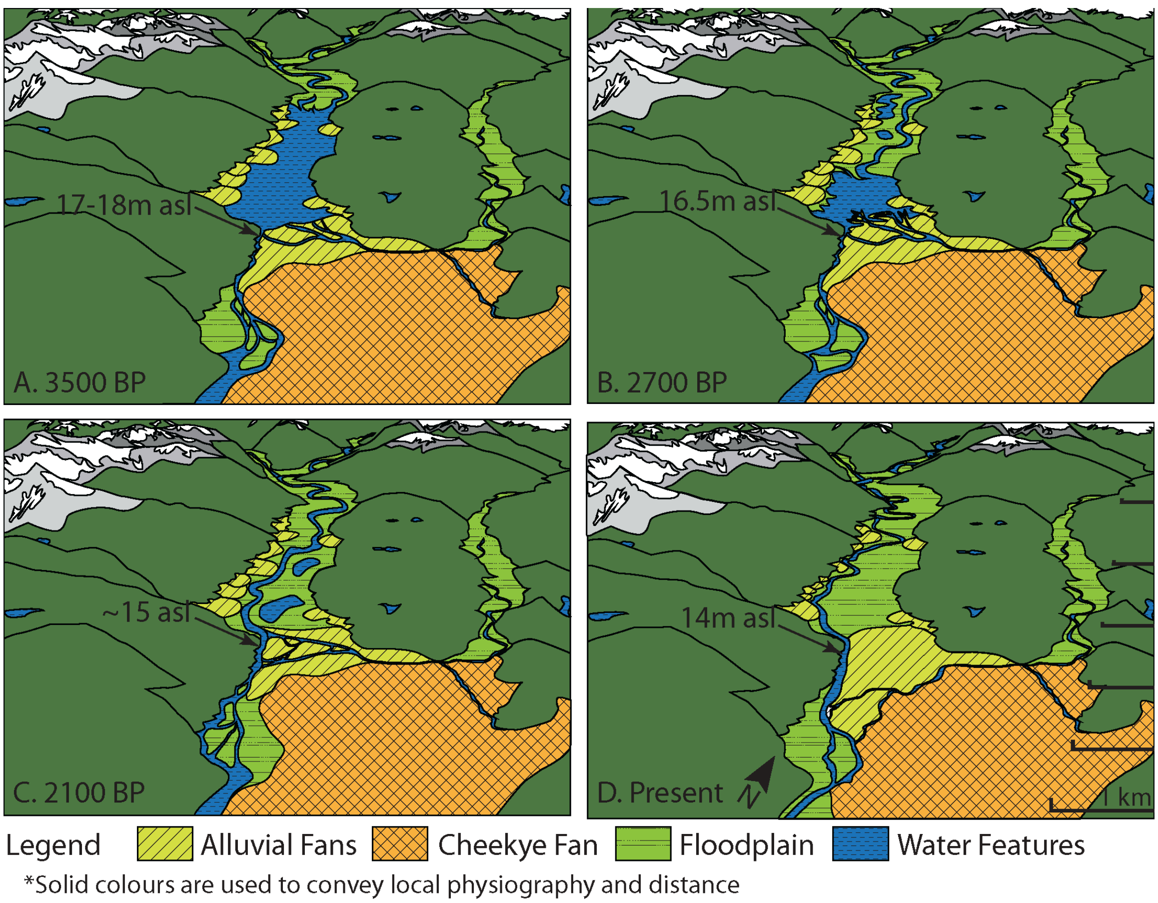

Figure 2.18. Inferred evolution of the Squamish River valley in the study area over the past 3500 years.

2.6. Evolution of Squamish River and its floodplain

2.6.1. Extensive lacustrine phase (3400–3000 years ago)

A lake extended at least 7 km and perhaps as much as 9.5 km upvalley of Cheekye Fan approximately 3400 to 3000 years before present. Detrital wood retrieved from facies 1 at section A was deposited 3140–3320 years ago at about 19 m asl (Figure 2.6). I found no datable organic material in facies 2 sediments exposed at about 20 m asl at section R, but presumably they are substantially older than a 2200-2400-year-old horizon more than a metre higher in the section. Farther downstream, at section T, a detrital log collected from facies 2 at 13.5 m asl yielded a calibrated radiocarbon age of 3320-3430 yr BP (Figure 2.8). This log is lower in elevation than the low-water level of Squamish River at its constricted reach near section Z. If it was deposited in a quiet-water environment 3300 years ago, base level must have been higher than today, but no higher than the uppermost level of facies 1 at section A.

Available data allow two possible interpretations of the elevation of the lake outlet at Cheekye Fan. First, organic-poor silt at section T accumulated in a shallow lake with an outlet at about 19-20 m asl. In this case, fine sand and silt at section R may have been deposited at the Squamish River delta front. As Squamish River lowered the lake outlet, local base level fell and the river eroded the sand and silt. An alternative interpretation is that, by 3500 years ago, the lake outlet was already 17-18 m asl, or about the same elevation as cobble-boulder gravel exposed at section Z (Figure 2.18A). In this case, fine sand and silt at section R is an erosional remnant of a lake with a higher outlet. The shape of the long profile near section R suggests that the section of river between sections B and G may represent an older delta surface graded to approximately 20–22 m asl (Figures 2.4, 2.17). As the delta prograded, the fringing wetlands on the shores of the lake likewise advanced. This scenario is manifested by a decrease, over time, in the elevation of organic-rich silt and peat in the downvalley direction. 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 Lillooet Lake fell, the delta at its north end rapidly advanced into the lake (Gilbert, 1972; Jordan and Slaymaker, 1991). I favour the second interpretation outlined above, because it better reflects the likely elevation of the lake surface based on maximum rooting depths for sedges in facies 1.

2.6.2. *Shrinking lake (3000–2400 years ago)*

A fall in local base level from 3400 to 3000 years ago caused Squamish River to deposit sediment over newly exposed portions of the lake floor. A stick recovered from organic-rich silt and peat (facies 1) at 16 m asl at section L yielded a calibrated radiocarbon age of 2680-2800 years (Figure 2.6). Peat samples taken about 40 cm below the stick contain sedge seeds and graminoid stems and rhizomes. The species of sedge identified at this section commonly grow in shallow water, therefore I assume that lake level at the site was no higher than 16.5 m asl 2700-2800 years ago.

Wood collected from facies 2 at section N (ca. 15 m asl) yielded a calibrated radiocarbon age of 2430-2770 years and accumulated in a shallow lake extending at least that far upstream (Figure 2.4). Farther upstream, at section J, in situ roots from organic-rich silt and peat at 17.5 m asl returned an age of 2430-2770 years. Tree bark at 18.2 m asl at section E, collected from organic-rich silt and peat, gave an age of 2810-2830 years. The wood at section N was deposited in about 1 m of water in a shallow lake with an outlet at 16.5 m asl, as defined by the base of facies 1 at section L. The lake extended north to section L at this time, but the lake floor at section L became exposed soon thereafter as the outlet at Cheekye Fan lowered (Figure 2.18B). The tree bark at section E and the roots upvalley at section J are associated with a very low-gradient river system. The gradient between sections L and E 2400-2800 years ago was no higher than 0.0005. This value is a maximum, because peat at section E was deposited on the Squamish River delta above the lake surface.

2.6.3. *Incipient floodplain (2300–2000 years ago)*

By 2300 years ago, the Squamish River delta had advanced to Cheekye Fan and the lake upstream of the fan had become completely filled in. Squamish River continued to erode the barrier at the Cheakamus-Squamish confluence, both downward and headward. Sediment supply to the confluence was probably high enough to periodically maintain or even raise local base level, especially when the confluence was located in the most constricted reach of Squamish River, but the general trend was, and still is, slow incision. The oldest radiocarbon ages related to a vegetated floodplain on the former lake floor, all on charcoal, come from section R (21.5 m asl; 2220-2390 years), section W (15.8 m asl; 2180-2370 years), and section AK (17.5 m asl; 2100-2360 years) (Figure 2.8). These and other occurrences of charcoal are evidence of either human habitation on the valley floor or forest fires. A fire hearth found at 16.9 m asl at section W provides definitive evidence of human habitation in the area. The hearth contained a thin layer of oxidized silt and was capped by fine sand and silt. Charcoal recovered from the hearth is 2010-2170 years old. The oldest in-situ conifer stumps in upstream bank exposures occur at about the same stratigraphic level as the hearth. A stump at section E at 19.6 m asl returned an age of 2060-2180 years, and a stump at section T at 15.5 m asl gave an age of 2110-2350 years. Macrofossil samples collected near the stump at section E are largely of monocot rhizomes and sedge seeds, suggesting a sedge-dominated wetland environment. The presence of charcoal layers, hearths, and trees indicates that, by 2000–2300 years ago, the lake had drained and had been replaced by a vegetated floodplain occupied by humans (Figure 2.18C).

2.6.4. Mature floodplain (2000 years ago - present)

Sediments less than 2000 years old reflect this changed sedimentary environment. Silt continued to accumulate at sections I and J, where tree or shrub roots within facies 1 at 17 m and 19 m asl returned calibrated radiocarbon ages of, respectively, 1240-1360 years and 1130-1290 years. By 900 years ago, the dominant sediment being deposited on the valley floor was sand or alternating silt and sand. Macrofossil samples from 23.5 m asl at section A, near the contact of facies 1 and 4, include western redcedar seeds and scales, and broadleaf deciduous detritus. Wood collected from this horizon yielded a calibrated radiocarbon age of 990-1020 years. Macrofossils in sand at about 18 m asl at section L are dominated by cedar scales and conifer needles, and include still-green moss fragments. Both samples indicate a local treed environment. Together with the 1300-year-old roots at sections I and J, they indicate the presence of widespread forest and shrubland on the floodplain (Figure 2.18D).

2.7. Discussion

Widespread fine-grained sediments on the Squamish River floodplain were deposited in an extensive shallow lake upstream of the long-lived Cheekye and Cheakamus fan complex. Declining sediment delivery during the late Holocene allowed Squamish River to gradually lower local base level from a high of about 20–22 m asl to its present height of about 14 m asl at the upstream edge of the Cheakamus fan. The present floodplain contains backswamps and oxbows, but these floodplain elements do not explain the widespread occurrence of fine-grained sediments beneath the valley floor upstream of Cheekye Fan. The sediments are better explained as remants of a shallow lake that filled in and drained during the late Holocene.

2.7.1. Concave bank-benches and the origins of fine-grained sediment

Hickin (1979) describes accretion of fine-grained silty sand on concave bank benches along Squamish River. His thesis is that the bank benches formed at meander bends where flow separated in eddies away from the main thalweg. Silty sand was deposited from suspension during periods of high discharge and trapped in horsetail (*Equisetum* sp.) mats on bench surfaces. Channel avulsions after 1978 isolated the bench deposits and they were no longer accreting sediment. Structures like these, and their associated deposits, have limited areal extent and cannot alone explain the widespread fine-grained sediments on the floodplain. There is only one known area of concave bank benches on the present Squamish River floodplain, near section B. Bank-bench sediment is actively accumulating near a sharp bend in the river where the channel is bordered by a bedrock wall on the west. As the southeast bank retreats near section B, the concave bank bench on the northwest side of the river will accrete southward, in the direction of erosion.

Concave transverse profiles of banks, which might be mistaken for concave bank benches, are the result of differential erosion of loose sandy sediment overlying fine-grained cohesive fen and lake deposits. Typically, the fine-grained sediments extend only 1–2 m above the low-water river surface, resulting in a superficial resemblance to concave bank benches.

Examination of airphotos reveals relict meander bends in the study reach, including a recently abandoned series of meanders between sections G and I. The extensive fine-grained deposits in the southern part of the study area, however, impede meander migration. As Squamish River continues to lower the remnant barrier at Cheekye Fan, the river likely will maintain a straight to gently sinuous planform in this reach.

2.7.2. Effects of downstream base-level control in other watersheds

Fans and other barriers have affected upstream river planform and depositional environments in many watersheds in western Canada. Smith (1972) documented widespread fine-grained sediment deposition upstream of two alluvial fans near the confluence of Alexandra and North Saskatchewan rivers in the Rocky Mountains of Alberta. The Upper Saskatchewan fan, which blocks Alexandra River, has persistently raised local base level, allowing the river to aggrade over the Holocene. Gravel and sand in this system are restricted to anastomosing river channels. Organic-rich fine sediments and peat dominate inter-channel basins bordered by high river levees, and organic-poor silt and clay accumulate in intermittently connected ponds within inter-channel basins that are breached at one end (Smith and Smith, 1980).

Columbia River upstream of the town of Golden in southeastern British Columbia is also an aggrading, anastomosing system with deposits similar to those in the Alexandra River valley. Golden is located on a fan built out across the Columbia River valley by Kicking Horse River. The fan controls local base level in the Columbia River valley south of Golden (Smith, 1983). Anastomosing behaviour is most pronounced in a reach 40–60 km south of Golden, where sediment-charged Spillimacheen River enters Columbia River (Makaske et al., 2009). In this example, upstream sediment supply is also driving extensive fine-grained sediment deposition in the Columbia River valley south of Golden.

Hewitt (2006) coined the term "disturbance regime landscape" to describe river valleys that are frequently and persistently affected by disturbances such as landslides. Streams in such systems never achieve Mackin's (1948) graded profile. Typical landforms include relict landslide barriers, broad, low-gradient floodplains upstream of the barriers, and degradational terraces developed on lacustrine sediments. In the Alexandra River example mentioned above, an alluvial fan created a distinct signature in the long profile of the river – flat above the fan, and steeper across and downstream of it (Smith, 1972). Korup (2006) comments that many rivers impounded by landslides in mountainous regions have flattened profiles upstream of landslide barriers due to aggradation and are steepened by incomplete erosion downstream of the barriers. Likewise, the long profile of Squamish River is irregular, with steeper sections at and below Mt. Cayley due to landslides (Brooks and Hickin, 1991), and at the Cheekye-Cheakamus fan barrier. Framework-supported, cobble-boulder gravel at the old Cheakamus-Squamish confluence, which still affects the planform of Squamish River upstream, is a lag derived by winnowing of landslide-derived Cheakamus River bedload and Cheekye River debris flow deposits.

Sediment supply from Mt. Garibaldi has declined through the Holocene (Friele et al., 1999; Friele and Clague, 2009). Although there is still potential for large landslides from Mt. Garibaldi, most large slope failures occurred during and immediately after deglaciation (Friele et al., 1999; Ékes and Friele, 2003). Much sediment remains in the Cheekye basin, both in the headwalls and in the upper and middle fan, but sediment delivery has clearly decreased and Cheekye Fan is no longer building outward as it did in the past. In larger watersheds, there are larger stores of primary paraglacial sediment on valley sides and floors. An alluvial fan sourced in such a basin will continue to grow long after glaciation has ended, such as the upper Saskatchewan fan at the junction of North Saskatchewan and Alexandra rivers.

Cheekye Fan has had an extended effect on Squamish River. Although the amount of sediment delivered to the fan has declined, its effect upstream has persisted long beyond the deglaciation. It is possible, therefore, that Squamish valley represents a disturbance-regime landscape created by paraglacial landform development in the early Holocene (Hewitt, 2006). Future disturbances in the Cheekye basin will introduce pulses of sediment downstream, but they are unlikely to change the form or extent of Cheekye Fan, neither are they likely to elevate base level on Squamish River for an extended period of time.

2.8. Conclusion

Thick fine-grained sediments exposed in the banks of Squamish River north of Brackendale record a perturbation in local base level related to the building and incision of a downstream debris flow fan. Sediment supply to Cheekye and Cheakamus fans has been sufficient to maintain high, although falling local base level through much of the Holocene. Squamish River could be in the last stage of adjusting to this fall in local base level; if so, it will become more entrenched in its floodplain as headward and downward incision of the fan barrier continues. Sporadic and temporary increases in local base level, however, are possible in the future if large debris flows reach Cheakamus or Squamish rivers. The size and duration of this effect would depend on the position of the Cheakamus-Squamish confluence and the path of Cheekye River across Cheekye Fan.

3. A record of aggradation and flooding in Squamish River valley

3.1. Abstract

Squamish River is a flood-prone coastal river in southwestern British Columbia. Most floods result from rain-on-snow events, usually in the fall. There is also a possibility of rare, extremely large outburst floods caused by breaching of landslide dams near Mount Cayley, a Quaternary stratovolcano 45 km upstream of Squamish. Fine sand-silt couplets exposed in the banks of Squamish River upstream of Brackendale, British Columbia, record more than 1500 years of overbank flooding. In this chapter, I describe a technique for determining the average flood frequency over the 1500-year period of record. I calculated the average period between floods using an age-depth model obtained from radiocarbon ages. The age-depth model suggests that overbank floods have occurred, on average, every 5-15 years. The two sections on which this study is based, however, may under-record floods, in which case the average return period is shorter. On the other hand, historical hydrological data show that Squamish River floods have occurred, on average about every 18 years over the past 1500 years, less frequently than the estimated longer-term flood recurrence. I also looked for evidence of a catastrophic flood after Squamish River was blocked by a large landslide at Mt. Cayley about 1100 years ago. Although I found no evidence for a catastrophic flood, the Squamish River channel aggraded following the landslide.

3.2. Introduction

Paleoflood hydrology uses a set of earth science tools to extend historic flood records back into geologic time. The tools have been developed and used because the the length of gauged records on rivers, even those extending back more than 100 years, is commonly insufficient to determine the risks from rare, high-magnitude flood events.

The most successful method used in paleoflood hydrology research to date is the slackwater deposit paleostage-indicator method (Kochel and Baker, 1982; Baker, 1987). This method has been applied principally to flood sediments in semiarid bedrock canyons (Kochel and Baker, 1982; Kochel et al., 1982; Benito et al., 2003). Flood discharge can be readily calculated from the elevations of preserved flood sediments in these canyons, because the channel cross-section can be accurately defined and the researcher can reasonably assume that this cross-section has not have changed over the period of interest. Also, bioturbation of flood sediments is less intense in arid and semiarid settings than in temperate ones, so there is less loss of detail in the sedimentary record.

Radiocarbon-dated flood couplets have been used to estimate ice-jam flood frequency over an approximately 150 km reach of Yukon River in Yukon Territory and Alaska (Livingston et al., 2009). In this study, the average flood frequency was determined by dividing radiocarbon-dated intervals by the number of flood couplets in each interval. The approach differs from that used in the aforementioned slackwater studies in that it was applied to an alluvial river flowing on a floodplain rather than in a bedrock canyon. Livingston et al. (2009) assumed that the level of the river channel had not changed and that the channel had not migrated over the period of the record and thus that overbank deposits resulted from ice-jam flooding alone. This technique is well-suited for northern environments because overbank floods onto seasonally frozen ground are less likely to erode older flood layers.

The use of alluvial deposits on unconfined floodplains in humid environments for paleoflood analysis is more challenging. Squamish River, a coastal river in southwestern British Columbia (Figure 3.1), provides exceptional challenges to the paleoflood hydrologist because the river is actively reworking its floodplain. Over the past 63 years, about 5.3 km^2 of floodplain sediment has been reworked by the river on a reach 15 km above Cheekye Fan (Bauch and Hickin, 2011). Much of this erosion has occurred in a very active reach of the river just north of my study area, but there has been significant reworking along my study reach as well. Because Squamish River is not deeply incised into its floodplain, and because it has an alluvial channel that likely shifts on timescales of decades to centuries, the magnitudes of prehistoric flood magnitudes are difficult to determine at a specific site.

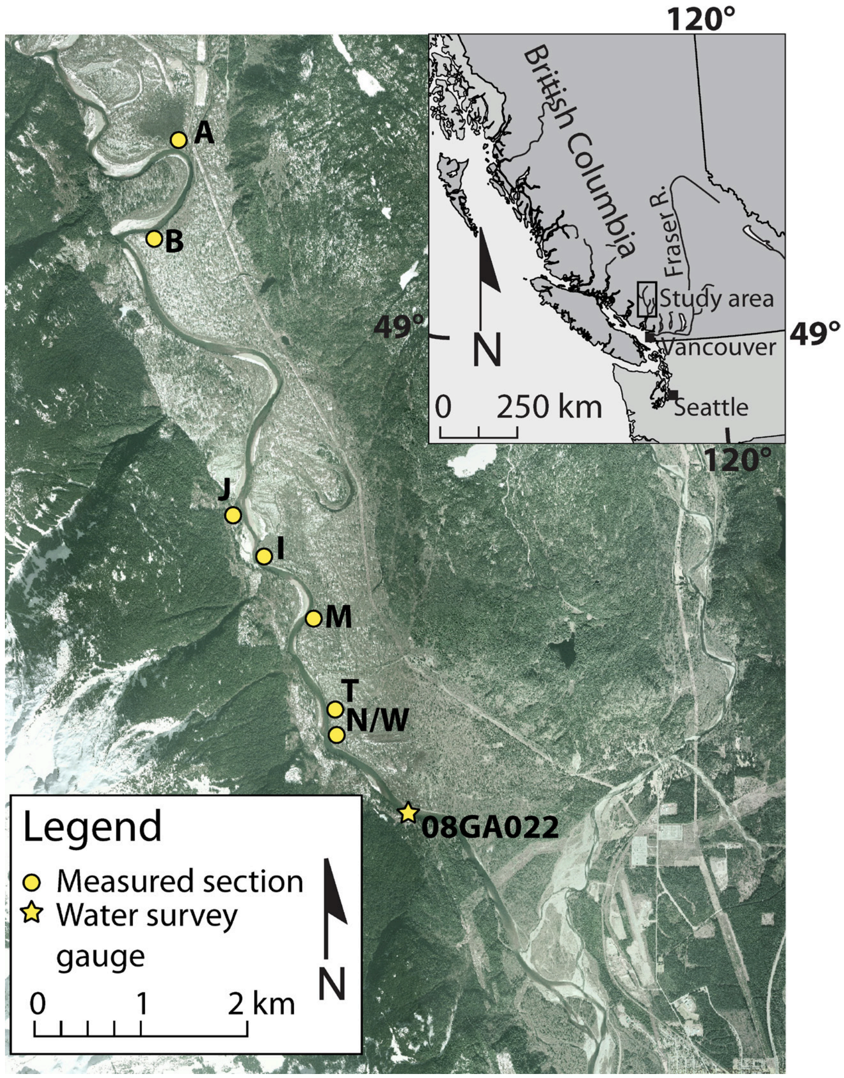

Figure 3.1. Sections along Squamish River that were documented in this study.

In this chapter, I describe and evaluate a technique that I developed to estimate the paleoflood frequency of Squamish River. The technique may be applicable to other low-gradient alluvial rivers. I also examine how breaching of an upstream landslide dam affected my study reach and whether Squamish River paleoflood deposits record flooding related to dam breaching.

3.2.1. Flood mechanisms

Squamish River has a strongly seasonal hydrology: low flows of 30–80 m^3/s occur from December through March, and high flows of 400–700 m^3/s occur during the summer freshet from June through August. Even larger overbank floods can occur from late September to December and are caused by "Pineapple Express" storms from subtropical latitudes that produce large amounts of rainfall and may melt the autumn snowpack.

Table 3.1. Recorded peak discharges from 1958 to 2012 for Squamish River above Brackendale (08GA022).

Date	Discharge (m^3/s)	Date	Discharge (m^3/s)	Date	Discharge (m^3/s)	Date	Discharge (m^3/s)
1958	1880	1972	1550	1986	1240	2000	1200
1959	1110	1973	1470	1987	1230	2001	1530
1960	1070	1974	844	1988	937	2002	1130
1961	1270	1975	1950	1989	1530	2003	3140
1962	1410	1976	1010	1990	2060	2004	1030
1963	1580	1977	932	1991	2460	2005	1280
1964	1160	1978	1190	1992	-	2006	1610
1965	1470	1979	1010	1993	906	2007	1460
1966	1170	1980	2180	1994	825	2008	1030
1967	-	1981	2270	1995	1660	2009	1510
1968	1840	1982	1340	1996	-	2010	1700
1969	1080	1983	1390	1997	1340	2011	1520
1970	912	1984	2610	1998	845	2012	1290
1971	1110	1985	978	1999	1350		

Daily peak discharges of the five largest floods of record exceed 2000 m^3/s, and the greatest recorded flood, on October 18, 2003, had an instantaneous peak discharge of 3140 m^3/s (Table 3.1; Figure 3.2; WSC 08GA022). Flood frequency analysis performed by Kerr Wood Leidal in 2011 suggests that the 2003 flood had a return period of 50-70 years (Table 3.2). Damages from Squamish River floods since 1980 have totalled over $20 million; most of this amount is attributable to the flood of record in October 2003 (Vancouver Sun, 2003; Septer, 2007). Infrastructure repairs and improvements subsequent to the flood are ongoing and expected to cost $18 million (Squamish Chief, 2013).

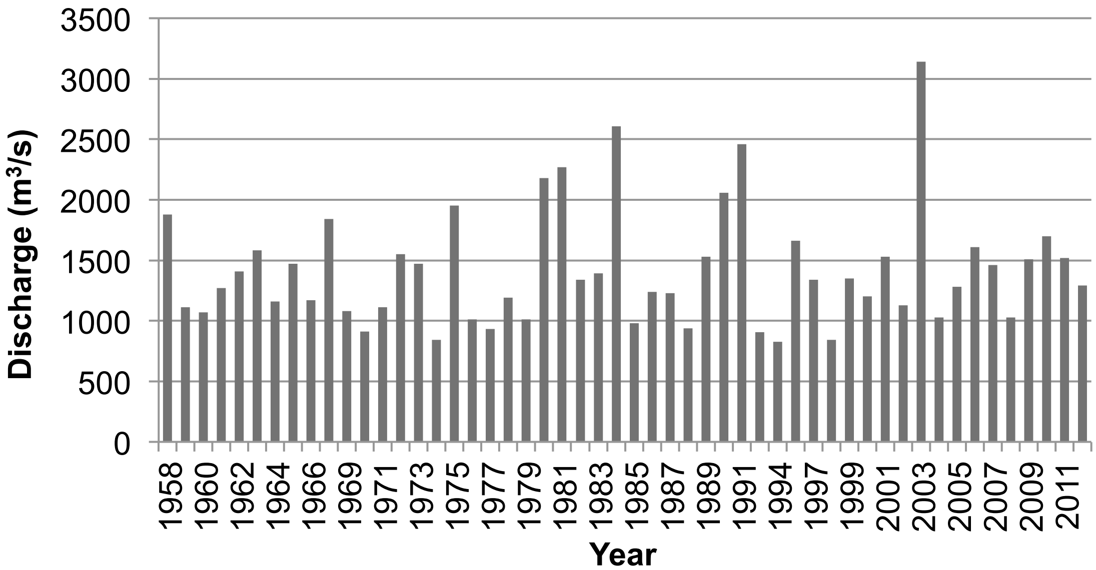

Figure 3.2. Peak discharges of Squamish River at Brackendale (08GA022), 1958-2012.

Table 3.2. Daily flood average discharges (peak instantaneous values in brackets) for Squamish River at Brackendale (08GA022) (Kerr Wood Leidal, 2011).

Return period (years)	Distribution			
	Generalized extreme value (m^3/s)	Three parameter lognormal (m^3/s)	Log Pearson III (m^3/s)	Average value (m^3/s)
2	1060 (1280)	1040 (1270)	1040 (1260)	1047 (1270)
5	1470 (1720)	1470 (1730)	1460 (1710)	1467 (1720)
10	1780 (2060)	1830 (2100)	1810 (2090)	1807 (2083)
20	2120 (2420)	2210 (2510)	2210 (2520)	2180 (2483)
50	2620 (2970)	2780 (3110)	2840 (3190)	2747 (3090)
100	3050 (3450)	3260 (3620)	3410 (3790)	3240 (3620)
200	3530 (3980)	3790 (4180)	4070 (4480)	3797 (4213)

An additional flood mechanism is breaching of blockages of Squamish River resulting from landslides at Mt. Cayley, a Quaternary stratovolcano 45 km upstream of Squamish. Such dams have formed many times in the past (Brooks and Hickin, 1991; Evans and Brooks, 1991). Although there is no published record of paleo-outburst floods on Squamish River, it seems possible that a large landslide at Mt. Cayley could impound a lake that would drain suddenly, producing a flood much larger than the 1:200 year design flood at Squamish (Woods, 1987). High flows related to landslide dam breaching have occurred elsewhere in the region, for example in the Lillooet River valley in 2010, following breaching of landslide dams on Meager Creek (Guthrie et al 2012).

3.2.2. Geomorphic context

Upstream of Brackendale, Squamish River is inset in a floodplain that formed in the past 2300 years on deposits of a Holocene lake (Chapter 2). Cheekye and Cheakamus fans formed a barrier that impounded this lake, but declining sediment supply from Mt. Garibaldi, a Quaternary stratovolcano, allowed Squamish River to progressively incise the barrier and lower and finally empty the lake about 2300 years ago (Chapter 2). At least 1500 years of flood history on Squamish River are recorded in rhythmic couplets consisting of very fine to fine sand and oxidized humic silt that have accumulated on levees adjacent to the main channel. The coarser layers record floods, and the finer oxidized humic silt layers are soils that formed during intervening periods of non-deposition when plants became established on the floodplain.

Bankfull discharge at the Squamish River gauging station north of Brackendale (Figure 3.1, station 08GA022) is estimated to be 2384 m^3/s (Lynne Campo, Water Survey of Canada, personal communication, 2013). Lower discharges could inundate parts of the floodplain upstream of Brackendale, where the river is not gauged. Based on the Water Survey of Canada overbank estimate at its gauging station, Squamish River has inundated its floodplain upstream of Brackendale about three times during the gauged period – in 1984, 2004, and possibly in 1991 – yielding an average overbank flood frequency of about 18 years.

3.3. Methods

3.3.1. Stratigraphy

I measured 14 sections in riverbank exposures during 2012 and 2013 (Figure 3.1; labelled alphabetically). In the course of the fieldwork, I selected several sections for detailed bed-by-bed measurements for this study. I recorded grain-size, sedimentary structures, strata thickness, oxidation, and bioturbation. I chose sections B and W (Figure 3.3) for flood analysis, because each contains a large number of well-preserved flood couplets in uninterrupted vertical sequences 3.1 to 5.4 m thick, and with radiocarbon-dated boundaries. Other sections were not mapped in the same detail, have poorly preserved flood couplets, or lack chronological control.

Table 3.3. Radiocarbon ages used in age-depth modelling.

Sample	Radiocarbon age (^{14}C yr BP)	Calibrated age (calendar years before AD 2012)	Material	Latitude (N), Longitude (W)	Depth (m)
B2	1450 ± 15	1367–1434	Charcoal	49°51'24.5", 123°14'33.5"	5.7
B10	480 ± 15	566–697	Charcoal	49°51'24.5", 123°14'33.5"	1.2
N1	1140 ± 15	1038–1142	Charcoal	49°48'10'', 123°13'46''	2.5
N3	2460 ± 15	2428–2765	Log	49°48'10'', 123°13'46''	6.4
T1	2130 ± 15	2108–2352	Stump	49°48'19.5", 123°12'47.5"	6.2
T2	3090 ± 15	3428–3325	Log	49°48'19.5", 123°12'47.5"	8.1
T4	2030 ± 15	1990–2102	Charcoal	49°48'19.5", 123°12'47.5"	2.9
W10	2170 ± 20	2179–2369	Charcoal	49°48'09.5'', 123°12'46''	6.1
Skw'enp' 4 Station W	1610 ± 20	1477–1607	Charcoal	49°48'09.5'', 123°12'46''	3.9

3.3.2. Age-depth modelling

I used radiocarbon ages from the measured sections (Table 3.3) to estimate average sedimentation rates at the two study sites. I input the ages into Clam, a freeware program in R that produces age-depth models for sediment sequences from radiocarbon ages (Blaauw, 2010). Clam produces a best-fit age-depth model by processing a large number of randomly chosen age-depth models using calibrated radiocarbon age distributions. During a single run, the program randomly picks simulated ages at different depths based on the modelled ages. After many runs, the program determines the most likely ages at specific depths, and the most likely sequence of ages. This procedure is known as Monte Carlo, or 'bootstrap' modelling.

For this analysis, I combined samples from sections T, N, and W, all of which occur within similar facies and are close to one another. Caution was required in combining the samples, in that samples at slightly different depths at two or more sections may be stratigraphically equivalent. I also used Clam to model radiocarbon age-depth relationships for section B.

Blauuw (2010) recommends that a Clam age-depth model be based on 10,000 runs in order to best characterize the variability in the radiocarbon ages on which the model is based and to ensure that accumulation rates and modelled ages are best constrained. I did not use polynomial age-depth interpolations to smooth the sequence, because rivers are unstable environments with highly variable accumulation rates, thus I could not assume gradual changes in the rate of sedimentation. Because the number of ages considered in this study is small, I used personal judgment in rejecting outliers or age reversals. Specifically, I eliminated two problematic ages: (1) At section B, an older age on charcoal was eliminated and the younger charcoal age used. (2) At the composite T/N/W, section the age of charcoal at section W overlaps the age of a stump at section T. The two samples occur at nearly identical stratigraphic levels, so the stump was chosen as representing a better limiting age. Removing the problematic ages from section W reduced the number of model runs with reversed ages.

I estimated the time between the formation of individual flood couplets in each section by dividing the couplet thickness by accumulation rate at couplet depth. I assume that the couplet was deposited instantaneously, with no accumulation between flood events. In interpreting the result, I used median and modal values to express the central tendency of the data. Both sections contain bioturbated sediment layers; consequently the statistical mean may be biased towards layers that have been homogenized by bioturbation and do not accurately represent an interflood period. Because the degree of bioturbation differs over the floodplain, some sections will better represent this average flood recurrence interval than others. A way of dealing with this problem may be to look at the modal, or recurring, flood intervals. A large number of similar flood estimates may be a better representative of the overbank flood frequency than a mean flood frequency in sections with large numbers of bioturbated beds.

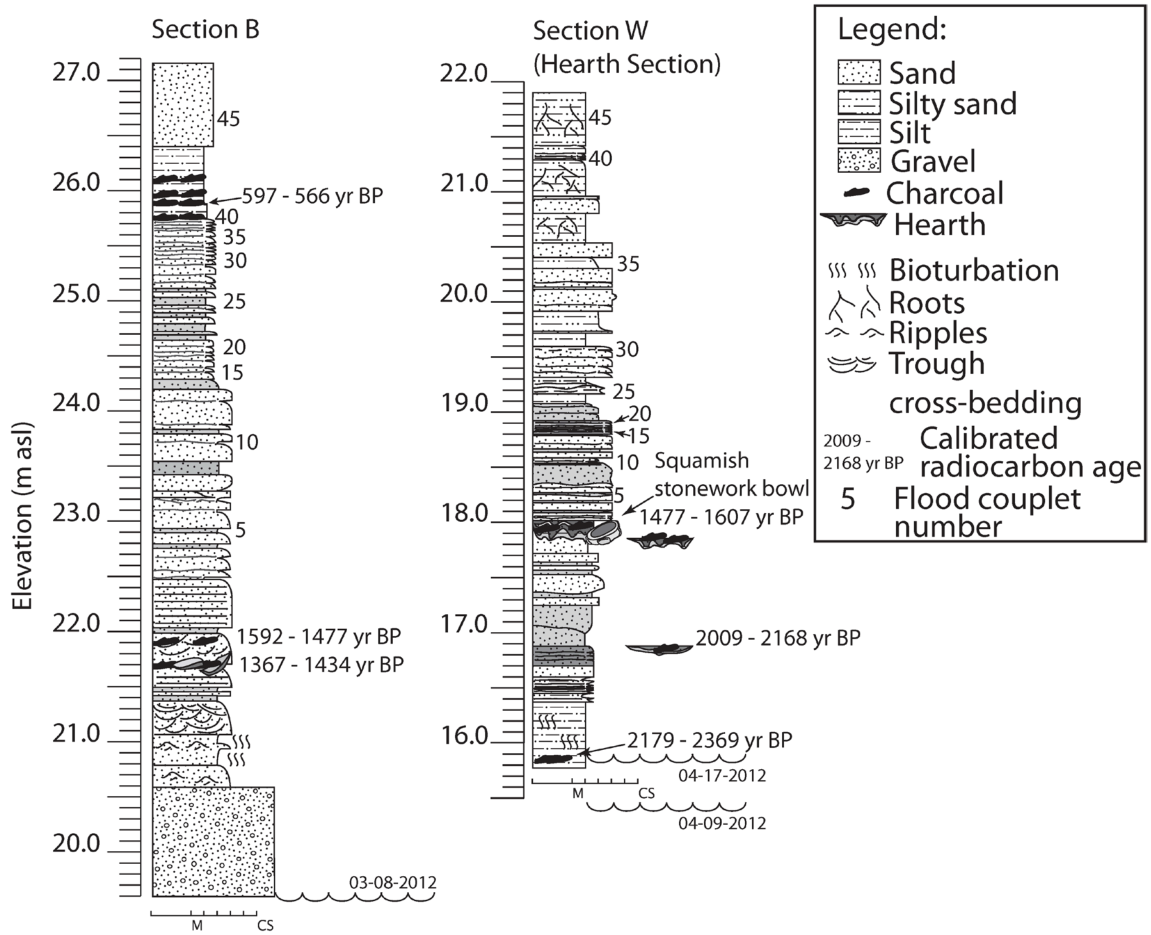

Figure 3.3. Stratigraphic sections with numbered flood couplets.

3.4. Results

3.4.1. Stratigraphy

Four sedimentary facies are relevant to the analysis performed in this study (Figure 3.3): (1) gravel (section B); (2) laminated silt (section W); (3) rippled, laminated, or cross-bedded stratified sand; and (4) interbedded fine to very fine-grained sand and humic silty layers. Laminated silt at section W was deposited in a former shallow lake upstream of Cheekye Fan (see Chapter 2). The basal gravel at section B is a Squamish River channel deposit (Brierley and Hickin, 1991). Rippled, laminated, or cross-bedded stratified sand was deposited on bars or at channel margins of Squamish River (Brierley and Hickin, 1991). Interbedded fine to very fine-grained sand and humic silty layers record recurrent floods that deposited sediment on top of levees (Brierley and Hickin, 1991; Chapter 2).

Section B (Figure 3.3) fines upward and, from bottom to top, consists of channel gravel (facies 1) older than 1350–1425 years; rippled, laminated, and cross-bedded stratified sand (facies 3); and interbedded, fine to very fine-grained sand and humic silty layers (facies 4). Because the dated interval begins near the top of facies 3, I assume that the time separating the cessation of facies 3 deposition and the first flood couplet of facies 4 is small.

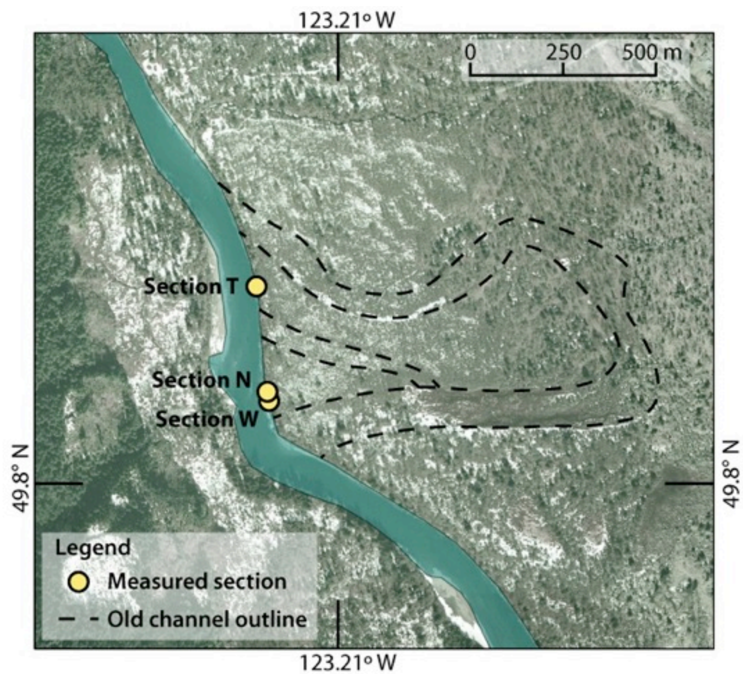

Figure 3.4. ***An abandoned meander on the Squamish River floodplain east of sections T, N, and W.***

The lowest exposed sediment at sections W is laminated silt (facies 2). This sediment is overlain by mottled stratified sand (facies 3), and rhythmic sand/silt flood layers (facies 4). An old meander scar is present near section W (Figure 3.4), but there is no evidence of channelling or an unconformity in nearby sections. The meander scar indicates that the channel migrated either sometime before or during deposition of the sand/silt flood layers. Therefore, the rate of sedimentation and couplet thickness may not have been uniform at section W. Variability in accumulation rate in the age-depth curve may indicate the influence of channel migration through the section (Figure 3.5).

Section W also contains numerous human artifacts; hearth features at this site date to about 2170–1480 yr BP. Human disturbance has altered several layers in this time range, rendering age-depth estimates suspect. Many of the layers containing artifacts appear to be silty lacustrine sediments (facies 2) or sand deposited in channels or at channel margins (facies 3). Sediment deposited after about 1500 years BP at section W most closely resembles overbank flood couplets and has not been disturbed by human activity. For these reasons, I have chosen to use couplets deposited in the past 1500 years at this section to estimate overbank flood frequency.

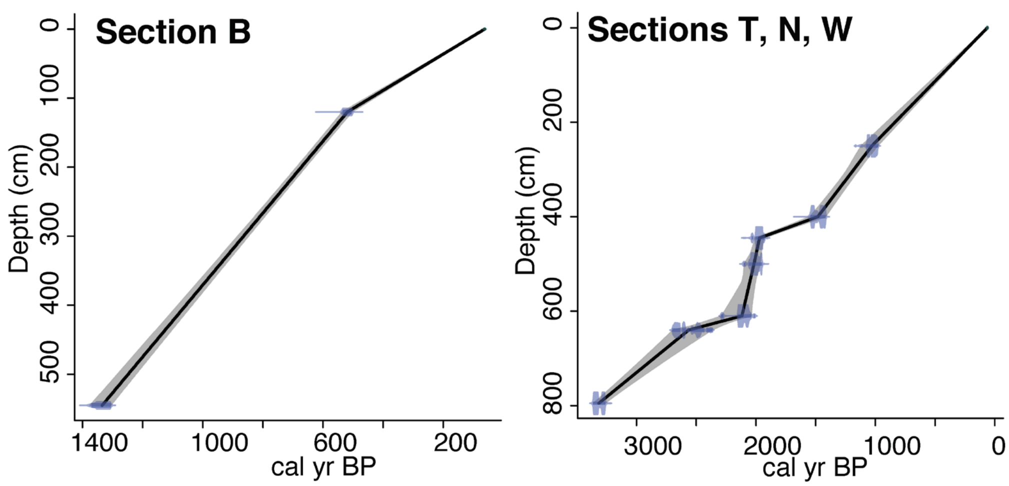

Figure 3.5. Age-depth models for studied sections.

3.4.2. Sediment accumulation rates

The age-depth relation for the flood sequence at combined section T/N/W, which has the best chronological control, suggests that there were periods with different average sedimentation rates (Figure 3.5). The average sedimentation rate between the oldest flood sediment (3428–3325 years) and sediment containing wood dated 2370–2180 years is about 2 mm/year. The average sedimentation rate decreases briefly between about 2180 and 2100 years ago to 0.7 mm/yr before increasing again to 10.8–11.9 mm/yr between 2100 and 1990 years ago. The interval between 2000 and 1480 years at section W has a low average sedimentation rate (~1 mm/year) that coincides with the hearths at this site. Anthropogenic fire-cracked rock and charcoal found at section B, several kilometres upstream, suggest widespread human use of the floodplain at this time. After this period, the average sedimentation rate at section W increases to 2.5–3 mm/year and remains at this level to the present.

I calculated two average sediment accumulation rates for section B: 5.2 mm/year from the fire-cracked rock horizon at 5.45 m depth (1430–1370 years) to 1.27 m depth (570-600 years), and 2.6 mm/year from 1.27 m depth to the surface.

Sediment accumulation rates on floodplains in an equilibrium state commonly decrease logarithmically over time as the floodplain aggrades and levees form. This trend is weakly expressed at section B (Figure 3.5) between the two radiocarbon-dated horizons, but not in section T/N/W. In the latter case, the sediment accumulation rate varies over time, but does not decrease over the entire period of record. Short-term changes in sediment delivery may be responsible for the variability observed at this site. The longer-term linear trend may reflect the unique character of flooding on Squamish River. Suspended sediment delivery is much greater during large fall and winter storms than in the snowmelt-driven, spring and summer freshet. Most overbank sedimentation on Squamish River, therefore, occurs during rare, rain-on-snow events, many of which are 1.5-3 times larger than the summer freshet (E.J. Hickin, personal communication, 2014).

3.4.3. Flood frequencies

Using sediment accumulation rates derived from age-depth models and thicknesses of measured flood couplets, I was able to estimate the average frequency of floods that overtopped the riverbank at my measured sections (Figure 3.6). Most estimates are less than 20 years. The median computed flood frequency is 16 years at section W, and 13.5 years at section B. The modal recurrence interval at both sections is between 5 and 10 years (Figure 3.6). Given the above data, floods in Squamish River have most likely occurred approximately every 5-15 years over the past 1500 years. Floods that recur at these intervals at present have instantaneous discharges of between 1700 and 2200 m^3/s (Table 3.2).

Based on the historic record, and using the Water Survey of Canada estimate of bankfull capacity (2384 m^3/s), the average out-of-channel flood interval in the study near

Brackendale is about 18 years (Figure 3.2). This value is similar to an average recurrence interval of about 20 years reported by Kerr Wood Leidal (2011) based on discharge frequency analysis (Table 3.2). The values for flood recurrence calculated using my method are thus slightly higher than those that would be expected to inundate the floodplain today. A possible explanation for this difference is that earlier floods in the sequence were depositing sediment over smaller, lower levees.

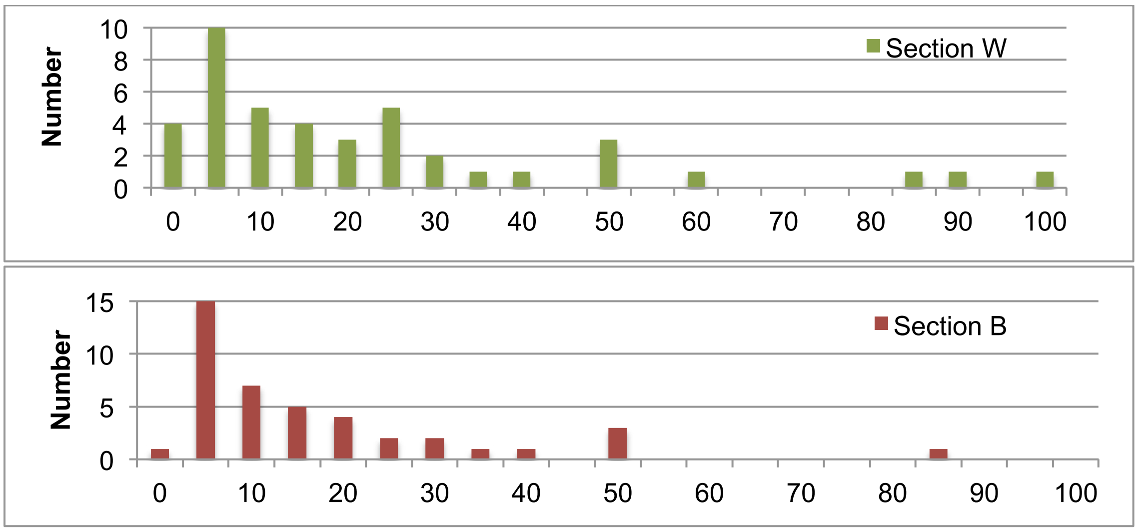

Figure 3.6. Histograms of calculated flood recurrence intervals for sections W and B on Squamish River (intervals over 100 years are not included).

Computations based on counts of flood couplets between radiocarbon-dated intervals provide different estimates of flood frequencies. At section B, there are 41 flood couplets between the fire-cracked rock horizon and the upper dated charcoal horizon (Figure 3.3). The expected average flood return interval is 19-22 years for the lowest 41 couplets, but 190–200 years for the upper three couplets. Section W has 22 flood couplets between the hearth layer (1480–1610 yr BP, 3.9 m below the bank top) and a higher charcoal horizon (1140–1040 yr BP), which yields an average flood return interval of 15–26 years. In contrast the average return interval over the uppermost 23 couplets is 45–50 years. The estimates of flood frequency obtained by counting couplets between radiocarbon-dated intervals are therefore slightly higher than those obtained using my method.

3.5. Discussion

3.5.1. Completeness of the flood record

Sediments near the top of the studied bank sections have been bioturbated, and it is possible that the thick couplets there are products of two or more floods (Figure 3.7). These thick couplets yield large recurrence intervals, commonly in excess of 100 years; at section B, the uppermost couplet is over 1 m thick and yields a recurrence interval of about 400 years. Two very large floods happened in 1984 and 2003, thus the uppermost sediments at section B could be a composite bed produced by those two events. It seems more likely, however, that the uppermost sediments at section B record several large floods, including those in 1984 and 2003. A limitation of the technique I use is that levees form and banks become higher through time; progressively larger floods are required to overtop the banks at a measured section. Accordingly, not only does the apparent flood frequency at the measured section decrease through time (see section 3.5.2 below), but the period over which plants become established and bioturbate sediments increases.

Another confounding issue is that particularly large floods might erode previously deposited flood sediments. Brierley and Hickin (1991) noted lenses of sand with inclined erosional basal contacts farther up-valley and interpreted them to be deposits of particularly large Squamish River floods that eroded underlying layers. I measured in detail several sections of flood couplets that are not described in this chapter, but they contained too few flood couplets or insufficient chronological control to provide a meaningful estimate of average flood frequency. It is possible that some flood couplets at these sections were either eroded or homogenized by bioturbation. Alternatively, these sections may not be favourably positioned to capture all Squamish River floods. In any case, the sections described in this chapter contain the largest number of flood couplets and thus are thought to come closest to archiving the full record of floods over the past 1500 years.

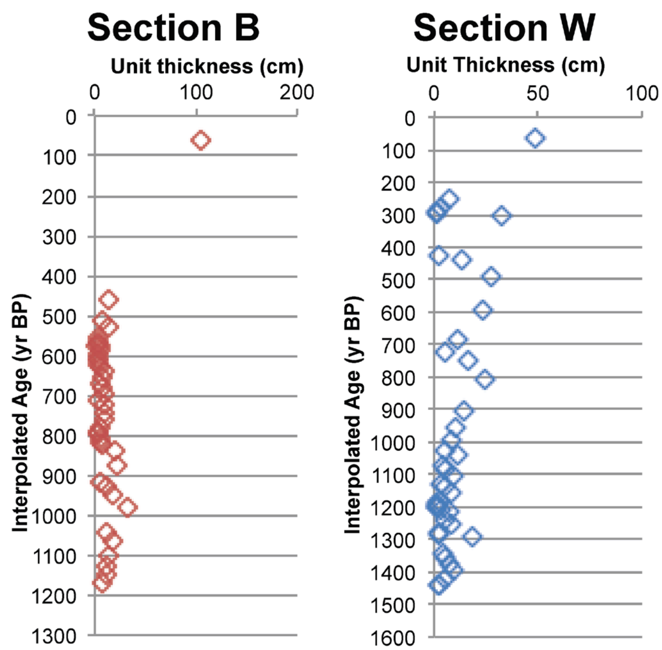

Figure 3.7. Couplet thickness versus interpolated age.

3.5.2. Effect of bank height on flood frequency values

While conducting fieldwork in Squamish Valley, I recorded water levels at different sections on different days using a differential GPS. Although the data I gathered were insufficient to construct rating curves for the studied sections, I was able to estimate the river gradient between the sections and the Water Survey of Canada gauge during both high- and low-flow periods. The elevation of the gauge itself could not be directly determined, because it operates using a local datum. I, therefore, accurately measured water levels at a section 350 m upstream of the gauge to estimate the elevation of the gauge (Table 3.4). I then used this estimate to match the station's rating curve to elevations of the river surface (Figure 3.8). The stream gradient in this section of the river is only about 0.0002, thus water surface elevations at the calibration section are about 7 cm above those at the Water Survey of Canada gauge.

Using my estimate of gauge elevation and measured water surface elvations at the section 350 m upstream, I extrapolated water surface elevations farther upriver to sections B, W, and M (Table 3.5). This procedure is inferior to using the Manning equation and back-step modelling software such as HEC-RAS to estimate bankfull capacity at measured sections, but it does give a sense of the magnitude of floods required to overtop the bank and deposit sediment.

Table 3.4. Estimates of the elevation of the Water Survey of Canada gauge at Brackendale (Station 08GA022).

Time and date	Bank height (m)[1]	Waterline (m asl)[1]	WSC water depth (m)	WSC gauge elevation (m asl)
10:00 04-18-2012	4.6	15.72	2.47	13.18
16:00 07-02-2012	3.05	17.27	4.42	12.78
14:30 07-01-2013	2.76	17.56	4.84	12.65
			Average	12.87
			Standard deviation	0.28

[1] Bank height and waterline elevation taken at a section 350 m upstream of the gauge, minus a 7 cm gradient correction. I subtracted ank height from bank elevation to obtain waterline elevation at a particular time.

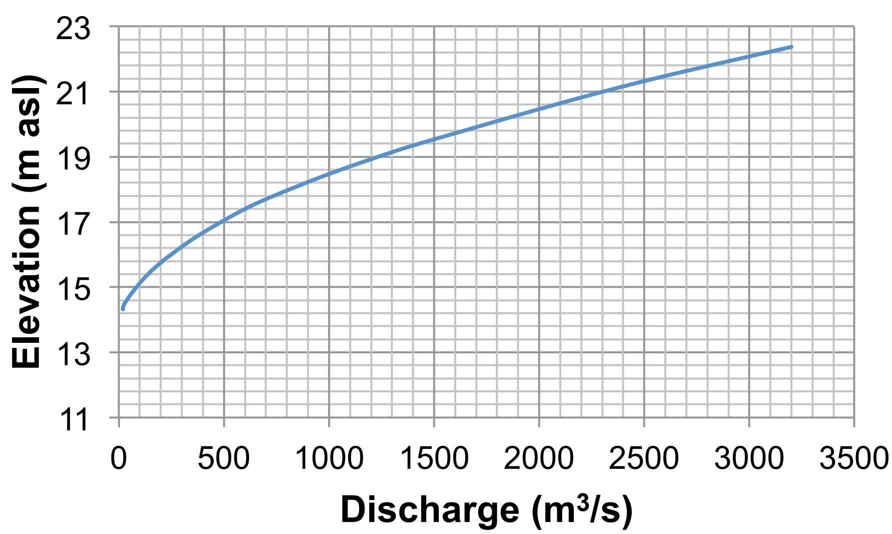

Figure 3.8. Elevation-corrected rating curve of Squamish River at Brackendale (08GA022).

Using the gradient in Table 3.5 and the rating curve at station 08GA022 (Figure 3.8), I estimate that a 25-35-year flood (2700 m^3/s) would overtop the bank at section B. If so, of historic floods, only those in 1984 and 2003 were likely capable of depositing the uppermost layer at that seciton. A ten-year flood at the gauge (2080 m^3/s) would reach the 45th couplet (26.4 m asl) at section B, and a five-year flood (1720 m^3/s) would reach the 35th flood couplet (25.6 m asl) there. If these estimates are correct, section B should record hundreds, not tens, of floods. Even if floods deposited sediments only 20 years on average, there should be, at a minimum, 70 flood couplets at section B. I offer three possible explanations for this inconsistency: (1) not all floods deposited couplets on the river bank at this section; (2) many couplets were destroyed by bioturbation; (3) most sediment was deposited over a riverbank of similar height to the one at this location today, and that bank has since been removed by erosion as the river migrated laterally. Option three would give more time for bioturbation to destroy flood couplets away from the riverbanks, although the sedimentary record in the studied sections suggests flooding was, if anything, slightly more frequent in the past. In reality, all three processes working together may cause the riverbanks to record fewer floods than expected.

Table 3.5. Data used to calculate water surface gradients between sections.

Section	Section elevation (m asl)	Gauge elevation (m asl)	Horizontal distance (m)	Gradient	Q at WSC gauge (m^3/s)
B	20.6	15.7	9070	0.00050	142-178
B	23.2	17.5	9070	0.00062	705-722
W	15.9	15.7	980	0.0002	130-142
M	18.8	17.5	2525	0.00050	705-713

An approximately 20-year flood is required to overtop the river bank at section W (21.9 m asl). A ten-year flood at section W would reach the 40th flood couplet at this section (21.3 m asl), and a five-year flood would reach the 35th couplet (20.5 m asl). As at section B, the sedimentary sequence under-records major floods at this site. In conclusion, bioturbation, erosion of flood layers, and other factors make it is difficult to use stratigraphy to determine flood frequency.

3.5.3. Potential for floods from breaching of upstream landslide dams

A flood routing study conducted by the BC Ministry of Environment suggests that landslides from Mt. Cayley are capable of causing large outburst floods that could affect the study reach. Woods (1987) estimated that the peak discharge of a hypothetical outburst flood from a landslide-dammed lake upstream of Mount Cayley and with a water surface of 160 m asl might be larger than 4500 m^3/s at Brackendale. This flood is much larger than the estimated 200-year normal hydrologic flood based on the historic record (Table 3.2), and would certainly be recorded in the Squamish River bank stratigraphy. Large landslides on Mt. Cayley dammed Squamish River about 500 and 1100 years ago (Brooks and Hickin, 1991; Evans and Brooks, 1991). If the landslide barriers were rapidly breached, there should be thick flood couplets of this age in the Squamish River sediment records.

I have observed no evidence for such floods – no flood couplets that are thicker than average date to either 500 or 1100 years ago (Figure 3.7), and none of the study sections contains gravel lenses, rip-up clasts, or unconformities. Historic landslide and glacial lake outburst floods in the British Columbia Coast Mountains (Desloges and Church, 1991; Kershaw et al., 2005), Nepal (Cenderelli and Wohl, 2003), and other areas have left unconformities and gravel lags in river valleys downstream.

3.5.4. Other sedimentary effects from landslide impacts

There is, however, evidence that upstream landslides have affected Squamish River in other ways. As shown in Chapter 2, extensive fen deposits consisting of interlayered peat and organic-rich silt are exposed near the base of many bank sections within the study reach. This sediment is sharply overlain by massive fine-grained sand and silt.

Radiocarbon ages on wood collected near the transition between the two units at sections A, I, J, and M are summarized in Table 3.6. The outer rings of a tree stump in growth position slightly above the transition at section M yielded an age of 748–800 years, and wood in a channel infill just above the transition at section J returned an age of 803–970 yr BP (Figure 3.9). In-situ woody roots occur in peat and organic-rich silt layers at sections I and J. The roots at section I, which are 70 cm below a gradational contact between the peat/silt unit and overlying sand, returned an age of 1244–1357 years. The roots at section J are about 30 cm below a contact between the peat/silt unit and a channel fill of medium to coarse sand; they yielded an age of 1128–1293 yr BP.

Finally, detrital branches collected at the contact between peat and organic-rich silt and stratified sand at section A gave an age of 988–1024 yr BP. Based on these ages, fen termination appears to date to 1100–1000 yr BP.

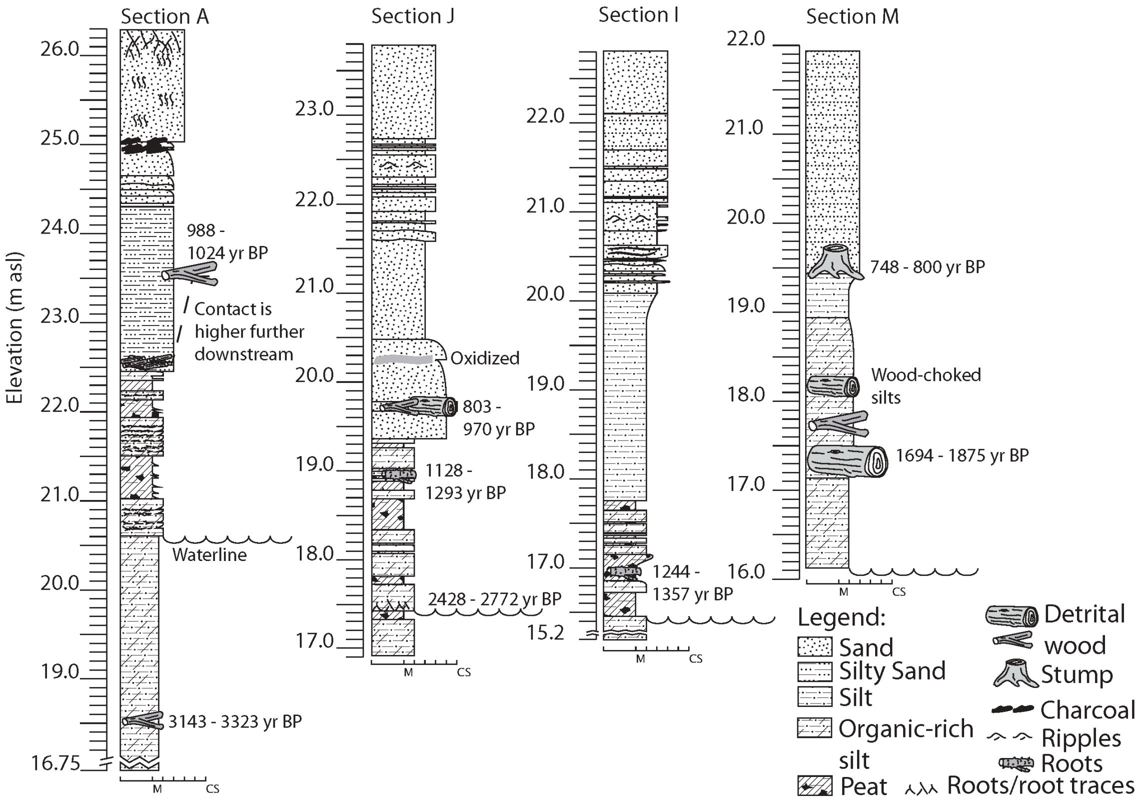

Figure 3.9. Sections providing evidence for the termination of fens in Squamish Valley.

Table 3.6. Radiocarbon ages associated with fen abandonment.

Sample	Radiocarbon age (^{14}C yr BP)	Calibrated age	Material	Latitude (N), Longitude (W)
A3	1030 ± 15	988 – 1027	Detrital wood	49°51’57.3”, 123°14’18.6”
I1	1320 ± 20	1244 – 1357	Horizontal root	49°49’20.7”, 123°13’29.6”
J3	900 ± 20	803 – 970	Detrital wood	49°49’36.1”, 123°13’40.4”
J2	1215 ± 20	1128 – 1293	Horizontal root	49°49’36.1”, 123°13’40.4”
M	810 ± 15	748 – 800	Stump	49°48’52.7”, 123°13’00.1”

Four radiocarbon ages have been obtained on the 1100-year-old Mt. Cayley landslide, two from the pre-landslide land surface and two from the landslide debris itself

(Table 3.7). Collectively, the four ages show that the landslide occurred shortly before the fens were buried.

Table 3.7. Limiting ages for the 1100-year-old landslide at Mt. Cayley (Brooks and Evans, 1991).

Laboratory no.	Radiocarbon age (^{14}C yr BP)	Calibrated age (cal yr BP)	Context	Interpretation
GSC-4770	1270 ± 50	1078 – 1289	Pre-landslide surface	Maximum age
GSC-4843	1250 ± 110	938 – 1344	Pre-landslide surface	Maximum age
GSC-4904	1010 ± 60	788 – 1056	Landslide debris	Maximum age
GSC-4298	1060 ± 60	798 – 1168	Landslide debris	Maximum age

Because the landslide and burial of the floodplain fens occurred at about the same time, it is possible that the latter was a response to the passage of a wave of sediment through the study reach derived from breaching of the landslide dam. Aggradation of the river channel may have led to more frequent flooding and levee breaching. Recent riverbed aggradation in lowermost Cheakamus River valley has been linked to a large landslide at The Barrier, 20 km north of Brackendale (Clague et al., 2003b). Similarly, sediment reworked from the deposit of the 2010 Mt. Meager landslide is building up in the channel of Lillooet River in the vicinity of Pemberton and reducing the effectiveness of the protective river diking system (Guthrie et al., 2012).

Another possible explanation for the disappearance of the fens is that the environment to which they were adapted was no longer present. During the late Holocene, the Cheekye Fan barrier lowered as the floodplain continued to aggrade. At some time, backswamp areas on Squamish River may have become too elevated above the watercourse to store water on the surface; in other words, the water table might have lowered enough that the fens drained. Although it is possible that the fens crossed this geomorphic threshold at the same time as the 1100-year-old Mt. Cayley landslide, the sedimentary, chronological, and biostratigraphic evidence strongly suggests that the change was caused by increased sediment supply from the landslide itself.

3.6. Non-stationarity in the flood record

Squamish River has aggraded several metres since its floodplain formed about 2300 years ago. As discussed above, successively younger floods would have had to reach higher and higher levels to leave a sedimentary record on the levees and floodplain. A two- or five-year flood 2300 years ago would leave a thicker and possibly coarser flood layer than a seven- or ten-year flood today. In addition, because Squamish River has incised its channel at Cheekye Fan over this period, larger flows are required to overtop the riverbanks now than in the past. Anomalously thick couplets at the top of measured sections, coupled with evidence of root bioturbation indicate lower flood couplet preservation. The flood record thus becomes more poorly preserved as bank height increases.

Because the level of Squamish River is controlled by an unstable fan, some differences in flood frequency or sedimentation could reflect a shift in the location of the Squamish-Cheakamus confluence. A recent southward shift of the confluence (Chapter 2) has slightly lowered local Squamish River base level over the past century. A northern shift in the confluence to a more constricted reach of Squamish River might cause the fan to aggrade more rapidly at this location, thus temporarily raising base level.

Climate change may alter flood frequency on Squamish River. Although local base level has dropped recently, theoretically lowering the possibility that floods will be archived in the sediment record on levees, the frequency and severity of large floods on Squamish River has increased over the past 30 years (Bauch and Hickin, 2011). Similar changes in climate in the past may have had an effect on the flood record by either depositing larger couplets than normal or by eroding parts of the stratigraphic record.

3.7. Conclusion

Radiocarbon-dated sand/silt flood couplets exposed in the banks of lower Squamish River suggest that out-of-channel floods have occurred, on average, once every 5-15, and almost certainly more frequently than every 20 years over the past 1500 years. I calculated flood recurrence intervals by measuring flood couplets and dividing them by sediment accumulation rates. This method does not take into account bioturbation or floods that do not deposit sediment on the river bank. However, it does provide a measure of the likely flood recurrence interval. Calculated average recurrence intervals between radiocarbon-dated intervals provide measures of flood recurrence that are reasonable, as long as the river channel is stable and the river bank does not significantly aggrade. Such conditions, however, are rare, and it is much more likely that more floods were captured in the sedimentary record when river banks were lower than present.

Several factors limit the use of this method. First, imprecise or insufficient dating may introduce errors in flood frequency estimates. Second, anomalously thick couplets need to be inspected carefully because they could be amalgamated deposits of two or more floods. Third, changes in floodplain geomorphology may misrepresent true flood frequency. Fourth, extreme floods may remove part of the record of earlier floods. These limitations can be addressed in several ways. First, radiocarbon dating should be focused on sections that contain large numbers of well preserved couplets and without obvious unconformities and bioturbation. Second, fossils in growth position should, whenever possible, be dated; if such materials are unavailable, delicate fossils such as twigs and plant leaves, which are unlikely to have been reworked, should be dated. Third, age-depth modelling using Bayesian statistics will improve the flood chronology. Improvements in, and testing of, the method applied in this study may allow it to be more widely used for determining long-term average flood frequencies on geomorphically active, humid floodplains.

In addition to providing an estimate of average flood frequency in the Squamish Valley during the late Holocene, I have presented evidence for increased sedimentation following a large upstream landslide 1100 years ago. Although there is no evidence in the flood record to support a large-scale outburst flood from the breached landslide dam, there is evidence that the sediment from the barrier was mobilized as a wave that moved downstream over a period of years, inundating channel-side fens and causing localized channel aggradation.

4. Discussion and recommendations for further work

I have examined Squamish River in several contexts. First, I investigated the effect of a barrier (Cheekye and Cheakamus fans) on river evolution over the late Holocene (Chapter 2). I compared the planform and sedimentary environments of Squamish River to those of other similar streams (Columbia River and Alexandra River) that are impacted by large alluvial fans. Sediments deposited in the past 3500 years in Squamish Valley show that paraglacial landforms like Cheekye Fan can affect sediment sequences upstream for centuries to millennia. Even though Cheekye Fan is largely a relict landform, avulsions of Cheekye River have affected sedimentation at the confluence of Squamish and Cheakamus rivers, which in turn has altered local base level upstream of the fan.

Second, I have estimated flood frequency on Squamish River over the past 1500 years using overbank flood couplets (Chapter 3). The method I used, which may be applicable in other areas, employs age-depth modelling to estimate intervals between floods. The method seeks repeated flood recurrence intervals to estimate flood frequency at sites. It does not acceptably compensate for floodplain processes that destroy previously deposited flood sediments. With further work and better age constraints, the method could be applied in other contexts.

Third, I have considered how upstream changes in sediment supply, specifically from a large landslide, may have affected sedimentation and flooding downstream on Squamish River.

The remainder of this thesis deals with theoretical frameworks that best explain my observations. I suggest how an understanding of these frameworks may improve future studies of coastal rivers in British Columbia.

4.1. The paraglacial sedimentary framework

A framework for understanding landform development and sedimentary sequences in Squamish Valley is the paraglacial sediment model, a disturbance landscape model first postulated by Church and Ryder (1972) and later applied by Brooks (1994) to the Squamish River watershed. A paraglacial sediment response refers to the large quantity of sediment mobilized and deposited during and immediately after deglaciation in formerly glaciated areas of the world. Like disturbance regime processes described by Hewitt (2006), paraglacial sedimentation substantially alters a landscape, with effects that extend thousands of years after deglaciation (Ballantyne 2002). The response is temporally and spatially dampened as basin size increases (Church and Slaymaker, 1989; Church, 2002).

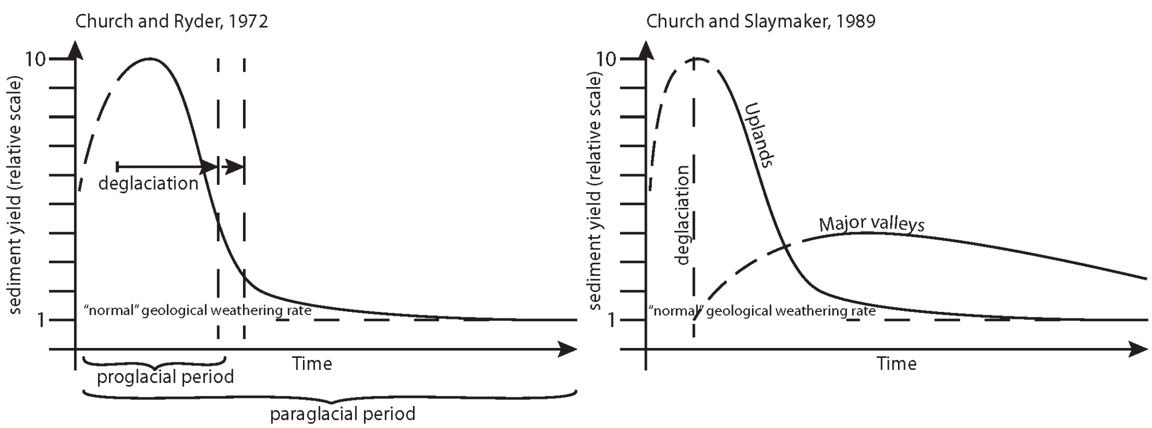

Figure 4.1. Paraglacial model of delayed sediment release through basin storage (Church and Slaymaker, 1989).

Church and Slaymaker (1989) observed that sediment yield in formerly glaciated basins in British Columbia follows an inverted U-shaped curve with respect to basin area. Smaller basins (<10^3 km^2) have smaller specific sediment yields, medium-sized basins (~10^3 – 10^4 km^2) have the largest yields, and the largest basins (>10^4 km^2) have slightly smaller yields than medium-sized basins. Church and Slaymaker (1989) suggest that the mechanism of this response is temporary basin storage. This hypothesis led Church (2002) to conceive of the paraglacial sediment pulse as propagating through a series of linked basins, with a net response corresponding to a decaying gamma function with respect to basin area (Figure 4.1).

Ballantyne (2002) suggests that paraglacial sedimentation can be represented as a process of exponential exhaustion for an individual basin (Figure 4.2). The degree of initial sediment availability is conditioned by the size and steepness of the basin, and the rate of change in sediment reworking (κ) is inversely proportional to basin area. Therefore, what appears to be a lagged peak may in fact be an intrinsic response of a larger basin to deglacial events. He suggests that the paraglacial response may extend, at a low magnitude, for a longer time in larger basins. Ballantyne's approach also implies some sedimentary storage component.

Paraglacial sedimentation is described as both process- and time-linked by Ballantyne (2002). The time required for paraglacial landform adjustment differs for glacier forelands, drift-mantled slopes, rock mass creep, alluvial fans, talus accumulation, and rock-slope failures. Specific processes may operate over timescales of 10^1–10^4 years. Rock slopes may take tens of thousands of years to adjust to deglaciation, for example, by forming relaxation joints, whereas drift-covered slopes may adjust over a much shorter time.

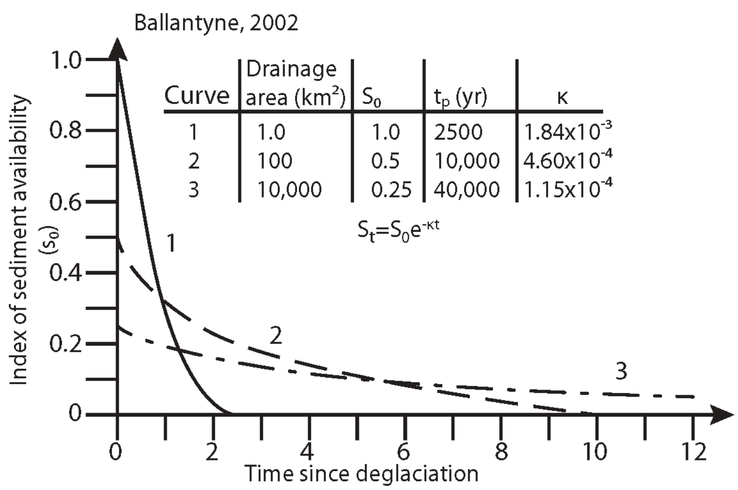

Figure 4.2. Primary exhaustion paraglacial model of Ballantyne (2002).

Coastal volcanoes in British Columbia are an example of landforms that have responded rapidly to deglaciation because they have very steep slopes and comprise weak pyroclastic rocks and lava flows. At the peak of the last glaciation, Mt. Garibaldi erupted, forming a summit cone that was partially supported by glacier ice in Cheakamus and Squamish valleys to the west. As these glaciers downwasted and retreated, the cone collapsed into the headwaters of the Cheekye River watershed. Sediment yield from Plio-Pleistocene volcanoes in southwestern British Columbia, including Mt. Meager, Mt. Cayley, and Mt. Garibaldi, has been described as an end member in the paraglacial sediment regime (Friele and Clague, 2009).

Landslides from Mt. Cayley have repeatedly dammed Squamish River upstream of Cheekye Fan during the Holocene (Brooks and Hickin, 1991), and reworking of collapsed volcanic materials in the Cheekye River watershed is responsible for the rapid growth of Cheekye fan and the impoundment of a lake in Squamish River valley in the early Holocene. I argue below, based on analogues from other basins, that sediments in Squamish Valley are a response to paraglacial land disturbance and represent a disturbance regime landscape (Hewitt, 2006).

Alluvial fans near the intersection of Alexandra and North Saskatchewan rivers in Alberta (Smith, 1972; Smith and Smith, 1980; Smith, 1983), and upstream of Golden, BC, (Smith and Smith; 1980; Smith, 1983; Makaske et al., 2002, 2009) have created long-lived basins that are actively accumulating sediment. The upper Saskatchewan River fan in the Alberta Rocky Mountains is still actively aggrading and is responsible for the anastomosing planform and continuing vertical accretion on the Alexandra River floodplain upstream (Smith, 1972). The fan at Golden is also aggrading (Kelley and Holland, 1961), probably by recycling terrace sand and gravel from upstream. Kicking Horse River is similar to other rivers in British Columbia in that much of the sediment it transports is recycled from older paraglacial stores (Church and Slaymaker, 1989). North of its confluence with Kicking Horse River, Columbia River has a steepened river profile and aggradation at the confluence is at least partly responsible for vertical accretion on the Columbia River floodplain upstream (Smith, 1983)[1]. The currently aggrading floodplains of Columbia and Alexandra rivers. and the stable to slowly degrading floodplain of Squamish River thus represent secondary sediment stores upstream of paraglacial fans.

[1] Makaske et al. (2009) suggest that sediment supply controls the planform of this reach of Columbia River, especially where the river is strongly anastomosing, far upstream of the fan. This conclusion, however, does not preclude an influence by the alluvial fan downstream.

There is evidence that prehistoric landslides that dammed rivers in the American Southwest are also related to glacial activity. Landslides on the Rio Grande River in New Mexico have been linked to a wetter late-glacial climate in the region 12.3-13.7 ka BP (Reneau and Dethier, 1996). The landslides created impoundments in which lacustrine sediments accumulated, and the river has not removed the landslide barriers in this area. Post-disturbance landforms include lacustrine terraces and abandoned spillway channels. Although this landscape cannot be considered paraglacial, it is a disturbance-regime landscape conditioned by late Pleistocene climate change and regional tectonic uplift. Because the youngest landslides are early Holocene in age, however, the area is no longer subject to the same degree of disturbance as it once was.

Brooks (1994) observed that about 415 x 10^6 m^3 of paraglacial sediments were transferred into Squamish Valley during the late Pleistocene and early Holocene. This amount is only enough to prograde the present Squamish River delta another 2 km into Howe Sound. More sediment, however, has remained in storage in tributary valleys and is being released at a slow residual rate into Squamish Valley. The current sediment flux to Howe Sound is 1.29 x 10^6 m^3/year and is mainly sourced from Mt. Cayley and Mt. Garibaldi, and from alpine glaciers (Brooks, 1994). Alpine glaciers cover about 11% of the watershed, and still contribute large amounts of sediment to Squamish River.

Slaymaker and Jordan (1991) inferred a large sediment deficit in the Lillooet River watershed by comparing progradation of Lillooet River delta and aggradation of the Lillooet River floodplain with sources of sediment in upstream reaches of the river. Significant sources include debris flows, landslides, and glacial erosion. Based on their calculations, more than 10^6 m^3 of sediment is missing from the sediment budget. Clague and Friele (2009) observed that landslide contributions from Mt. Meager, a nearby Quaternary stratovolcano, were sufficient to balance the budget and were underestimated in the previous study. Rapid propagation of a sediment wave following the large landslide from Mt. Meager in 2010 supports this interpretation (Guthrie et al., 2012). As paraglacial sedimentation has slowed in the Lillooet watershed, sediment delivery to Lillooet River is increasingly being driven by stochastic disturbance events related to continuing instability of Mt. Meager (Slaymaker and Jordan, 1991; Friele and Clague, 2009).

In my opinion, the amount of paraglacial sediment contributed to Squamish River is not as important as how that sediment has shaped the basin. What makes Cheekye Fan important, from the perspective of this study, is that it has disturbed the normal sediment cycle in part of the watershed for thousands of years. Cheekye Fan has impacted Squamish Valley at least as far upstream as Ashlu Creek, producing valley-floor morphology and sedimentary environments that differ from those of other nearby rivers. Landslides from Mt. Cayley have similarly affected the valley, and Squamish River has yet to completely remove the barrier created by a 4800-year-old landslide (Brooks and Hickin, 1991). Both of these disturbance features still exert an important geomorphic influence on Squamish River.

Disturbances in Squamish Valley have created a floodplain that is polygenetic in origin. The characteristic shape and steep slopes of the valley are the result of recurrent glacial erosion during the Pleistocene. Widespread silt and peat deposits in the lower portion of the valley reflect lacustrine sedimentation and fen development behind a paraglacial debris flow fan. Subsequent infilling of the lake and barrier incision are linked processes, somewhat analogous to a forced regression in sequence stratigraphy. Evidence for this forced regression lingers in the landscape in erosional remnants of high-level lacustrine deposits exposed at section R and the flattening of the river profile nearby (Figure 2.17). Fen cessation around 1100 years ago is partly related to local base level lowering and partly to an influx of sediment resulting from breaching of a landslide barrier near Mt. Cayley. This flood of sediment may have “finished off” a landsystem in decline. Lateral accretion sediments being deposited today in Squamish Valley are representative of the current state of the system, in which barrier incision and upstream aggradation have steepened the valley gradient. Because there is no large lake in the valley to act as a sediment sink, gravel and sand are accumulating on top of older fine-grained lacustrine sediments, while the river erodes them. The cohesive nature of these sediments, however, presently restricts the natual meandering tendency of the river and will slow development of a wide meander belt in Squamish Valley in future. Incision of cohesive fine-grained sediment may be the cause of the straight reach just upstream of Cheekye Fan.

The polygenetic nature of the Squamish River floodplain and the persistence of paraglacial modification of the landscape long after the end of the Pleistocene indicates that paraglacial landform development in southwestern British Columbia is a disturbance regime, as described by Hewitt (2006). Glaciation is one process that conditions a landscape for long-term disturbance. Just as uplift and climate change triggered landslides in the U.S. Southwest, uplift and glaciation have created conditions favourable for widespread landsliding in New Zealand (Korup, 2005) and in the Himalaya (Hewitt, 2002, 2006, 2009). As the influence of paraglacial processes and features wanes in Squamish River valley, the potential for large landslides and mass movements, especially from Mt. Garibaldi and Mt. Cayley, remains. The landscape, conditioned to fail by glaciers and ice-contact volcanism, will remain subject to disturbance into the future.

4.2. Further Work

Additional research would improve understanding of Squamish River and other coastal rivers in British Columbia. This study lacked deep sediment cores from the Squamish River floodplain. All sections that I studied were riverbank exposures of the uppermost 6–10 m of the valley fill, and many of these sections are situated on levees. Cross-valley sections (Figures 4.3, 4.4) show prominent levees on both sides of the river and gently sloping concave-upward topography away from riverbanks. Sedimentary sequences distant from the river might differ from those that I have documented. For example, they are not likely to contain the same sequences of stacked flood deposits and paleosols.

I completed several GPR transects on the valley floor, but fine-grained sediment rapidly attenuates the GPR signal, making deep investigation impossible (Appendix D). Resistivity or electromagnetic techniques might provide deeper subsurface information, particularly if done in conjunction with drilling or augering. These techniques cannot resolve sedimentary bedforms like GPR does, but they can locate boundaries between high-conductivity silt and low-conductivity sediments such as gravel or sand. Boreholes should be located along surveyed EM or resistivity lines to refine the electromagnetic or resistivity models. A combination of these two techniques used on a valley-wide scale and complemented by drilling would provide much additional information on the Holocene history of lower Squamish River valley.

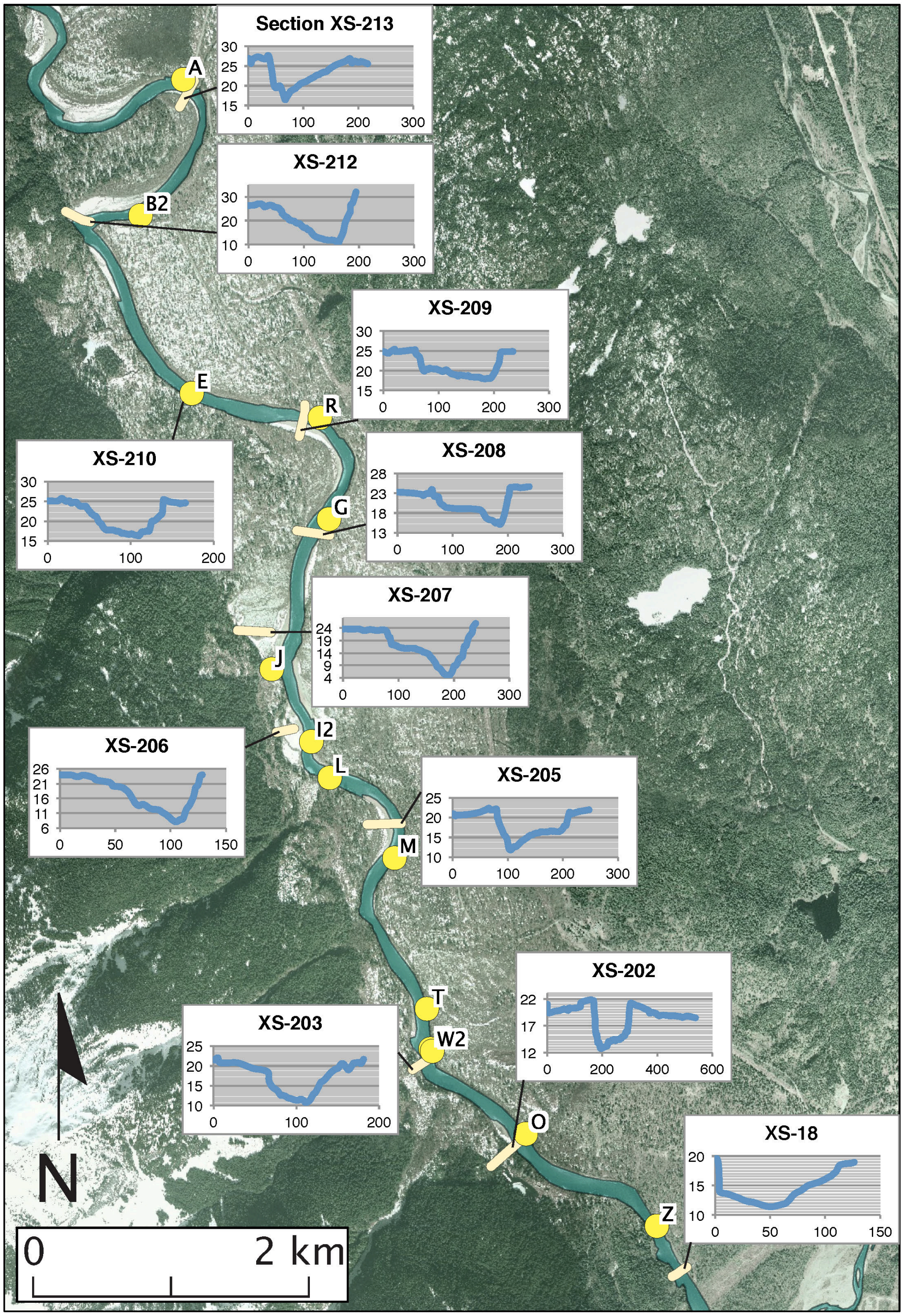

Figure 4.3. ***Surveyed Squamish Valley cross-sections; vertical and horizontal scales in metres. Survey data from BC Ministry of Environment (1976-1978).***

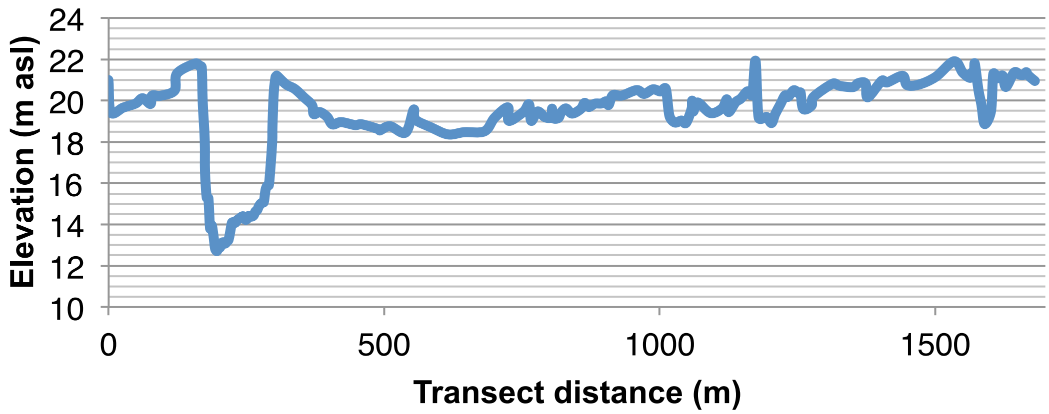

Figure 4.4. ***Cross-valley transect XS-202; see figure 4.3 for location (BC Ministry of Environment, 1976-1978).***

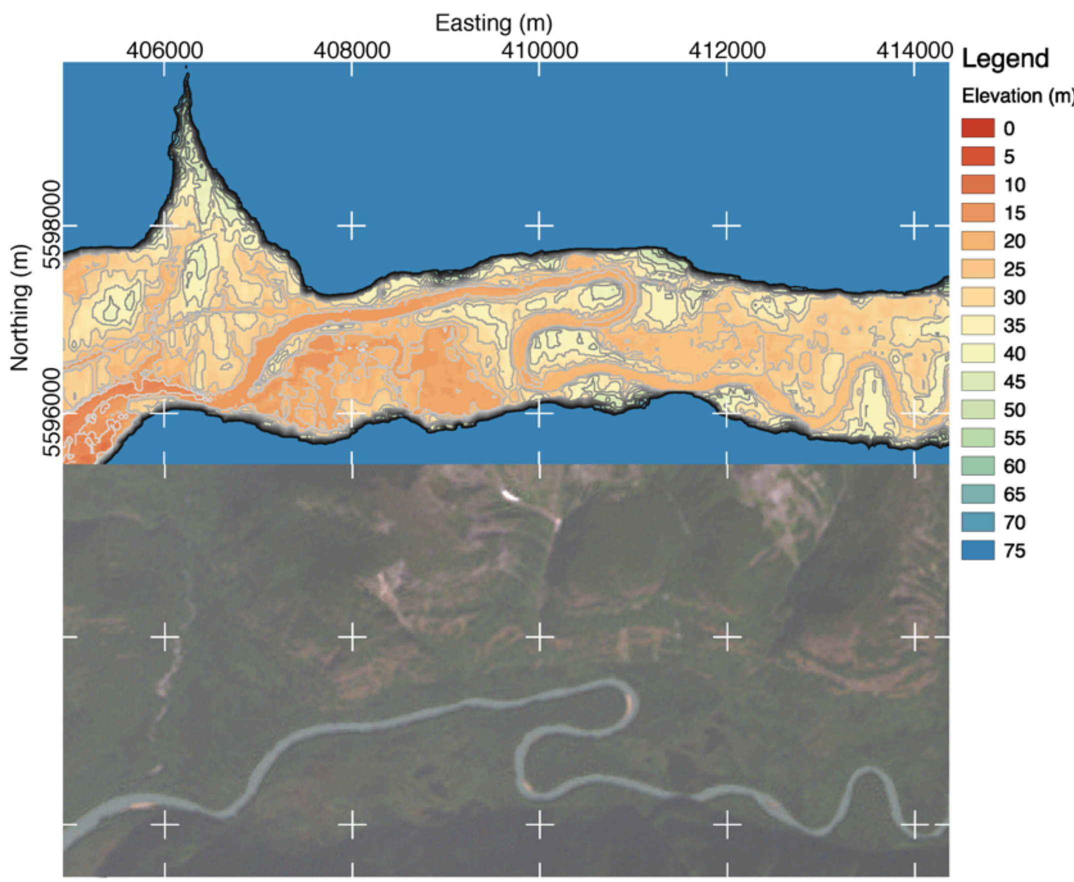

Figure 4.5. ***Topographic map (top) and Landsat 7 image (bottom) of Toba River in south-coastal British Columbia. The river is impeded by an alluvial fan (left). The Toba River floodplain at the right has a low gradient.***

The flood frequency analysis that I performed could also be better constrained; it could be strengthened by reach-scale river modelling and additional radiocarbon ages. Additional radiocarbon ages from the upper parts of section W and sections AK, R, and B might reveal a more complex history of floodplain aggradation, with periods of higher and lower sedimentation rates. Ideally, radiocarbon samples should be collected and analyzed from humic silty layers at the top of flood couplets, although these materials present problems with contamination by younger carbon from plant roots. The best samples for this kind of analysis are small delicate fossils that are unlikely to survive subaerial exposure or resedimentation (seeds, twigs, leaves, needles, or terrestrial beetle fragments). I expect that such additional chronological control would reveal century-scale cycles in flooding influenced by upstream sediment supply, variations in the position of the mouth of Cheakamus River, debris flow activity on Cheekye Fan, and late Holocene climate change.

Drilling at sections W, AK, T, and N would help determine the timespan of the lake upstream of Cheekye Fan. Lithologic and geochemical analyses of silt and sand layers deposited in the lake might reveal debris flow activity on Cheekye Fan and distant landslides on Mount Cayley.

I also recommend a similar study of a good analogue of Squamish River in coastal British Columbia. Toba River is impeded by an alluvial fan near its mouth (50°30.5'N, 124°19.5'W). Upstream of the fan, the river is characterized by a low-gradient, meandering channel bordered by a swampy floodplain (Figure 4.5). Activity on the fan should impact local base level in a manner similar to Squamish River upstream of Cheekye Fan.

5. Conclusion

Late Holocene sediments exposed in the banks of Squamish River were deposited in a shallow lake dammed by the composite Cheakamus-Cheekye Fan at the confluence of Cheakamus and Squamish rivers. Slow incision of the fan complex is increasing the gradient of Squamish River; over time, the planform of the river upstream of the barrier will straighten. However, if a sufficiently large debris flow were to travel down Cheekye River and reach Cheakamus and Squamish rivers, a higher-level barrier could be re-established. I estimate that as little as 300,000 m^3 of sediment could temporarily raise the channel of Squamish River at Cheekye Fan to about 19 m asl, significantly lowering the gradient of the river upstream. Much of the change in Squamish River upstream of Cheekye Fan during the late Holocene can be explained using the paraglacial paradigm. The landscape is currently recovering from massive changes caused by late Pleistocene glaciation and from the large amounts of sediment mobilized and transported into valleys at the end of glaciation. The two largest perturbations that have affected Squamish River in the Holocene are upstream aggradation and flattening related to the Cheekye-Cheakamus fan complex and Holocene landslides on Mount Cayley (Evans and Brooks 1991; Brooks and Hickin, 1991). The latter created barriers that Squamish River has not yet totally removed and that are sources of large amounts of sediment that have caused local downstream channel aggradation in the past. In this sense, the history of sedimentation in Squamish Valley shows that the concept of the disturbance regime landscape advocated by Hewitt (2006) is compatible with, and overlaps, the concept of paraglacial sediment regime. Glaciation is arguably a disturbance with both short-term and extended effects that traps landscapes in a disequilibrium state (Church and Slaymaker, 1989).

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Appendices

Appendix A. Radiocarbon ages.

Sample no.	Radiocarbon age (^{14}C yr BP)	Calibrated age (calendar years before AD 2012)	Dated material	Latitude (N), Longitude (W)	Elevation (m asl)
A1	2995 ± 15	3143–3323	*Taxus brevifolia* root	49°51’57’’, 123°14’17.5’’	18.8
A3	1030 ± 15	988–1024	In-situ root	49°51’57’’, 123°14’17.5’’	23.5
B2	1450 ± 15	1367–1434	Charcoal	49°51’24.5’’, 123°14’33.5’’	21.5
B3	1595 ± 15	1477–1592	Charcoal	49°51’24.5’’, 123°14’33.5’’	21.7
B10	480 ± 20	566–597	Charcoal	49°51’24.5’’, 123°14’33.5’’	26
E2	85 ± 15	93–317	Log	49°50’42’’, 123°14’13.5’’	23.5
E5	2085 ± 15	2059–2178	*Picea sitchensis* stump	49°50’42’’, 123°14’13.5’’	19.7
E6	2640 ± 15	2807–2834	Bark	49°50’42’’, 123°14’13.5’’	18.2
G6	180 ± 15	59–346	Log	49°50’14’’, 123°13’23’’	21.1
I1	1320 ± 20	1244–1357	In-situ root	49°49’20.5’, 123°13’29.5’’	17
J1	2470 ± 20	2428–2772	In-situ root	49°49’36’’, 123°13’40.5’’	17.5
J2	1215 ± 20	1128–1293	In-situ root	49°49’36’’, 123°13’40.5’’	19
J3	900 ± 20	803–970	Branch	49°49’36’’, 123°13’40.5’’	19.7
L1	890 ± 20	797–967	In-situ root	49°49’13.5’’, 123°13’25’’	19.7
L3	1740 ± 20	1632–1771	In-situ root	49°49’13.5’’, 123°13’25’’	18.6
L5	2560 ± 15	2683–2809	*Thuja plicata* log	49°49’13.5’’, 123°13’25’’	15.9
M1	1795 ± 15	1694–1875	*T. plicata* log	49°48’52.5’’, 123°13’01’’	17.2
M2	810 ± 15	748–800	*Picea sitchensis* stump	49°48’52.5’’, 123°13’01’’	19.5
N1	1140 ± 15	1038–1142	Charcoal	49°48’10’’, 123°13’46’’	19
N3	2460 ± 15	2428–2765	*Malus fusca* log	49°48’10’’, 123°13’46’’	15.1
O3	2135 ± 20	2103–2359	Charcoal	49°47’49’’, 123°12’10.5’’	17.5
R1	2230 ± 15	2220–2392	Charcoal	49°50’38’’, 123°13’28’’	21.6
T1	2130 ± 15	2108–2352	*Picea sitchensis* stump	49°48’19.5’, 123°12’47.5’’	15.5
T2	3090 ± 15	3325–3428	*Picea sitchensis* log	49°48’19.5’, 123°12’47.5’’	13.6
T4	2030 ± 15	1990–2102	Charcoal	49°48’19.5’, 123°12’47.5’’	17.8
W10	2170 ± 20	2179–2369	Charcoal	49°48’09.5’’, 123°12’46’’	15.8
W11	2050 ± 15	2009–2168	Charcoal	49°48’09.5’’, 123°12’46’’	16.9
Skw'enp' 4 Station W	1610 ± 20	1477–1607	Charcoal	49°48’09.5’’, 123°12’46’’	18

Appendix B. Plant macrofossils.

Table B1. Macrofossil composition of peat samples.

		Section A						Section E	
Material	Indicator[1]	40-45 cm	80-90 cm	133-143 cm	163-175 cm	185-195 cm	L4	E7	E8
Carex aquatilis (seeds)	Obl		3	6	5		134	25	109
C. canescens (seeds)	Obl		7		6	26		1	
C. livida (seeds)	Obl	8?	2		1	3			
Carex sp.				12				1	
Comarum palustre	Obl				2?			6	
Menyanthes trifoliata (seeds)	Obl		46	4	3 halves	2	1?		
Potamogeton spp.	Obl				2?	7?	1		1?
Picea sitchensis (needles)	FAC						2		
Thuja plicata (scales)	FAC				1		1		
Thuja plicata (seeds)	FAC			3?	1				
Valved seeds, unidentifiable					3				
Midge body					1				
Insect parts/various				8	2			3	4
Unidentified seeds, various									3

[1] Obligate (Obl) plants are almost always found in wetlands. Facultative (FAC) plants are tolerant of wetland conditions. Wetland plant definitions are from Lichvar (2012).

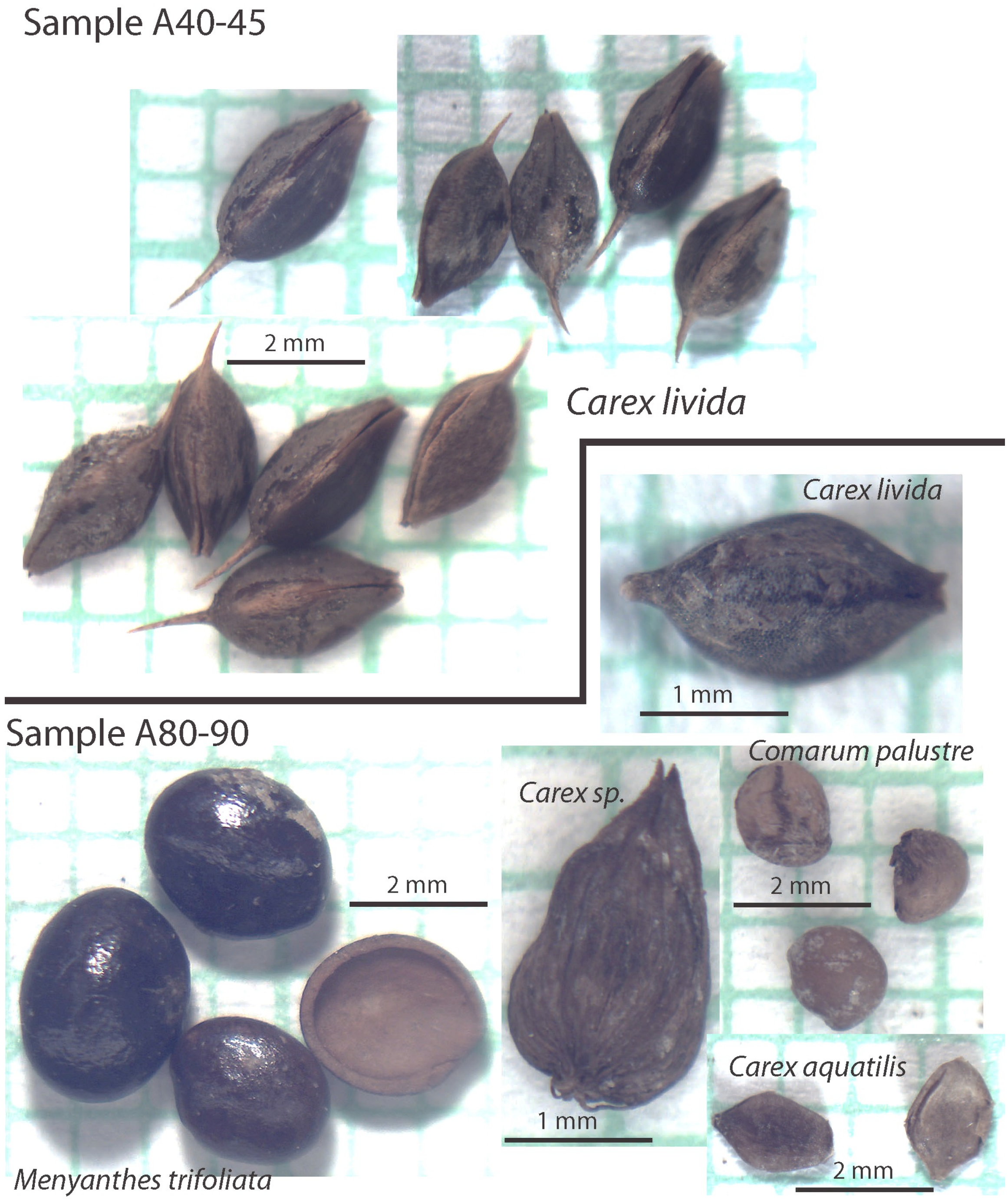


Figure B1. Photographs of macrofossils from samples A40-45 cm and A80-90 cm.

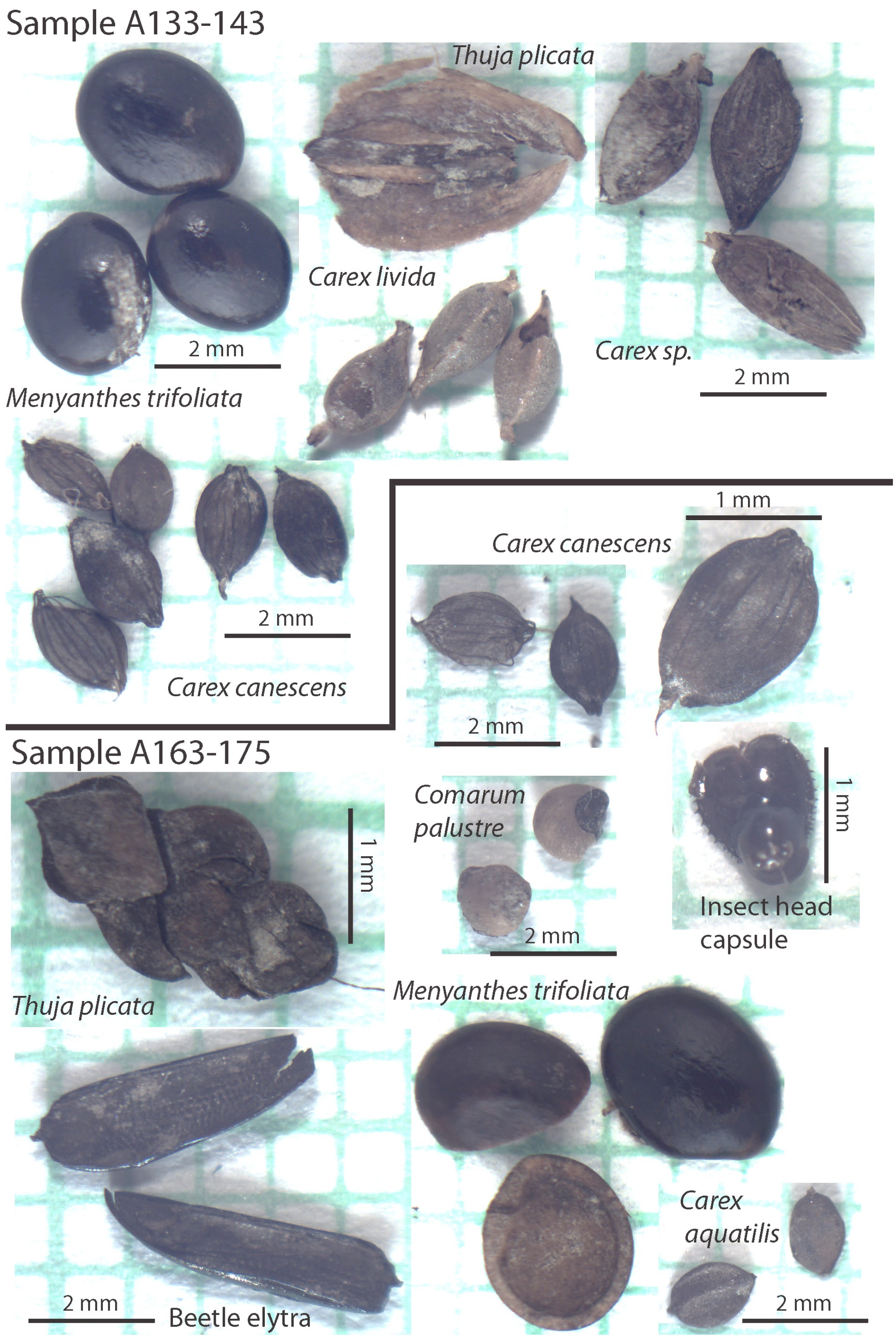


Figure B2. Photographs of macrofossils from samples A133-143 cm and A163-175 cm.

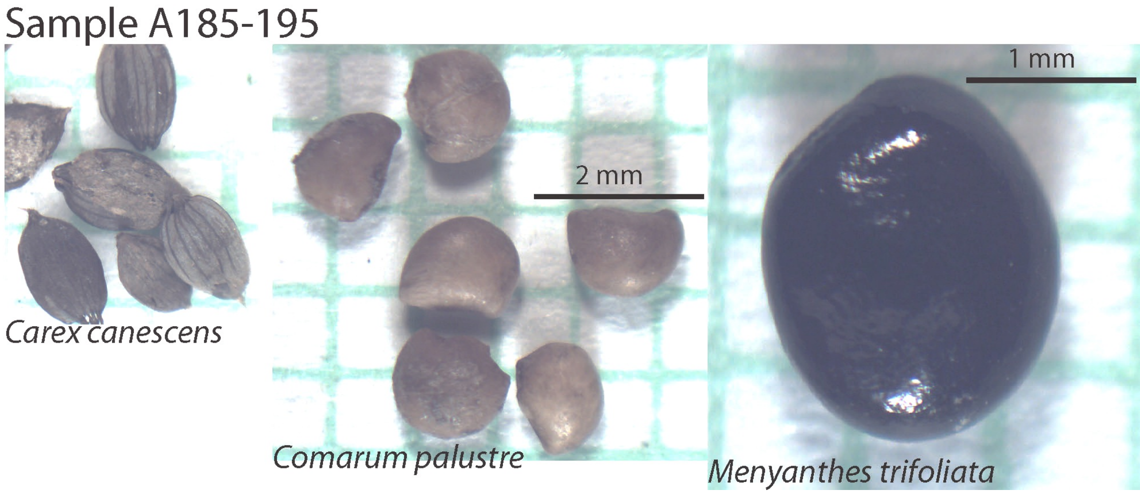


Figure B3. Photographs of macrofossils from sample A185-195 cm.

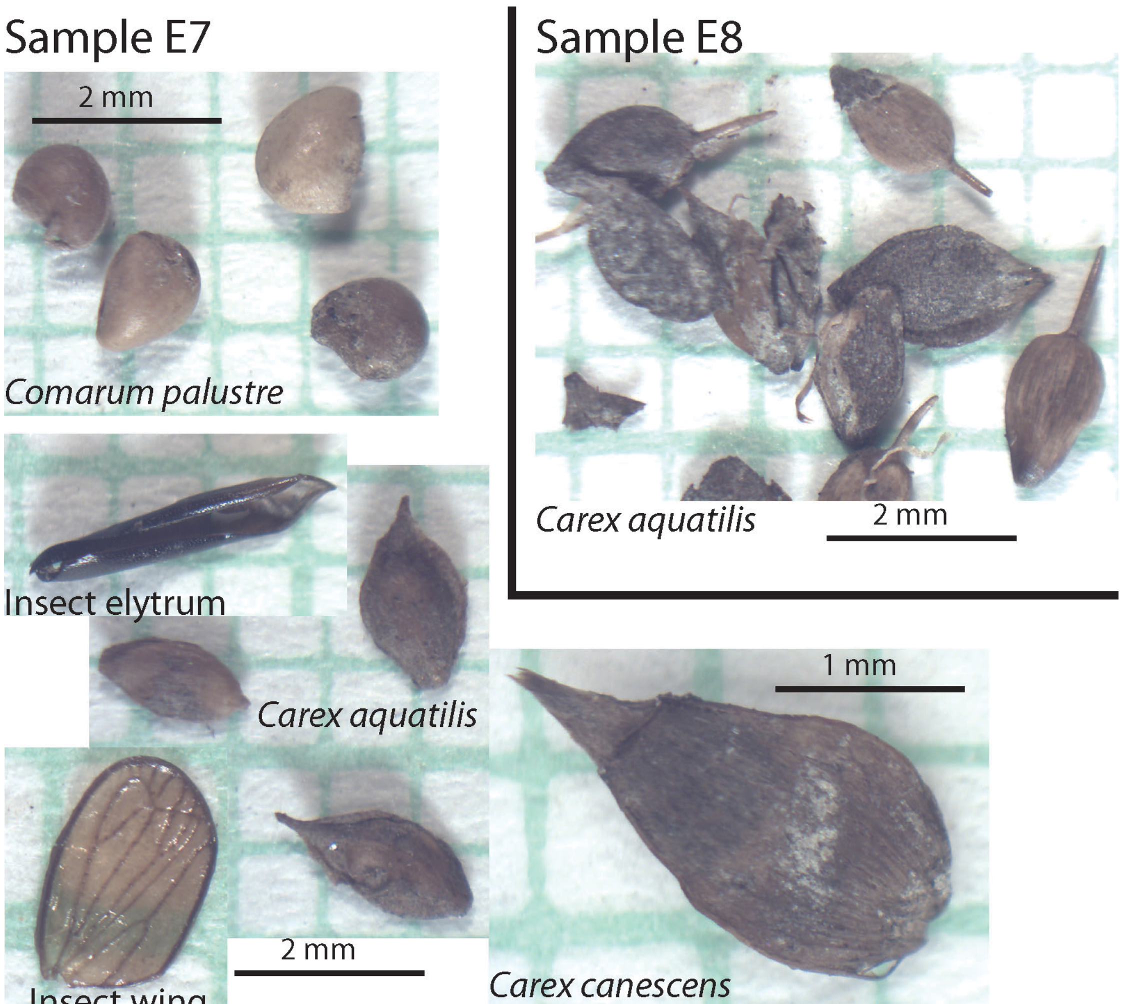


Figure B4. Photographs of macrofossils from samples E7 and E8.

Sample L4

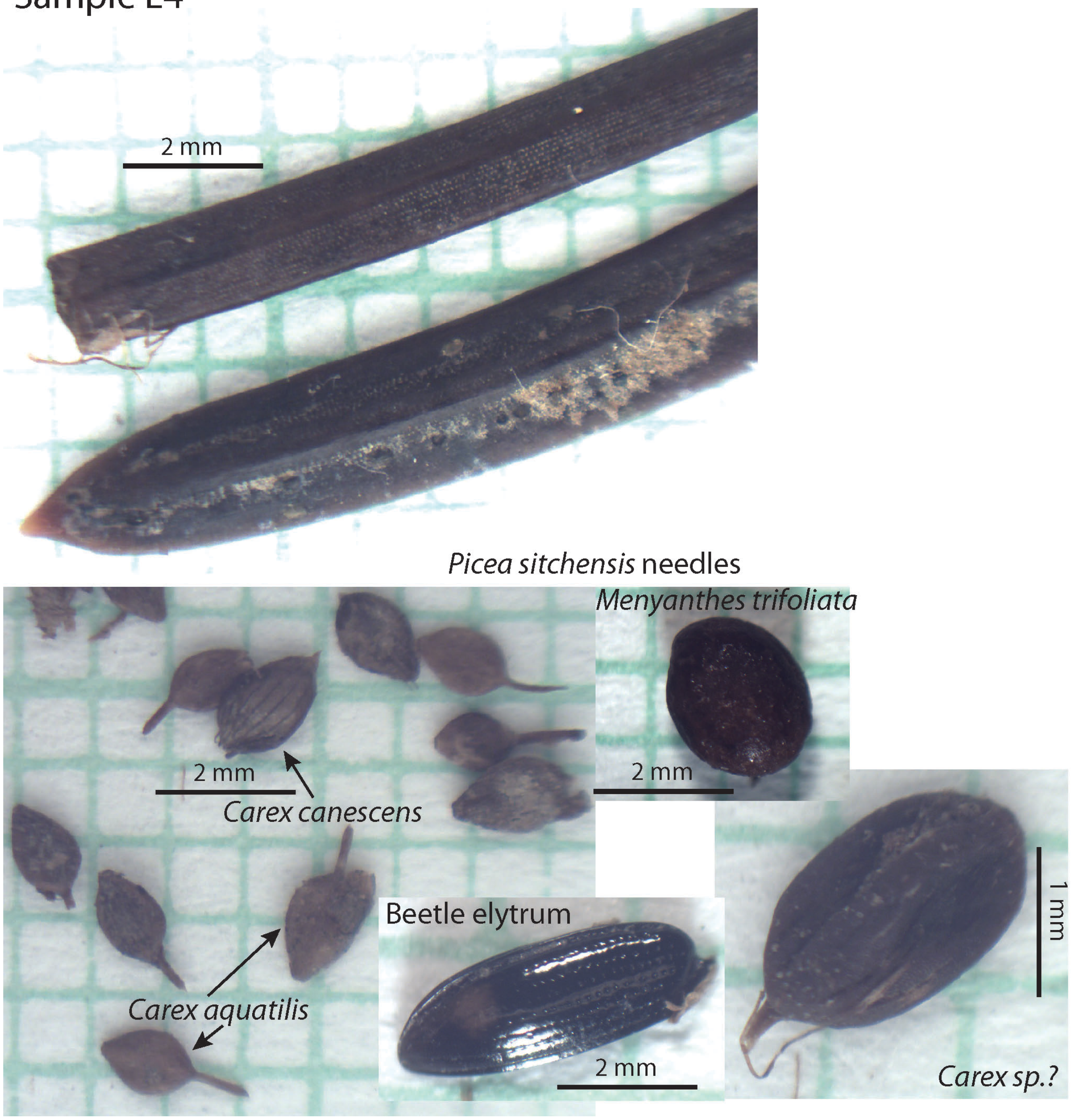


Figure B5. Photographs of macrofossils from sample L4.

Notes:

Squamish River peat samples have an aquatic signature and support the interpretation that facies 1 (interbedded peat and silt) was deposited in shallopw water or sedge fens. Most seeds are three species of sedge; the most common are *Carex canescens* and *Carex aquatilis*. I identified trigonous sedge seeds as *Carex livida*, another common wetland sedge. Common accessory plants are *Menyanthes trifoliata* (Buckbean) and *Comarum palustre* (Marsh cinquefoil), a common aquatic plant. *Menyanthes trifoliata* is a characteristic fen species in eastern North America.

Table B2. Radiocarbon-dated wood species identification.[1]

Sample	Material	Species	Interpretation
T2	Log	*Thuja plicata* (Western redcedar)	Tolerates a broad variety of moisture conditions; floodplains and uplands
A1	Log	*Taxus brevifolia* (Western yew)	Understory tree in coastal coniferous forests
L5	Log	*Thuja plicata*	Tolerates a broad variety of moisture conditions; floodplains and uplands
N3	Log	*Malus fusca* (Pacific crab apple)	Found in nutrient-rich wetlands (fens); fringing wetlands during late lake phase
T1	Stump	*Picea sitchensis* (Sitka spruce)	Common floodplain tree; requires wet, nutrient-rich soils
E5	Stump	*Picea sitchensis*	Common floodplain tree; requires wet, nutrient-rich soils
M1	Log	*Thuja plicata*	Tolerates a broad variety of moisture conditions; floodplains and uplands
M2	Stump	*Picea sitchensis*	Common floodplain tree; requires wet, nutrient-rich soils

[1] I identified wood in thin sections prepared as described by Hoadley (1990), and using the keys of Panshin et al. (1964) and Friedman (1978).

Appendix C. GNSS survey results.

Table C1. GNSS survey points.

Name	Station	Latitude	Longitude	Elevation (m asl)	δXY (m)[1]	δZ (m)[2]
131_K1	2013A	49°53'19.55"	123°17'16.25"	31.5	0.02	0.02
132_K1	2013B	49°52'14.16"	123°15'16.64"	27.5	<0.01	0.01
133_K1	2013C	49°51'48.80"	123°14'32.79"	26.8	<0.01	<0.01
A120523	A	49°51'56.70"	123°14'16.31"	26.0	0.01	0.01
101_K1	A	49°51'57.15"	123°14'17.51"	26.3	0.12	0.08
124_K1	A	49°51'57.02"	123°14'17.33"	26.4	<0.01	<0.01
125_K1	A2	49°51'57.32"	123°14'18.57"	26.3	<0.01	<0.01
126_K1	A2-WL[3]	49°51'57.10"	123°14'19.09"	20.6	<0.01	<0.01
102_K1	B	49°51'24.46"	123°14'33.72"	27.2	0.01	0.02
B120824	B	49°51'22.13"	123°14'39.83"	26.7	<0.01	<0.01
127_K1	B	49°51'23.68"	123°14'37.09"	26.8	<0.01	<0.01
119_K1	B_WL	49°51'24.20"	123°14'37.70"	18.8	0.01	0.01
109_K1	E	49°50'42.23"	123°14'13.74"	25.0	0.02	0.02
120_K1	E_WL	49°50'42.59"	123°14'13.92"	18.3	0.01	0.01
103_K1	R	49°50'38.08"	123°13'27.07"	24.5	0.23	0.17
122_K1	R	49°50'38.16"	123°13'27.86"	24.8	<0.01	<0.01
123_K1	R_WL	49°50'38.03"	123°13'28.23"	17.9	0.01	0.01
104_K1	G	49°50'14.10"	123°13'22.87"	24.9	0.1	0.08
121_K1	G_WL	49°50'14.22"	123°13'23.48"	17.2	<0.01	0.01
110_K1	J	49°49'36.12"	123°13'40.39"	23.8	0.02	0.02
111_K1	I	49°49'20.69"	123°13'29.58"	22.8	0.01	0.01
112_K1	L	49°49'13.11"	123°13'25.08"	22.94	0.01	0.02
STAL218	L_WL	49°49'13.60"	123°13'24.51"	15.411	<0.01	0.01
105_K1	M	49°48'52.67"	123°13'00.92"	21.93	0.01	0.04
129_K1	T	49°48'19.53"	123°12'47.38"	21.318	<0.01	<0.01
STAT218	T_WL	49°48'18.86"	123°12'47.64"	15.1	<0.01	0.02
128_K1	T_WL	49°48'19.13"	123°12'47.63"	15.3	<0.01	<0.01

Name	Station	Latitude	Longitude	Elevation (m asl)	δXY (m)	δZ (m)
139_K1	T	49°48'19.47"	123°12'47.19"	21.8	<0.01	0.01
136_K1	N	49°48'09.90"	123°12'45.84"	21.7	0.01	0.01
138_K1	N	49°48'10.83"	123°12'46.04"	21.5	<0.01	0.01
107_K1	W	49°48'09.32"	123°12'45.80"	22.0	<0.01	0.01
108_K1	W_AH[4]	49°48'09.28"	123°12'45.95"	17.4	0.01	0.01
134_K1	W	49°48'09.44"	123°12'45.89"	21.9	<0.01	<0.01
135_K1	W	49°48'09.44"	123°12'45.89"	21.9	<0.01	<0.01
137_K1	W	49°48'09.43"	123°12'45.86"	21.9	<0.01	0.01
130_K1	FP_BS[5]	49°48'24.34"	123°12'45.08"	20.5	0.01	0.01
106_K1	AK/O[6]	49°47'48.97"	123°12'10.61"	20.3	<0.01	0.01
Sill		49°47'15.24"	123°11'11.40"	14.4	0.01	0.01
113_K1	Z	49°47'29.17"	123°11'23.79"	20.3	0.32	0.26
114_K1	Z-WL	49°47'25.32"	123°11'20.82"	14.5	<0.01	0.01
117_K1	SRS81[7]	49°46'26.13"	123°09'58.15"	25.7	0.02	0.03
118_K1	SRS81	49°46'29.29"	123°09'59.37"	27.2	0.01	0.02
140_K1	SRS81	49°46'26.85"	123°09'57.79"	25.9	0.01	0.01
116_K1	CP[8]	49°47'07.81"	123°09'23.55"	69.1	<0.01	0.01

[1] Horizontal error rounded to nearest 1 cm.

[2] Vertical error rounded to nearest 1 cm.

[3] WL stations are readings taken at water level for a specific section.

[4] W-AH is taken at the uppermost hearth at station W: AH stands for ‘anthropogenic horizon’.

[5] Floodplain backswamp station located near W and T.

[6] AK and O are essentially the same station.

[7] SRS81 points are located at the top of an abandoned scarp of Cheekye Fan and give base-level control for a diagram in a fieldtrip guidebook (Eisbacher, 1983).

[8] Ground Control Point 83C211. Measured location is: 49°47’7.81” ± 0.003 m, 123°9’23.54829” ± 0.002 m, 69.101 m asl (NAD83 CSRS).

Table C2. GNSS point error analysis.

Name	Station	Date	Duration	Solution[1]	GPS	GLO[2]	HDOP[3]	VDOP[4]
131_K1	2013A	18/4/2013 19:06:55	0:27:35	Fix I.F.	7	6	0.978	1.493
132_K1	2013B	18/4/2013 20:28:55	1:26:20	Fix L1+L2	9	8	1.115	1.601
133_K1	2013C	18/4/2013 22:26:00	0:42:45	Fix L1+L2	11	9	0.839	1.424
A120523	A	23/5/2012 19:45:40	0:21:25	Fix L1+L2	6	6	1.267	2.847
101_K1	A	23/5/2012 20:24:50	0:18:05	Fl. L1+L2	8	6	1.069	1.697
124_K1	A	9/4/2013 01:15:15	0:32:40	Fix L1+L2	9	8	0.951	1.398
125_K1	A2	8/4/2013 19:34:55	1:34:10	Fix L1+L2	10	6	1.167	1.995
126_K1	A2-WL	8/4/2013 21:21:00	2:20:00	Fix L1+L2	13	10	1.03	1.719
102_K1	B	23/5/2012 21:20:55	0:09:50	Fix L1+L2	10	8	0.894	1.464
B120824	B	24/8/2012 20:20:45	3:12:50	Fix L1+L2	12	12	0.916	1.537
127_K1	B	8/4/2013 23:44:20	0:39:15	Fix L1+L2	10	8	0.896	1.682
119_K1	B_WL	18/2/2013 21:42:30	0:20:45	Fix L1+L2	8	8	0.926	1.21
109_K1	E	30/5/2012 19:19:00	0:10:35	Fix L1+L2	8	5	1.09	1.537
120_K1	E_WL	18/2/2013 22:37:00	0:31:15	Fix L1+L2	6	6	1.235	1.886
103_K1	R	23/5/2012 23:18:10	0:10:25	Fl. L1+L2	5	7	1.164	1.819
122_K1	R	30/3/2013 22:02:15	4:02:15	Fix L1+L2	16	13	0.946	1.573
123_K1	R_WL	31/3/2013 02:10:20	0:10:55	Fix L1+L2	7	7	1.06	1.42
104_K1	G	23/5/2012 23:47:55	0:19:55	Fl. L1+L2	10	8	0.964	1.29
121_K1	G_WL	18/2/2013 23:35:15	0:20:45	Fix L1+L2	8	6	0.905	1.557
110_K1	J	30/5/2012 20:01:40	0:10:45	Fix L1+L2	7	6	1.078	1.889
111_K1	I	30/5/2012 20:29:35	0:10:05	Fix L1+L2	7	7	0.939	1.461
112_K1	L	30/5/2012 21:02:05	0:15:00	Fix L1+L2	9	7	0.913	1.553
STAL218	L_WL	19/2/2013 00:37:10	0:11:15	Fix L1+L2	7	5	1.043	1.635
105_K1	M	24/5/2012 00:39:25	0:13:05	Fix L1+L2	8	7	1.111	1.991
129_K1	T	16/4/2013 22:01:10	2:14:20	Fix L1+L2	12	10	0.95	1.679
STAT218	T_WL	19/2/2013 01:22:35	0:14:20	Fix L1+L2	5	6	1.394	3.432
128_K1	T_WL	16/4/2013 19:57:00	1:57:40	Fix L1+L2	9	7	1.232	2.149
139_K1	T	24/4/2013 22:52:10	0:19:10	Fix L1+L2	9	8	0.946	1.689
136_K1	N	24/4/2013 21:27:40	0:15:25	Fix L1+L2	9	7	1.165	2.255
138_K1	N	24/4/2013 22:11:45	0:11:05	Fix L1+L2	10	7	1.035	1.81

Name	Station	Date	Duration	Solution	GPS	GLO	HDOP	VDOP
107_K1	W	29/5/2012 21:42:15	0:25:45	Fix L1+L2	7	6	1.921	2.677
108_K1	W_AH	29/5/2012 22:25:00	0:11:30	Fix L1+L2	4	5	2.114	3.398
134_K1	W	24/4/2013 19:09:35	1:21:35	Fix L1+L2	9	7	1.322	2.365
135_K1	W	24/4/2013 20:32:20	0:40:40	Fix L1+L2	6	7	1.358	2.645
137_K1	W	24/4/2013 21:47:35	0:12:50	Fix L1+L2	9	7	0.919	1.652
130_K1	FP_BS	17/4/2013 00:33:15	0:17:40	Fix L1+L2	6	8	1.535	2.06
106_K1	AK/O	29/5/2012 20:27:15	0:09:50	Fix L1+L2	10	7	0.74	1.294
Sill		2/2/2013 21:07:25	0:10:15	Fix L1+L2	6	7	0.881	1.709
113_K1	Z	2/2/2013 22:03:45	0:14:25	Fl. L1+L2	7	6	0.998	2.214
114_K1	Z-WL	2/2/2013 22:40:15	0:10:45	Fix L1+L2	7	8	1.04	1.704
117_K1	SRS81	3/2/2013 00:43:55	0:11:05	Fix L1+L2	8	5	1.09	1.77
118_K1	SRS81	3/2/2013 00:59:50	0:10:45	Fix L1+L2	6	4	1.327	2.774
140_K1	SRS81	25/4/2013 00:21:50	0:17:20	Fix L1+L2	8	7	1.248	1.777
116_K1	CP	2/2/2013 23:58:00	0:10:55	Fix L1+L2	7	5	1.142	1.753

[1] Solutions: Fix. I.F. – fixed ionospheric-free; Fix L1+L2 – L1 and L2 carrier fix; Fl. L1+L2 – L1 and L2 floating solution.

[2] GLO – number of Russian GLONASS satellites.

[3] HDOP – horizontal dilution of precision.

[4] VDOP – vertical dilution of precision.

Notes:

The accuracy of post-processed RTK GPS points is between 0.6 and 2 cm, but repeat measurements at several sites suggest that actual errors could be as large as 10 cm. Slight differences in ground elevation at the survey sites likely account for much of this error, except at station T where the difference between repeat measurements is 0.45 m. Difference in siting could account for several decimetres of this difference. Multipath errors, which are typically magnified in DGPS and RTK measurements, may also contribute to the error.

Table C3. Base station occupations.

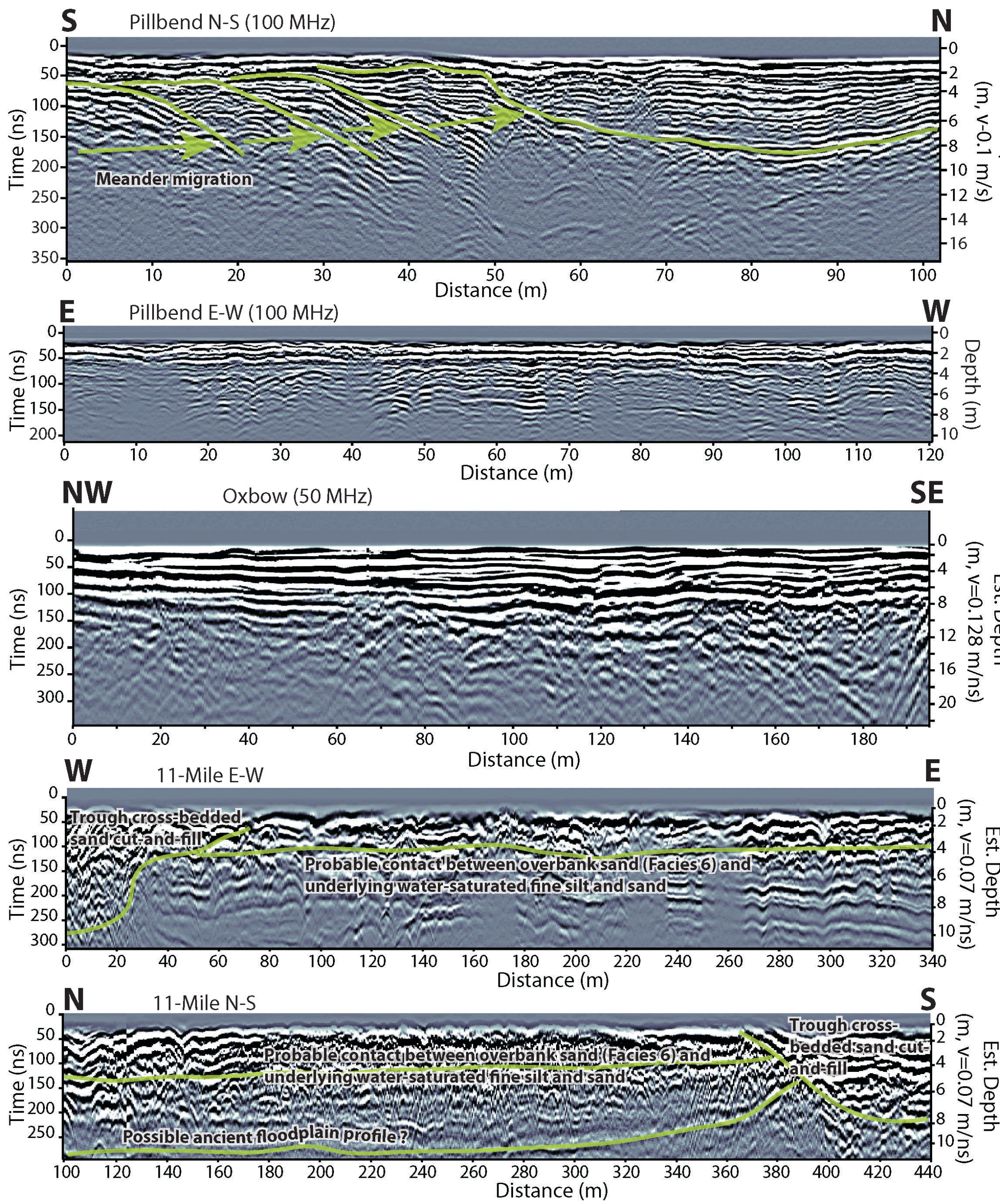
Station	Date	Latitude	Longitude	δN	δE	δZ	Elevation (m)
SquamB1	23/5/2012	49°47'54.83"	123°10'19.27"	0.005	0.007	0.02	46.915
SquamB2	29/5/2012	49°47'54.83"	123°10'19.27"	0.006	0.009	0.023	46.902
SquamB3	30/5/2012	49°47'54.83"	123°10'19.27"	0.005	0.007	0.021	46.897
SquamB4	24/8/2012	49°47'54.83"	123°10'19.27"	0.003	0.011	0.02	46.953
SquamB5	2/2/2013	49°47'54.83"	123°10'19.27"	0.005	0.01	0.022	46.929
SquamB6	18/2/2013	49°47'54.83"	123°10'19.27"	0.003	0.007	0.017	46.907
SquamB7	30/3/2013	49°47'54.83"	123°10'19.27"	0.006	0.008	0.021	46.881
SquamB8	8/4/2013	49°47'54.83"	123°10'19.27"	0.004	0.008	0.017	46.896
SquamB9	16/4/2013	49°47'54.83"	123°10'19.27"	0.003	0.007	0.017	46.899
SquamB10	18/4/2013	49°47'54.83"	123°10'19.27"	0.004	0.008	0.017	46.888
SquamB11	24/4/2013	49°47'54.83"	123°10'19.27"	0.004	0.007	0.016	46.882
Mean:		49°47'54.83"	123°10'19.27"				46.90

Table C4. Base station occupation times.

Station	Duration
SquamB1	6h 3m
SquamB2	4h 50m
SquamB3	6h 4m
SquamB4	5h 44m
SquamB5	5h 20m
SquamB6	7h 5m
SquamB7	5h 11m
SquamB8	7h 7m
SquamB9	7h 20m
SquamB10	7h 20m
SquamB11	7h 55m

Appendix D. Ground-penetrating radar profiles

I obtained several ground-penetrating radar profiles in Squamish River valley (see Figure D1 for locations). The profiles provided little information on subsurface structure other than horizontal bedding, although a profile near section B south of Pillchuck Creek revealed inclined beds indicative of past channel migration.



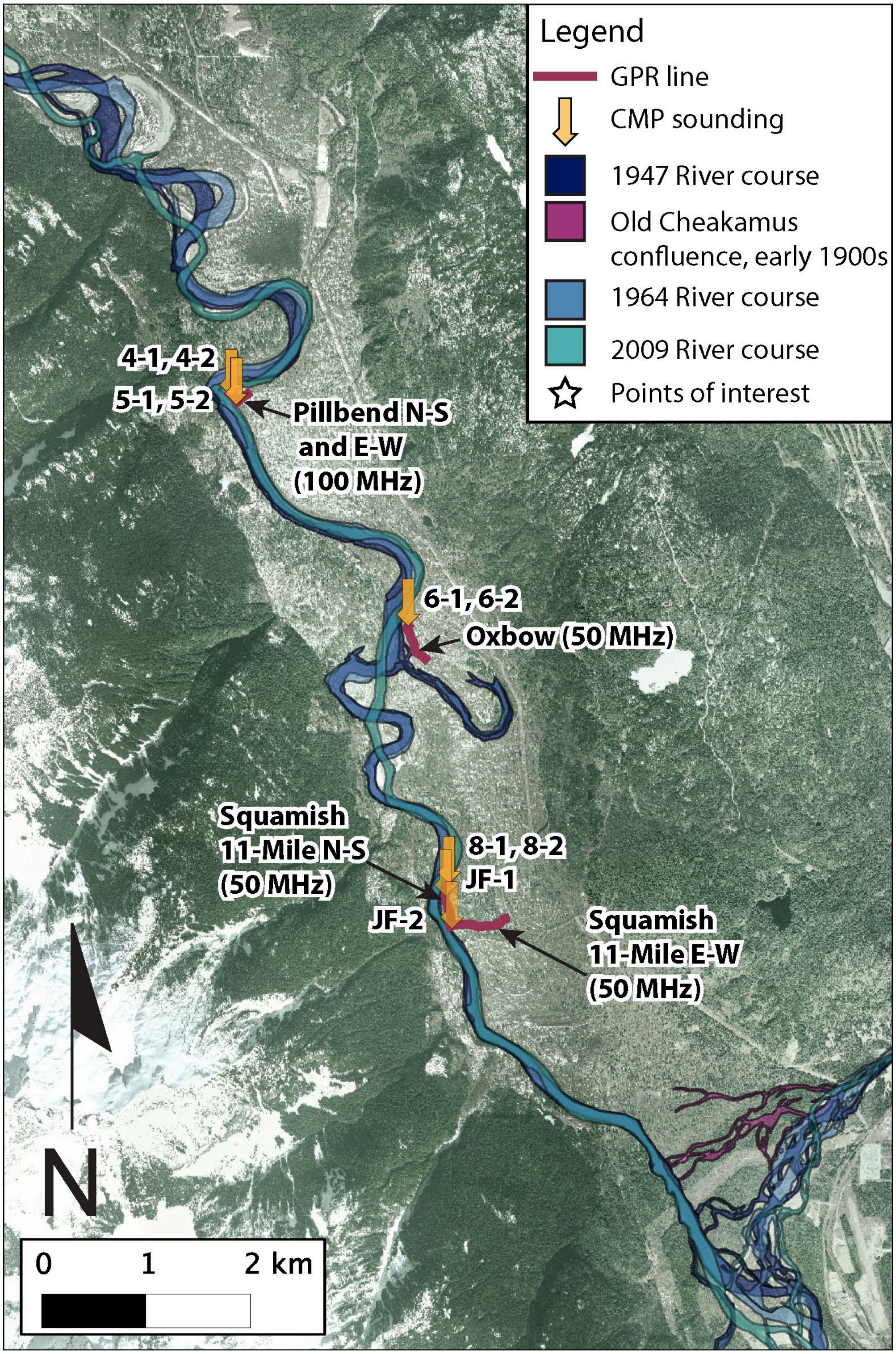


Figure D5.1. Map of GPR sites.

Appendix E. Grain-size analysis.

Table E1 Grain-size sample metadata.

Sample	Section	Sample elevation (m asl)	Sample weight (g)	Facies
W5	W	17.8	0.7	Organic-poor silt (2)
W2	W	16.3	0.7	Organic-poor silt (2)
W3	W	18.5	2.1	Organic-poor silt (2)
T4	T	16.2	0.7	Organic-poor silt (2)
E4	E	?	2	Interbedded sand and silt (6)
E9	E	19.4	0.7	Organic-rich silt and peat (1)
E7	E	19.5-19.7	0.7	Organic-rich silt and peat (1)
E8	E	19.85	0.7	Organic-rich silt and peat (1)
O2	O	16	0.7	Organic-poor silt (2)
G4	G	21.75	2	Stratified sand (4)
G2	G	21.2	2	Stratified sand (4)
G3	G	?	2	Stratified sand (4)
B4	B	22.2	2	Interbedded sand and silt (6)
B5	B	22.5	2	Interbedded sand and silt (6)
B6	B	21.8	1.9	Stratified sand (4)
A4	A	23.5	0.7	Organic-rich silt and peat (1)
L6	L	18	1.2	Organic-rich silt and peat (1)
L4	L	15.6	0.7	Organic-rich silt and peat (1)

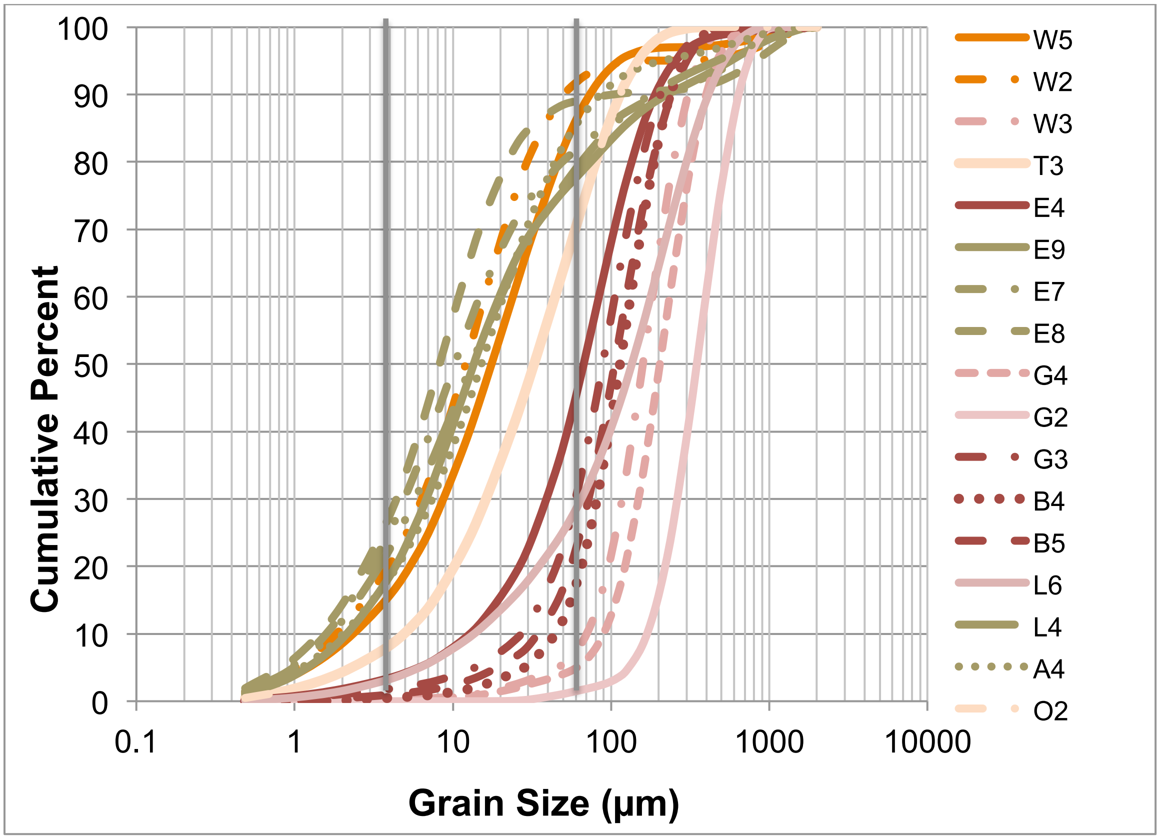


Figure E1. Particle-size cumulative frequency curves.

Table E2a. Particle-size data.

Size fraction	Upper limit (µm)	Sample W5 (% total)	Sample W2 (% total)	Sample W3 (% total)	Sample T3 (% total)	Sample O2 (% total)
Clay	3.906	15.4	20.0	0.1	7.2	8.1
Fine silt	31.25	53.2	61.4	3.2	41.3	40.5
Coarse silt	62.5	18.4	10.7	4.6	29.3	23.1
Very fine sand	125	8.7	2.8	25.8	17.8	20.2
Fine sand	250	1.3	0.1	46.6	3.3	7.4
Medium sand	500	0.4	0.4	19.2	0.2	0.6
Coarse sand	1000	1.4	2.3	0.4	0.5	0
V. coarse sand	2000	1.2	2.3	0	0.5	0

Table E2b. Particle-size data (continued).

Size fraction	Upper limit (μm)	Sample E4 (% total)	Sample E9 (% total)	Sample E7 (% tota)l	Sample E8 (% total)
Clay	3.906	3.4	18.2	24.75	27.11
Fine silt	31.25	20.42	51.31	50.05	58.12
Coarse silt	62.5	23.09	8.57	7.31	3.88
Very fine sand	125	30.31	7.48	5.28	1.09
Fine sand	250	17.51	4.94	3.33	0.47
Medium sand	500	4.1	3.69	3	1.39
Coarse sand	1000	0.8	3.99	4.07	4.41
V. coarse sand	2000	0.37	1.82	2.24	3.52

Table E2c. Particle-size data (continued).

Size fraction	Upper limit (μm)	Sample G4 (% total)	Sample G2 (% total)	Sample G3 (% total)	Sample B4 (% total)	Sample B5 (% total)
Clay	3.906	0.05	0	1.8	0.48	0.95
Fine silt	31.25	2.54	0.28	10.24	5.33	7.74
Coarse silt	62.5	2.59	1.31	19.96	12.74	15.34
Very fine sand	125	15.71	2.95	37.3	37.45	35.94
Fine sand	250	43.46	22.41	25.25	35.59	31.01
Medium sand	500	31.99	49.53	5.24	8.03	8.55
Coarse sand	1000	3.67	23.3	0.21	0.17	0.48
V. coarse sand	2000	0	0.23	0	0.2	0

Table E2d. Particle-size data (continued).

Size fraction	Upper limit (µm)	Sample L6 (% total)	Sample L4 (% total)	Sample A4 (% total)
Clay	3.906	3.2	22.2	18.0
Fine silt	31.25	15.3	46.7	53.8
Coarse silt	62.5	10.8	10.6	14.2
Very fine sand	125	18.1	7.8	6.9
Fine sand	250	25.9	4.8	2.4
Medium sand	500	21.1	3.3	1.6
Coarse sand	1000	5.6	3.1	2.2
V. coarse sand	2000	0.04	1.6	0.8

Notes:

Some samples had a coarse tail due to the presence of seeds and organic debris. To remove the coarse organic material, I initially crushed samples with a mortar and pestle, then sieved the crushed material using a 2000 µm screen, followed by treatment in hydrogen peroxide. In a second set of analyses, I crushed samples with a mortar and pestle, and sieved them using an 850 µm screen. In a third set of analyses, I sieved leftover material from the first run through an 850 µm screen.

Table E3a. Comparison of grain size distributions for sample E7 with different pretreatements.

Size	Sample E7 % total	Sample E7-2 % total	Sample E7-3 % total
Clay	24.75	20.85	22.00
Fine silt	50.05	61.92	61.95
Coarse silt	7.31	8.63	7.69
Very fine sand	5.28	3.75	3.69
Fine sand	3.33	1.39	1.53
Medium sand	3.00	0.66	1.11
Coarse sand	4.07	1.37	1.42
V. coarse sand	2.24	1.44	0.62

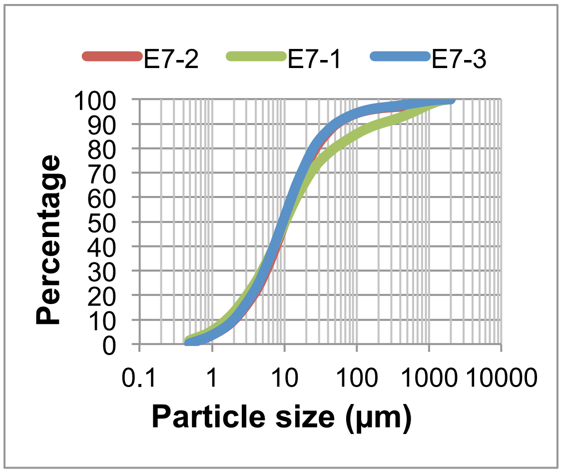


Table E3b. Comparison of grain size distributions for sample E8 with different pretreatments.

	Sample E8-1	Sample E8-2	Sample E8-3
Size	% total	% total	% total
Clay	27.1	23.2	20.0
Fine silt	58.1	63.0	72.7
Coarse silt	3.9	3.6	5.8
Very fine sand	1.1	1.3	1.3
Fine sand	0.5	0.8	0.2
Medium sand	1.4	1.5	0
Coarse sand	4.4	3.8	0
V. coarse sand	3.5	2.8	0

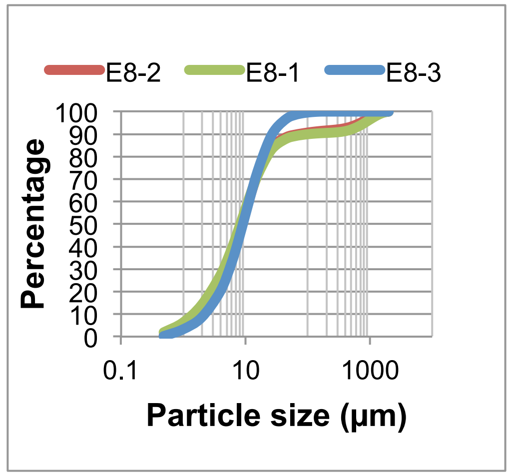


Table E3c. Comparison of grain size distributions for sample E8 with different pretreatments.

	Sample W2-1	Sample W2-2	Sample W2-3
Size	% total	% total	% total
Clay	19.9	16.81	14.51
Fine silt	61.49	69.70	69.65
Coarse silt	10.70	10.61	12.52
Very fine sand	2.78	2.64	3.14
Fine sand	0.14	0.25	0.18
Medium sand	0.43	0.00	0.00
Coarse sand	2.30	0.00	0.00
V. coarse sand	2.28	0.00	0.00

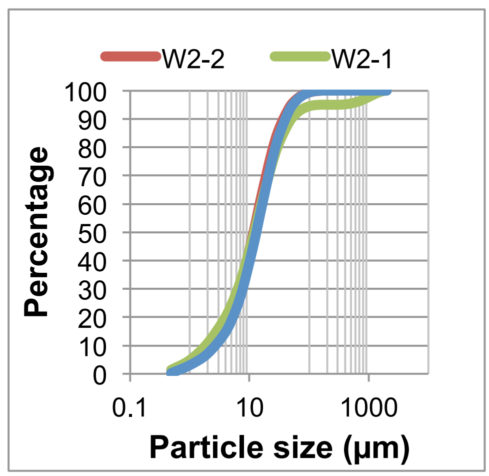


Table E3d. Comparison of grain-size distributions for sample T3 with different pretreatments.

	Sample T3-1	Sample T3-2	Sample T3-3
Size	% total	% total	% total
Clay	7.2	9.0	6.7
Fine silt	41.3	46.8	41.3
Coarse silt	29.3	25.9	29.1
Very fine sand	17.8	15.4	18.4
Fine sand	3.3	2.89	4.2
Medium sand	0.2	0.0	0.4
Coarse sand	0.5	0.0	0.0
V. coarse sand	0.4	0.0	0.0

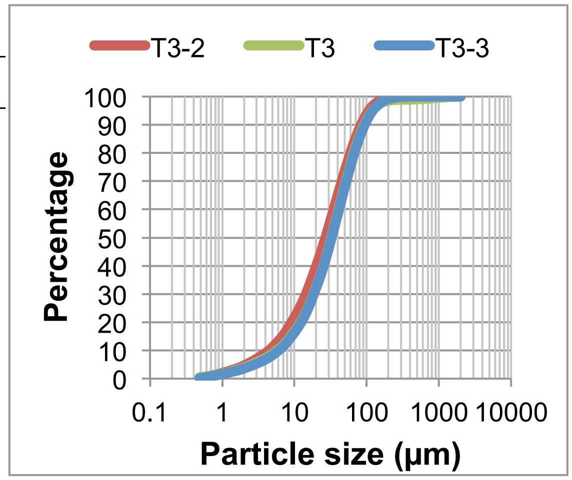


Table E3e. Comparison of grain-size distributions for sample O2 with different pretreatments.

	Sample O2-1	Sample O2-2	Sample O2-3
Size	% total	% total	% total
Clay	8.1	6.7	6.85
Fine silt	40.5	40.2	42.55
Coarse silt	23.1	22.5	23.01
Very fine sand	20.2	20.2	18.87
Fine sand	7.4	8.7	7.54
Medium sand	0.6	1.4	1.14
Coarse sand	0.00	0.3	0.0
V. coarse sand	0.00	0.0	0.0