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Surficial Geology and Pleistocene stratigraphy from Deep Bay to Nanoose Harbour, Vancouver Island, British Columbia

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Abstract

A detailed study of the surficial geology of the east coast of Vancouver Island from Deep Bay to Nanoose Harbour was undertaken as part of the *Nanaimo Lowland Ground Water Assessment Project*. This paper describes the results of the field mapping program and resulting surficial geology map. The map incorporates Pleistocene stratigraphy derived from new seismic reflection surveys and boreholes carried out by the GSC, and lithological information extracted from BC Ministry of Environment water well database.

Large parts of the coastal lowland are mantled by unconsolidated material over 100 metres thick, but the thickness is quite variable and bedrock outcrops are common. The surficial materials are dominated by deposits from two previous glaciations that are separated by non-glacial fluvial and marine sediments. During the last glaciation, the coastal plain was subjected to glacial advances from two distinct sources: local mountain glaciers expanding out of the Vancouver Island Ranges, and secondly, the Cordilleran Ice Sheet flowing from the Coast Mountains to the northeast. Quadra Sand, an extensive proglacial outwash, was deposited over the coastal plain with the approach of the Cordilleran Ice Sheet. At its maximum the ice sheet flowed over the Island Ranges, over-topping the local glaciers.

Deglaciation was marked by thinning and eventual separation of the two ice masses and marine inundating of the coastal plain to at least 150 m above present. At this time extensive gravels were deposited along the ice margins in the form of ice-contact deltas and terraces. With final deglaciation and rapidly falling base levels most sedimentation was concentrated at the mouths of the main rivers where deltas were built into progressively lower sea levels. In other places, transverse streams crossing the lowland either terraced pre-existing glacial deposits, or cut narrow canyons in the bedrock. A cobbly surface till covers most the flat-lying interfluves except below the marine limit where the till was partially reworked by marine action or covered by marine sands and silts in poorly drained areas. Modern alluvium is confined to the lower reaches of the larger rivers.

Introduction

The surficial geology and Pleistocene stratigraphy of a coastal segment of east-central Vancouver Island is documented here. The specific study area is the coastal lowland between Deep Bay and Nanoose Harbour, including the slopes around Horn and Cameron lakes, at about the 300 m contour elevation (Fig. 1). This work is a component of the *Nanaimo Lowland Groundwater Assessment Project* undertaken by the Geological Survey of Canada. Groundwater is an important source of potable water for most of the population in the study area, which include the municipalities of Parksville and Qualicum Beach (a combined population of approximately 20 thousand). The quality and abundance of groundwater supply is greatly dependent on the varied thickness and stratigraphy of unconsolidated deposits blanketing the lowland. These sediments are mostly marine, fluvial and glacial materials of Pleistocene and Holocene age deposited during and after glaciation. They generally form an extensive cover that can locally exceed 100 m in thickness. However, bedrock outcrops are not uncommon, reflecting the highly variable nature of the sediment cover.

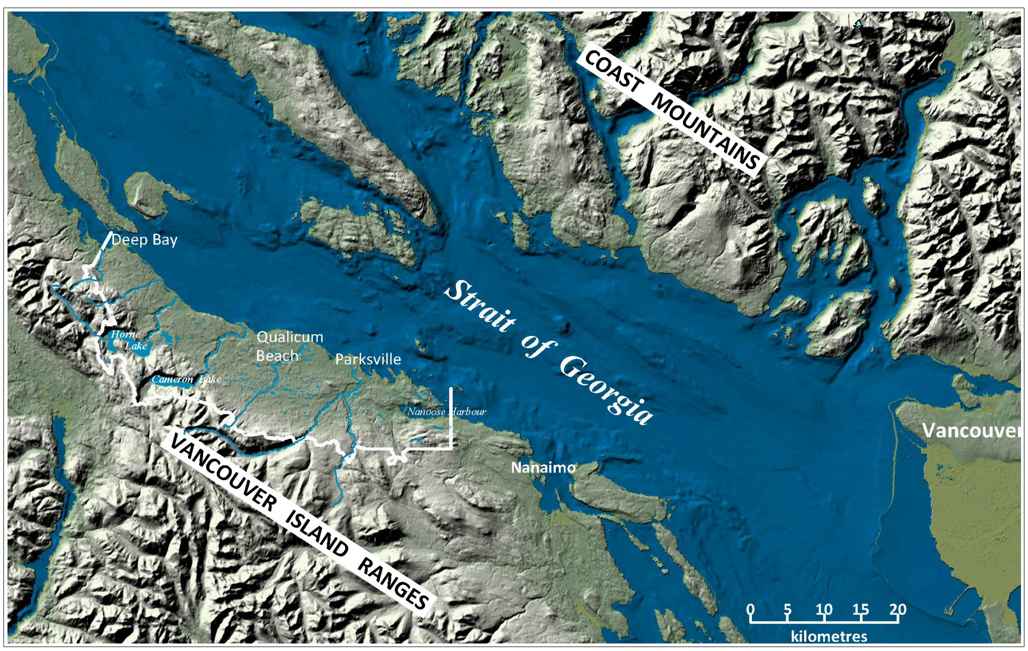


Figure 1. *East central Vancouver Island showing the Nanaimo Lowland groundwater project study area (white line).*

Physiography

The focus of this study is part of the Nanaimo Lowland, the unsubmerged southwestern part of Georgia Depression (Holland, 1964; Mathews, 1986) bordered by the Strait of Georgia (Strait of Georgia and Puget Sound to the south are collectively known as the Salish Sea; the name comes from the indigenous peoples who live in the region). The study area encompasses the coastal plain from Deep Bay to Nanoose Harbour (Fig. 1), an area about 46 km long and 5 to 14 km wide. The plain rises to the southwest with a gentle gain in elevation of about 15 m per 1 km until it meets the steep flanks of the Vancouver Island Ranges. Locally the highest point in this area is 1819 m, the summit of Mount Arrowsmith. The headwaters of the Englishman River emanate from glacier-free cirques on Mount Arrowsmith. Although the lowland is covered in thick Pleistocene deposits, bedrock outcrops are common throughout the area. This means that the underlying bedrock surface is irregular. In turn, an irregular basement means that the thickness of the overlying sediment is variable and individual strata are discontinuous. Pleistocene stratigraphy is exposed along major rivers that have incised the coastal plain.

These rivers emanate from mountain valleys and generally flow north and northeast as they cross the plain. Other important stratigraphic sections are exposed along coastal cliffs near Dashwood and Mapleguard Point.

Georgia Depression has undergone repeated intervals of subsidence and deposition since the Late Cretaceous (Mathews, 1972). Submerged areas include basins and troughs up to 430 m below sea level and shallow banks oriented northwest-southeast, probably formed by glacial scour of Tertiary and Cretaceous strata. Nonetheless, in places Pleistocene sediments on the floor of the Strait of Georgia are more than 550 m thick (Clague, 1976a). Horizontal strata within the submarine sediments are truncated by the present sea floor indicating that significant erosion took place. This erosion is also evident on islands in northern Strait of Georgia where stratified terrestrial sediments of Late Pleistocene age are unconformably overlain by till of the last, Fraser Glaciation. The sediments comprising these islands are thought to be the remnants of the extensive fill in Georgia Depression (Clague, 1976b). Clague (1976b, 1977) proposed that this stratified sediment extended across the full width of Georgia Depression before the last continental glaciation and was subsequently eroded during the Fraser Glaciation. Large parts of the study area are still underlain by these erosional remnants. Clague (1976b, 1977) defined Quadra Sand as proglacial outwash laid down during the advance of the last glaciation. The sand constitutes a major stratigraphic unit and important aquifer in the study area.

In contrast to the thick unconsolidated sediments covering much of the sea floor in Strait of Georgia, Pleistocene sediments underlying the sea floor nearest Vancouver Island are thought to be absent or very thin (Clague; 1976a).

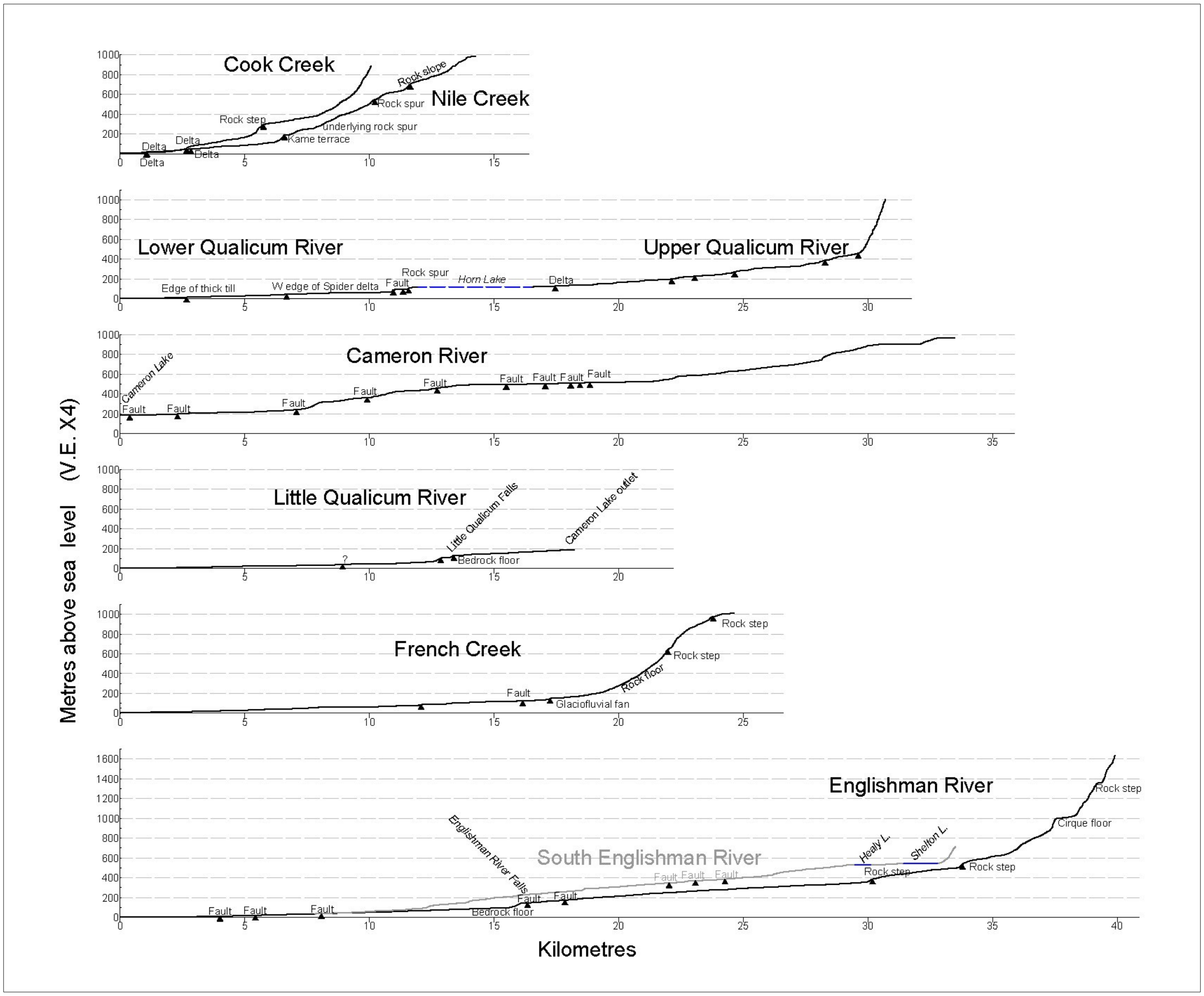
The Nanaimo Lowland consists of several low cuesta-like ridges separated by narrow valleys formed by differential erosion of the underlying bedrock. Mostly, the ridges are comprised of resistant sandstone and conglomerate beds, and the eroded valleys are underlain by softer shale or align with fault zones. The regional northwest-southeast structural trend coincided with large southeast-flowing glaciers occupying Georgia Depression during past glaciations which led to enhanced erosion. Extensive glacial erosion is also evident in the Vancouver Island Ranges in the form of steep-sided valleys, closed rock basins and cirques. Much of this erosion was caused by local valley glaciers emanating from the Vancouver Island Ranges.

As noted, prominent east-facing cirques on Mount Arrowsmith fed large glaciers that widened and steepened the valleys as they merged into a trunk glacier flowing eastward along Englishman River valley. This is further illustrated in Figure 2, which shows the profiles of the major rivers in the study area. At higher elevations of the Englishman River, prominent steps were carved into the bedrock where valley glaciers merged on Mount Arrowsmith. Most of the rivers also have nick points in their profiles at lower elevations. Some of these coincide with faults mapped in the bedrock (Massey et al., 2005), whereas, others coincide with surface features such as delta terraces or kames. Given that at any point along a stream course there is a general relationship between stream gradient and upstream catchment area (Hack, 1973), it is clear some river segments have not reached their equilibrium profiles.

Geological Setting

Tectonically, the Georgia Depression is a Cretaceous to Cenozoic forearc basin that overlaps Wrangellia Terrane on Vancouver Island (the Insular Belt) and the Coast Belt at the leading edge of the North American Plate. The forearc basin postdates the amalgamation of Wrangellia onto the North American Cordillera and overlies the now subducting Juan de Fuca Plate. Most of Vancouver Island is composed of Wrangellia Terrane that accreted to the west coast of North American about 100 My ago (England and Bustin, 1998).

Wrangellia rocks within the study area include the Sicker and Buttle Lake groups which are the oldest rocks on Vancouver



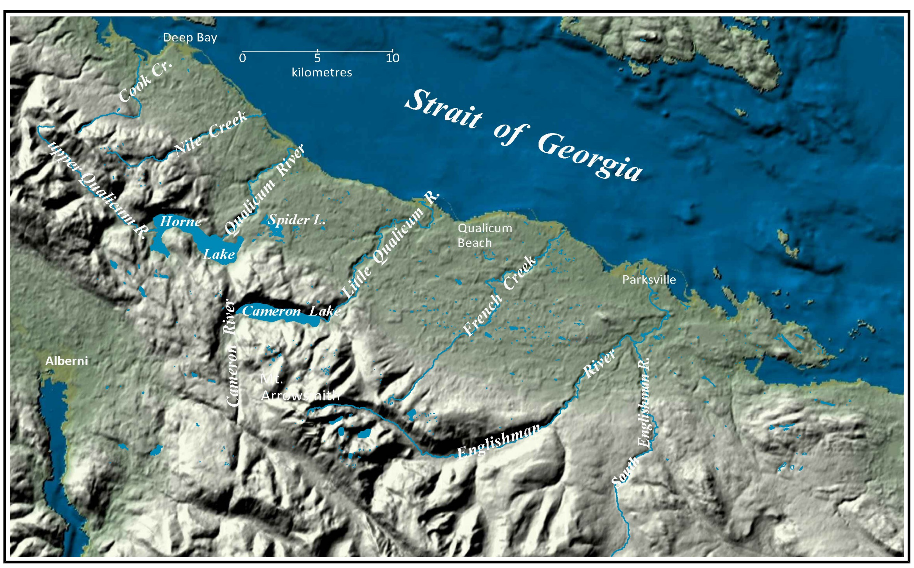


Figure 2. *Profiles of the main rivers in the study area and location map. Prominent nick points are indicated by the triangles.*

Island. These are mainly sea-floor and terrestrial volcanic rocks with some limestone of Devonian age (ca. 370 Ma ago). Wrangellia also includes younger rocks of the Karmutsen

Formation, part of the Vancouver Group and the most common rock type exposed on Vancouver Island. The Karmutsen Formation is dominated by sea-floor basalt (mostly pillow-basalt) of Triassic age (250-200 Ma ago), although, two small plutons of coeval Mount Hall Gabbro outcrop north of Horne Lake and west of Nanoose. The youngest rocks within Wrangellia are Jurassic age intrusive rocks of the Island Plutonic Suite and the West coast Crystalline Complex (Massey, et al. 2005; Fig. 3).

Nanaimo Group rocks form the basement under most of the study area. These sedimentary rocks were deposited in the basin between Wrangellia and North America during Upper Cretaceous time (85-65 My ago). Their initial origin is non-marine or deltaic fluvial, consisting of upward fining sequences of conglomerate, sandstone, shale and coal which are succeeded by marine sandstone, shale and thin-bedded shale-siltstone sequences (Muller and Jeletzky, 1970). The youngest rock to outcrop in the study area is a small exposure of

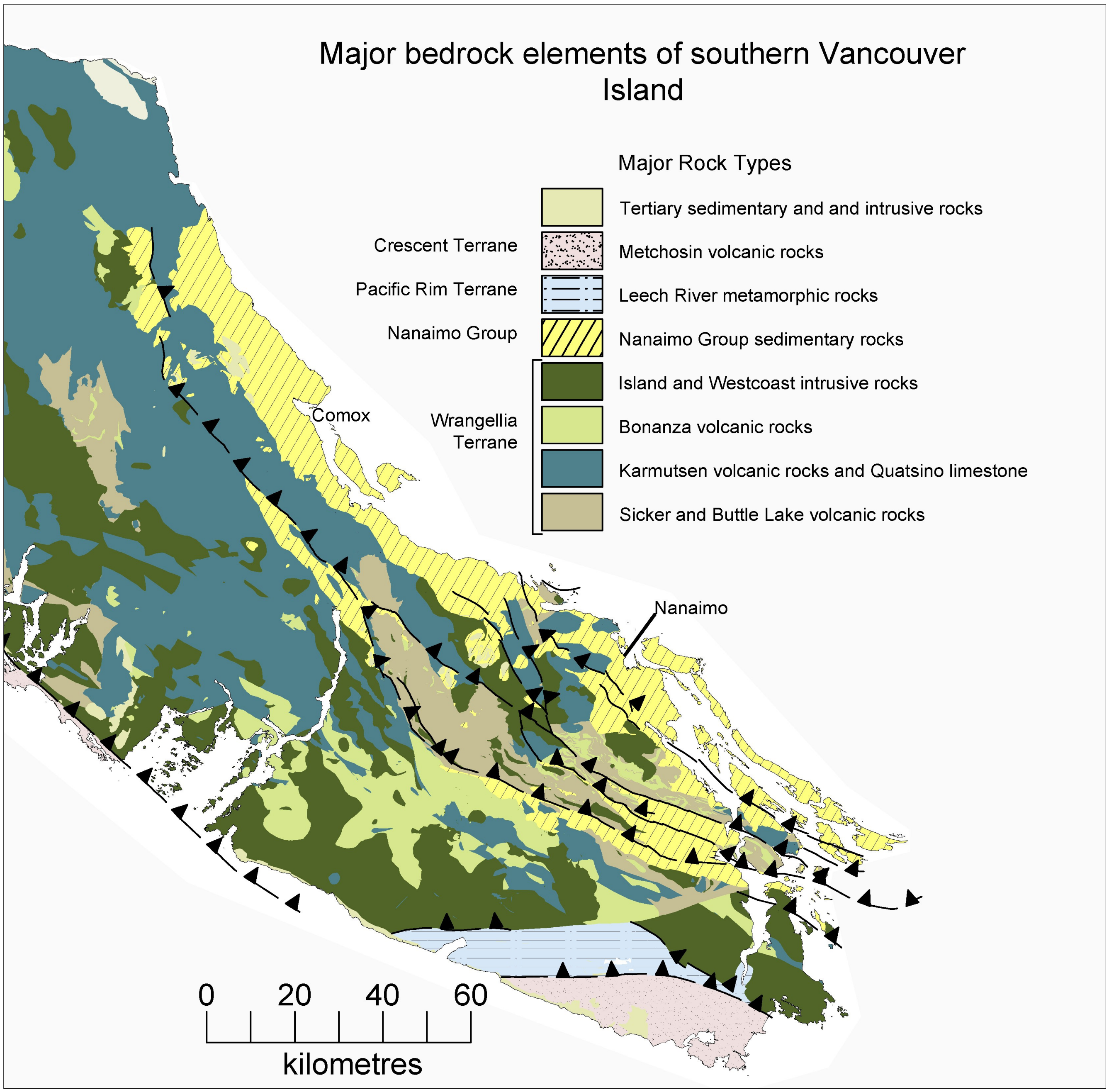


Figure 3. *Major bedrock elements of southern Vancouver Island (source: Massey, et al. 2005).*

quartz diorite, part of the Mount Washington Plutonic Suite of Eocene to Oligocene age (Massey, et al. 2005).

Most of the unconsolidated sediment overlying the basement on the Nanaimo Lowland is glacially-derived with the bulk of the sediment being locally eroded, and thus reflecting the local bedrock. Nevertheless, there is also a significant amount of far-travelled material whose relative abundance is determined by the flow paths of the former glaciers. Generally glaciers originating on Vancouver Island deposited sediments rich in volcanic, metamorphic and sedimentary rocks in contrast to the mainly plutonic lithologies of glacial sediments derived from the mainland Coast Mountains (Fig. 4).

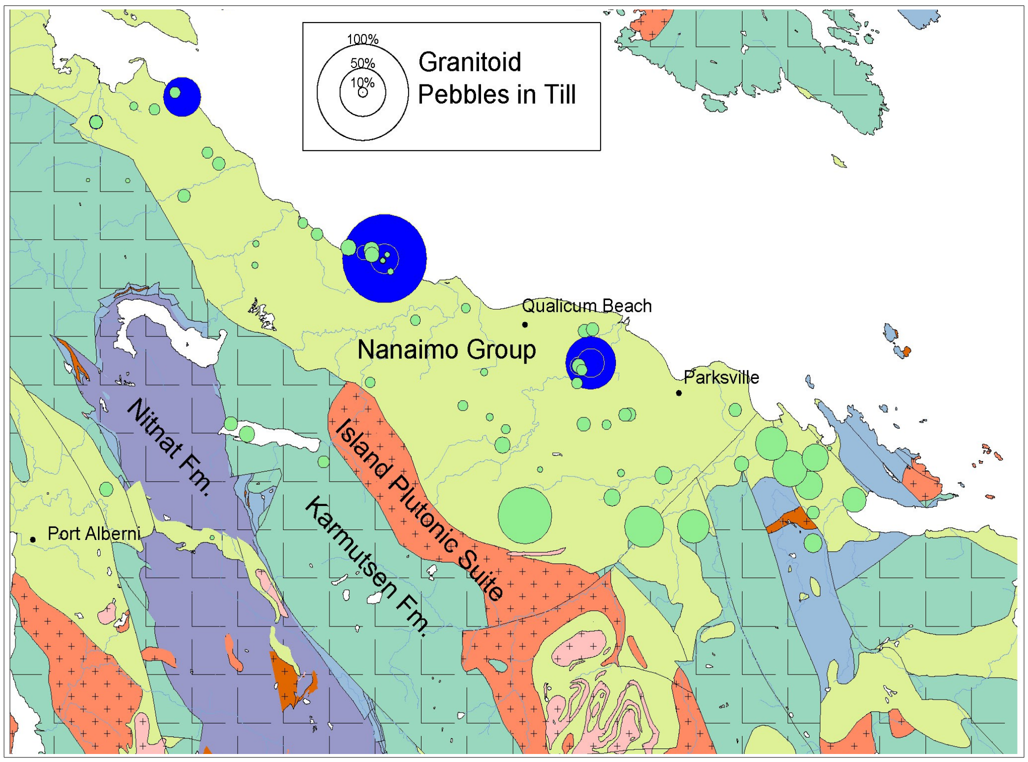


Figure 4. *Bedrock geology of the map area. Most of the Nanaimo Lowland is underlain by upper Cretaceous sedimentary Nanaimo Group and is bound to the southwest by volcanic rocks of the Devonian Nitnat and upper Triassic Karmutsen formations (after Massey, et al., 1994). The cross pattern indicates various intrusions of the Middle Jurassic, Island Plutonic Suite. The circles represent the percent granitoid pebbles in Dashwood (blue) and Vashon (green) tills (Source: Fyles, 1956; Hicock, 1980).*

Surficial Geology

Late Pleistocene sediments have been described on eastern Vancouver Island since the late nineteenth and twentieth centuries (Dawson, 1878, 1891; Clapp, 1913, 1914). By studying the provenance of glacial deposits and the landforms of glacial erosion the early workers were able to determine that Georgia Depression was once filled by glacial ice and that most of this ice originated from the Coastal Mountains. Ice-flow onto Vancouver Island was mainly from the north and northeast. Clapp (1914) discovered that there were at least two glacial epochs separated by an interval of non-glacial sedimentation. In describing the stratigraphy, Clapp adapted the same terminology used to describe similar events in Puget Sound by Willis (1898). Parts of this stratigraphic nomenclature remains in use today.

The most comprehensive work describing the surficial geology encompassing the study area was done by J.G. Fyles (1963), whereas Halstead (1966) mapped adjacent parts of the Nanaimo Lowland to the south. This report was largely guided by Fyles' ground breaking work.

Overview of Glacial History

Nanaimo Lowland contains some of the key stratigraphic sections that expose glacigenic sediments from at least two major glaciations separated by fluvial and marine deposits (Dawson, 1890; Clapp, 1914; Fyles, 1963). These glaciations were also recognized on the Fraser Lowland of southwest British Columbia where deposits of the penultimate glaciation are known as *Semiahmoo Drift* deposited during the *Semiahmoo Glaciation*, whereas V*ashon Drift* was deposited during the last glaciation, the Late Wisconsinan *Fraser Glaciation* (Armstrong, 1984). Deposits from the penultimate glaciation on east central Vancouver Island are known as *Dashwood Drift* and have been correlated with Semiahmoo Drift (Hicock, 1980). In contrast, the term Vashon Drift has been widely adopted to describe deposits of the last glaciation throughout the region. Moreover, on Vancouver Island, all the glacial deposits related to the Fraser Glaciation were categorized as Vashon Drift, implying that they were all deposited during a single advance. This may not be valid because in the Fraser Lowland and Coast Mountains the Fraser Glaciation consisted of several distinct advances or re-advances (e.g. Armstrong et al., 1965; Armstrong, 1984; Lian and Hickin, 1992). Currently, there is insufficient evidence to differentiate more than a single advance in the study area.

The general character of former ice sheets overriding the Nanaimo Lowland can be reconstructed from mapped paleo-ice flow indicators such as streamlined landforms and striated bedrock surfaces. However, as most of these features are the product of glacial erosion, they usually record only the last glacier movements to affect the area, hence only the last glaciation. In places, cross-cutting relationships and shifting flow directions with elevation provide a picture of glacier growth and decay. On a regional scale, the mapped paleo-ice flows show that the study area was impacted by glaciers flowing from two distinct accumulation areas (Fig. 5). There was a local source area over the mountains of Vancouver Island and a more distant source area over the Coast Mountains on the mainland. The local glaciation was characterized by expanded alpine glaciers that flowed down valleys and coalesced as piedmont lobes on the mountain flanks. During the height of this glaciation the alpine glaciers likely coalesced into several ice caps centred over Vancouver Island. Nevertheless the main source of ice that inundated Georgia Depression and ultimately Vancouver Island was the Cordilleran Ice Sheet flowing off the Coast Mountains. The Cordilleran Ice Sheet initially bridged onto Vancouver Island in the north where the flow spit into a northwest-flowing segment into Queen Charlotte Strait and a southeast-flowing segment that infilled Georgia Depression.

The configuration of the penultimate Dashwood advance is not well known, but it was probably of similar character as the final Vashon advance. The direction of paleo-ice flow inferred from till clast provenance and till fabrics suggest that the penultimate advance flowed down Georgia Depression much like the Vashon advance (Hicock, 1980; Hicock and Armstrong, 1983; Fig. 5).

On southern Vancouver Island the Cordilleran advance was characterized by a lobe of the ice sheet flowing southeastward down Georgia Depression and impinging the eastern flank of Vancouver Island. As the ice filled Georgia Depression it initially split into two lobes: one flowed down Puget Lowland, the other flowed down the Strait of Juan de Fuca where glaciolacustrine sediments on the southwest coast of Vancouver Island were deposited into lakes dammed by the lobe (Alley and Chatwin, 1979).

When the Cordilleran ice impinged on the eastern slopes of southern Vancouver Island it was at first deflected southeastward when it made contact with the expanded glaciers on Vancouver Island. However, at its maximum, the Cordilleran Ice Sheet surmounted most of the Island Ranges and flowed southwest across Vancouver Island until it reached the continental shelf (Clague, 1981). At its maximum the ice reached 1220-

1520 m in elevation over the mountains of Vancouver Island, about 1070 m over Victoria and about, 460 m near the west end of the Strait of Juan de Fuca (Mathews et al. 1970). However, Alley and Chatwin (1979) thought that the ice was ~1500 over Victoria and 800 m at the end of Juan de Fuca.

Mapping successive ice margins that

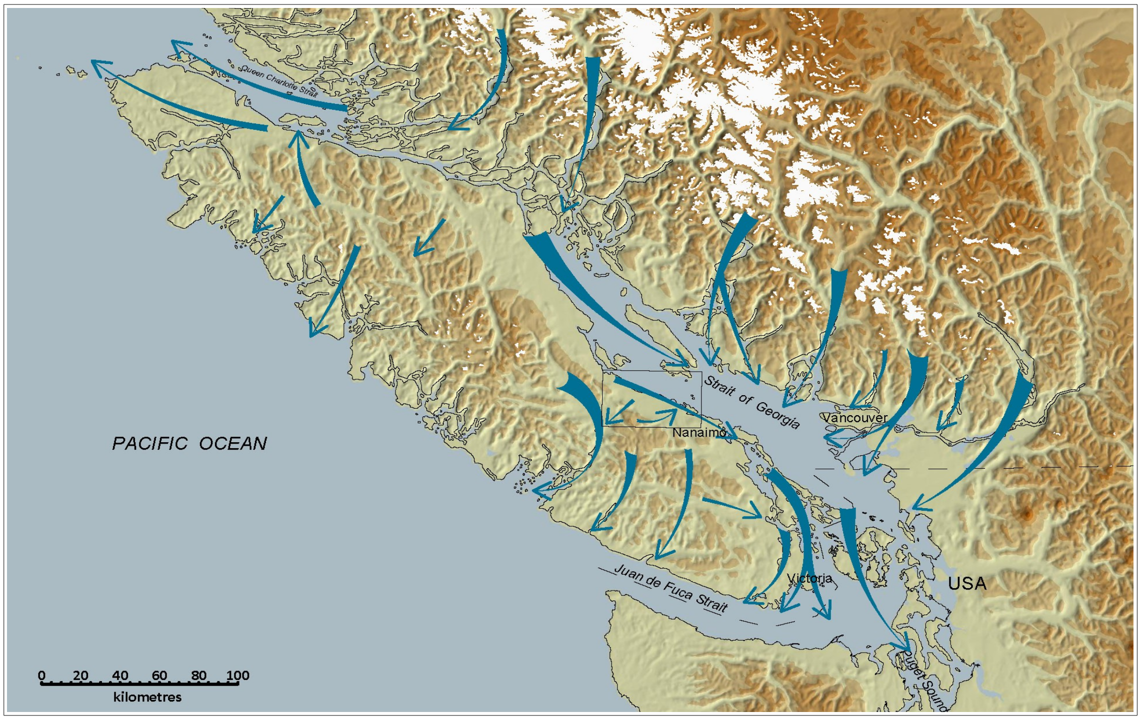


Figure 5A. *Regional paleo-ice flow directions from mapped ice-flow features, southwest British Columbia. Major ice flows originated off the mainland Coast Mountains and Vancouver Island Ranges. At the glacial maximum Georgia Depression was filled by the Cordilleran Ice Sheet which also overtopped Vancouver Island reaching Pacific Ocean (Alley and Chatwin, 1979; Fyles, 1956, 1963; Halstead, 1963, 1966; Hicock, 1980; Howes, 1981, 1983; Clague et al., 1982). Note modern snow and ice cover in white.*

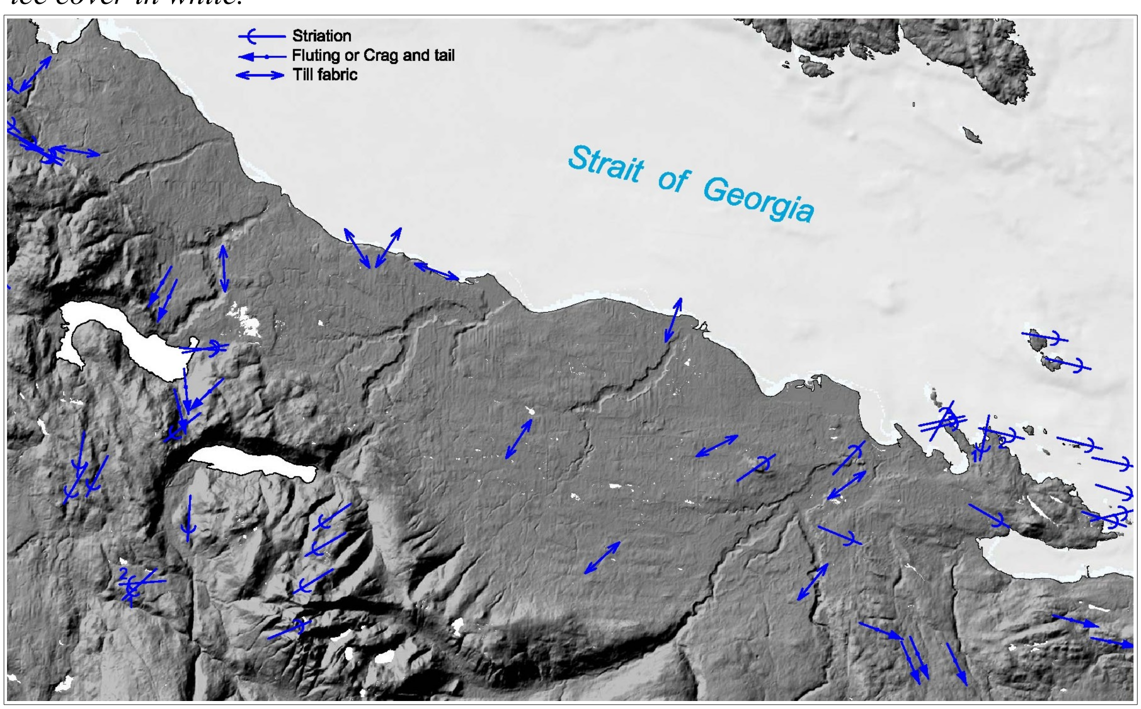


Figure 5B. *Paleo-ice flow features within the study area (Fyles, 1956, 1963; this study).*

can be dated with radiocarbon dates shows a progressive advance of the Cordilleran Ice Sheet from 18 ka ^{14}C BP (thousand radiocarbon years ago) to its maximum southern extent in Puget Sound about 14.5 ka ^{14}C BP. (Dyke et al., 2003; Fig. 6A). Subsequent retreat from the maximum southern extent took place about 14 ka ^{14}C BP, with almost complete deglaciation by about 10 ka ^{14}C BP (Dyke et al., 2003; Fig. 5B). The southernmost extent of the Cordilleran Ice Sheet in Puget Sound was around 14.5 ka ^{14}C

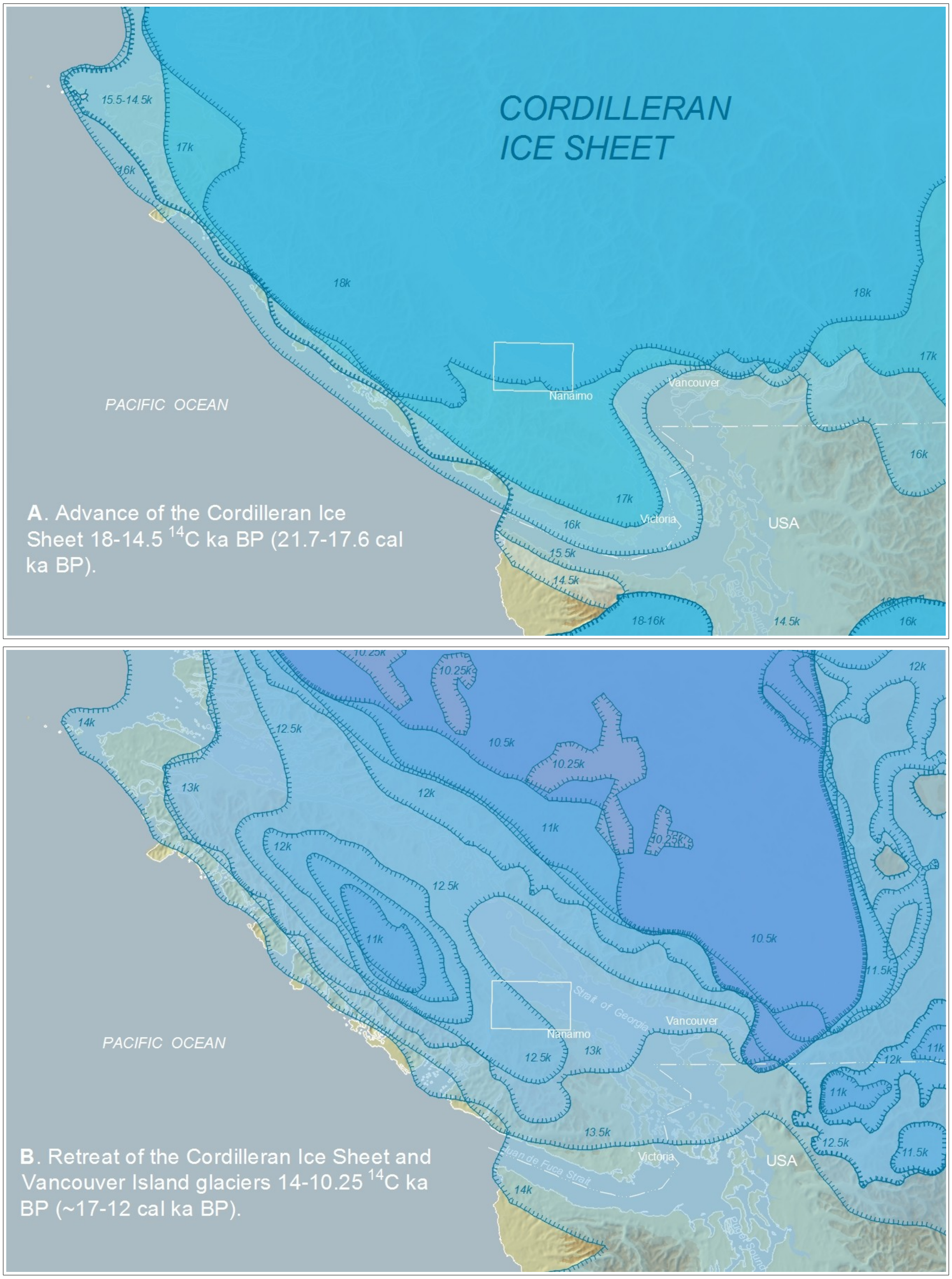


Figure 6. *The pattern of deglaciation of southwest British Columbia:* ***A.*** *The growth of the Cordilleran Ice Sheet from 18 ka to 14.5 ka ^{14}C BP (~21.7 to 17.6 cal ka BP);* ***B.*** *Deglaciation from the maximum southern extent of the Cordilleran Ice Sheet from 14 to 10.25 ka ^{14}C BP (~17 to 12 cal ka BP);(adapted from Dyke et al., 2003).*

BP (about 17.6 cal ka BP; calibrated years ago). This is later than the global last glacial maximum that occurred from 26.5 to 19 to 20 cal ka BP (Clark et al., 2009).

Cordilleran Ice Sheet first advanced into Georgia Depression as tongues of ice flowing down the fiords into the sea. The ice was relatively thin compared to the depth of water so that the glaciers became buoyant and may have formed ice shelves in places. Sea level was especially high because of crustal loading by the expanded ice sheet. It is likely that sea level was at least as high during the advance phase as when the ice was retreating which were at least 150 m above present sea level in the study area (Fig. 7). Glacial debris melting out from beneath the ice settled through the water column depositing a mix of coarse rock debris and fine sediment. These deposits are commonly fossiliferous and provide useful dating control. Nonetheless, glaciomarine sedimentation ceased during the glacial maximum when the sea in Georgia Depression was completely displaced by the Cordilleran Ice Sheet and the ice was in direct contact with the bed (Clague, 1981, 1986).

The Cordilleran ice that advanced down Georgia Depression formed a lobe fed by ice from the north. As the lobe advanced, meltwater was directed southeast towards the margins depositing extensive proglacial outwash that was subsequently overridden by the ice. The outwash is known as *Quadra Sand*. It is characteristically well-sorted sand with minor gravel up to 75 m thick and mostly below 100 m in elevation (Clague, 1976b, 1977). Quadra Sand is usually capped by impermeable Vashon till and is one of the most important aquifers in the Nanaimo Lowland. Quadra Sand is thought to have originated either as a series of distinct outwash fans and deltas that became amalgamated during the advance, or a formerly continuous outwash plain infilling the Georgia Depression that was subsequently partially eroded by the overriding ice. The Nanaimo Lowland also has thick sequences of outwash in the same stratigraphic position as Quadra Sand, but they are associated with the advance of local Vancouver Island glaciers.

Deglaciation of the Nanaimo Lowland was marked by thinning and separation of the Cordilleran lobe from the Island valley glaciers. Once separation occurred, ice-contact glaciofluvial terraces and deltas were deposited along the retreating ice margins. Eventually the sea flooded in the area from the southeast and glaciofluvial deltas were built into a high postglacial sea reaching 150 m above sea level. In places, such as the Englishman River valley, the local valley glaciers may have persisted and even re-advanced after the retreat of the Cordilleran lobe. A similar late glacial resurgence has also been documented in other parts of Vancouver Island (Alley and Chatwin, 1979).

With deglaciation complete and the isostatic load removed sea levels fell rapidly

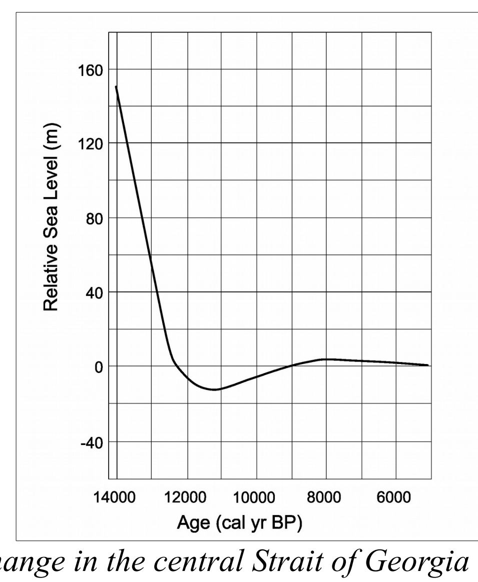


Figure 7. *Relative sea-level change in the central Strait of Georgia (after Hutchinson et al., 2004).*

(Clague and James, 2002) leaving the glaciofluvial deltas and terraces perched on mountain flanks. By 6 ka years ago sea level was below present (Fig. 7; Hutchinson, et al., 2004). Where sediment supply was adequate, the main rivers built deltas into progressively lower sea levels. In other places, streams crossing the lowland either cut terraces into preexisting glacial deposits, or cut narrow canyons into the bedrock. A cobbly surface till covers most the flat-lying interfluves. Below the marine limit, the till is partially reworked by marine action or covered by marine sands and silts in poorly drained areas. Modern alluvium is confined to the lower reaches of the larger rivers.

Table 1 summarizes new and previously published radiocarbon dates within the study area that were used to establish the stratigraphic column and facilitate the lithostratigraphic correlations.

Table 1. *Radiocarbon dates. See Fig. 8 for locations.*

Location	Site no.	Lat. (° 'N)	Long. (° 'W)	Elevation	Material	Lab no.	Uncorrected age[a]	Radiocarbon age[b]	Corrected age[c]	[d] Calibrated age
Englishman River	1	49 17.12796	124 16.47569	34	Wood	GSC- 1	12 400 ± 200	12 400 ± 100	12 400 ± 100	14 553 ± 444
Englishman River	1	49 17.12796	124 16.47569	34	Wood	I(GSC)- 1	12 000 ± 450	12 000 ± 225	12 000 ± 225	14 072 ± 688
Englishman River	1	49 17.12796	124 16.47569	34	Wood	L-391D	12 150 ± 250	12 150 ± 125	12 150 ± 125	14 175 ± 443
Englishman River	1	49 17.12796	124 16.47569	34	Marine shells	L-391E	12 350 ± 250	12 750 ± 125	11 800 ± 135	14 507 ± 519
Cochrane H	2	49 23.68975	124 39.97424	111	Marine shells	UCIAMS-135240		13 195 ± 35	12 245 ± 35	15 242 ± 144
Cochrane H	2	49 23.68975	124 39.97424	109	Shell valves	UCIAMS-135239		13 390 ± 40	12 440 ± 40	15 523 ± 208
Englishman River	3	49 17.22628	124 16.44098	30	Bivalves	UCIAMS-122340		13 045 ± 25	13 045 ± 25	15 010 ± 185
French Creek	4	49 19.78180	124 22.99957	50	*Abies* sp.	GSC-2452	25 200 ± 300	25 200 ± 150	25 200 ± 150	29 239 ± 388
Dashwood	5	49 22.13957	124 31.04397	~15	Wood	GSC- 14	26 000 ± 600	26 000 ± 300	26 000 ± 300	30 188 ± 672
Dashwood	5	49 22.13957	124 31.04397	~15	Wood	L- 221A (lignin)	25 850 ± 500	25 850 ± 250	25 850 ± 250	30 083 ± 629
Dashwood	5	49 22.13957	124 31.04397	~15	Wood	L- 221A (cellulose)	25 900 ± 300	25 900 ± 150	25 900 ± 150	30 141 ± 495
Dashwood	5	49 22.13957	124 31.04397	~15	Peat	GSC- 263	27 670 ± 410	27 670 ± 205	27 670 ± 205	31 502 ± 404
Dashwood	5	49 22.13957	124 31.04397	~15	Peat	L- 221B (lignin)	25 050 ± 300	25 050 ± 150	25 050 ± 150	29 106 ± 373
Dashwood	5	49 22.13957	124 31.04397	~15	Peat	L- 221B (cellulose)	23 450 ± 300	23 450 ± 150	23 450 ± 150	27 621 ± 228
Dashwood	6	49 22.48835	124 32.08160	~37	Wood	I-9332	27160 ± 790	27160 ± 790	27160 ± 790	31 507 ± 1779
Dashwood	6	49 22.48835	124 32.08160	~37	Wood	I-8448	29 010 ± 920	29010 ± 920	29010 ± 920	33 054 ± 1810
Spider G	7	49 21.88355	124 36.86111	61	Conifer needle fragments	UCIAMS-135206		31450 ± 340	31450 ± 340	35 397 ± 687
Dashwood	6	49 22.48835	124 32.08160	~37	Deciduous wood	I-9333	31 420 ±1130	31420 ± 1130	31420 ± 1130	36 131 ± 2505
Dashwood	6	49 22.48835	124 32.08160	~30	*Pseudotsuga menziesii*	GSC-2050	32 600 ± 550	32 600 ± 550	32 600 ± 550	36 733 ± 832
Dashwood	6	49 22.48835	124 32.08160	~29.5	*Picea, Polulus, Betula* sp.	GSC-2314	32 600 ± 600	32 600 ± 600	32 600 ± 600	36 753 ± 900
Dashwood	6	49 22.48835	124 32.08160	~29.5	*Alnus* sp.	GSC-3035	22 500 ± 230	22 500 ± 230	22 500 ± 230	26 821 ± 360
Dashwood	6	49 22.48835	124 32.08160	~27	*Picea* sp.	GSC-2192	> 39 000	> 39 000	> 39 000	> 42 616
Dashwood	8	49 22.56042	124 32.44666	~8	Marine shells	GSC- 207 2 IF 2L	> 37 400	> 37 800	> 36 850	> 41 634
Dashwood	8	49 22.56042	124 32.44666	~8	Marine shells	GSC- 207 IF 5L	> 40 500	> 40 900	> 39 950	> 43 725
Dashwood	8	49 22.56042	124 32.44666	~8	Marine shells	GSC- 207 OF 2L	37 100 +1500-1300	37 500 ± 750	36 550 ± 752	41497 ± 1242
Dashwood	8	49 22.56042	124 32.44666	~8	Marine shells	L- 475B	> 35 600	> 36 100	> 35 150	> 40 002
Deep Bay	9	49 27.10399	124 41.97980	24	Marine shells	UCIAMS-122341		42 500 ± 680	42 500 ± 680	45581 ± 1289
Dashwood	10	49 22.79480	124 34.26290	1	Marine shells	UCIAMS-122339		47 800 ± 1300	47 800 ± 1300	Date out of range
Spider G	7	49 21.88355	124 36.86111	22	2 shell fragments	UCIAMS-135238		49 400 ± 2400	49 400 ± 2400	Date out of range
Cochrane H2	11	49 23.68761	124 39.96884	12.5	Marine shells	UCIAMS-122342		51 200 ± 2000	51 200 ± 2000	Date out of range
Cochrane H2	11	49 23.68761	124 39.96884	12.3	Marine shells	UCIAMS-122343		53 300 ± 2600	53 300 ± 2600	Date out of range
Chef Creek	12	49 26.83327	124 45.22017	~23	Wood	GSC- 99	> 37 900	> 37 900	> 37 900	> 41 955
Wilfred Creek	13	49 28.61814	124 50.18917	~121	Peat	GSC-78	> 37 600	> 37 600	> 37 600	> 41 766

[a] **GSC raw machine age ± 2σ**

[b] **Ages normalized to $\delta^{13}C$ = -25‰ and uncertainties are 1σ; old GSC shell dates are adjusted by adding 400 years (Stuiver and Polach, 1977)**

[c] **Corrected age: -950 ±50 a for marine shells > 10ka BP; -720 ± 90 for marine shells < 10ka BP (Hutchinson et al., 2004)**

[d] **Calibrated age: Oxcal v4.2.3 (Ramsey, 2013); Intcal-13 atmospheric curve and Marine-13 marine curve (Reimer et al., 2013)**

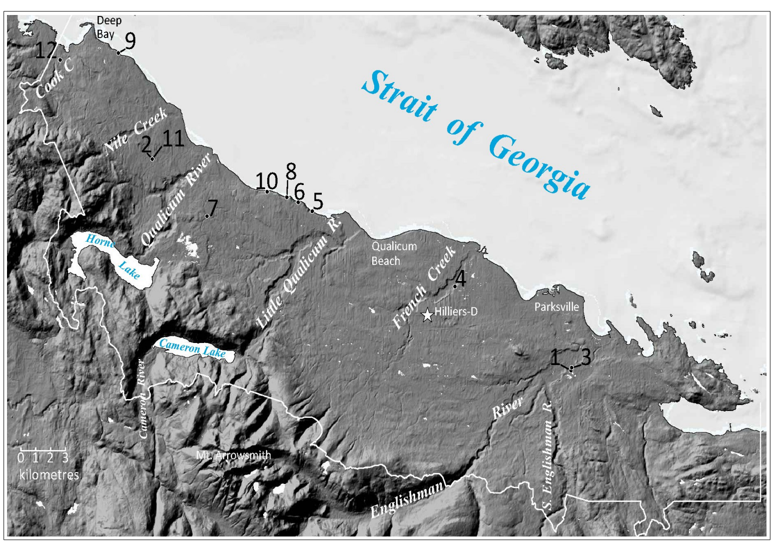


Figure 8. *Location of radiocarbon dated samples in the study area. Sites 2 and 7 are also the locations of boreholes Cochrane-H/H2 and Spider-G respectively. The star shows the location of Hilliers-D borehole.*

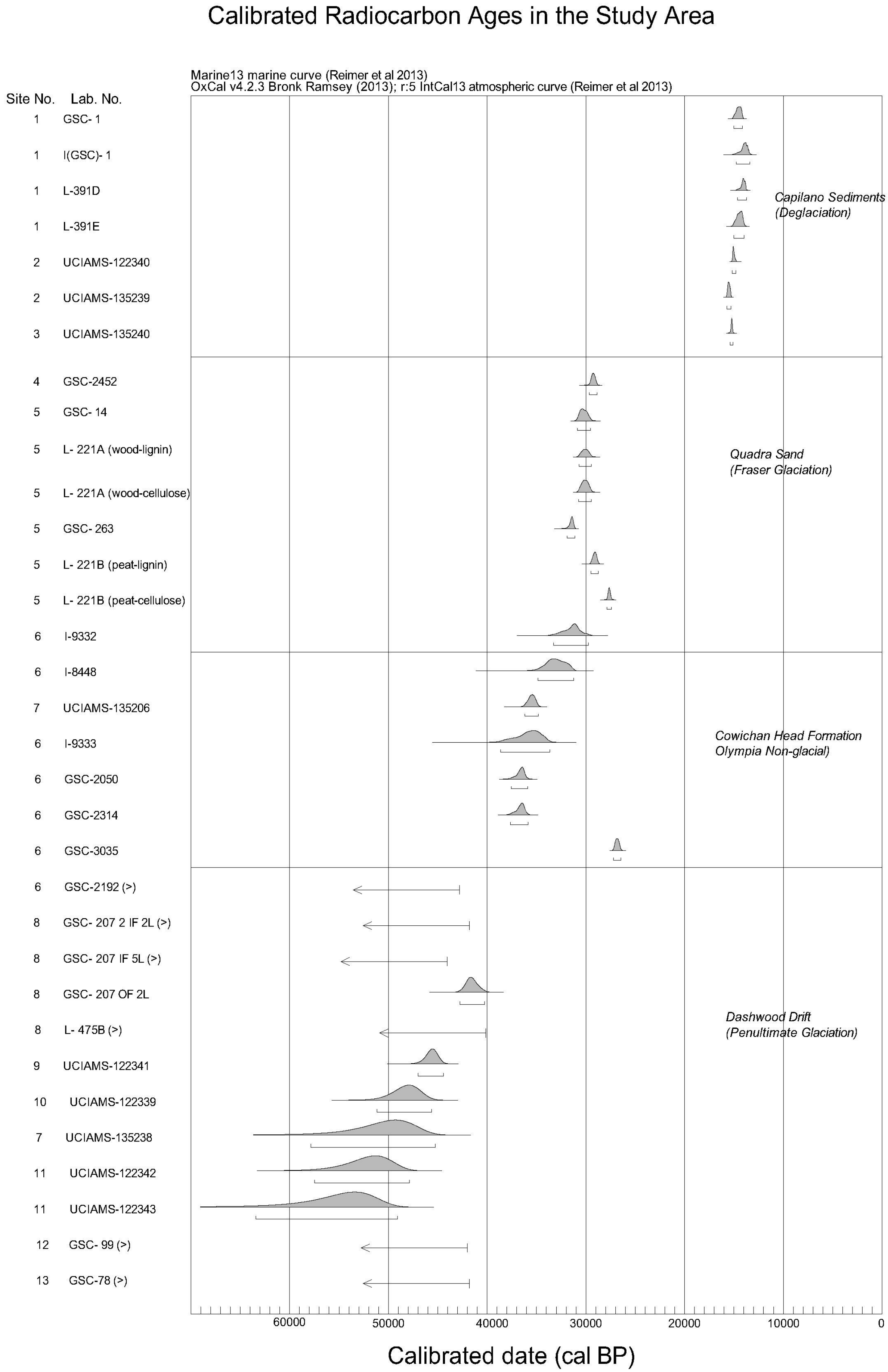


Figure 9. *Calibrated radiocarbon ages within the stratigraphic framework (from Table 1).*

Stratigraphic Framework

The study area is covered by a thick succession of unconsolidated sediment recording the glacial history outlined in the previous section, namely an interval of glacial sedimentation followed by nonglacial sedimentation, in turn, followed by an interval of glacial sedimentation, and all overlain by postglacial marine and fluvial deposits (Fyles, 1963). Numerous radiocarbon dates and good stratigraphic control suggest that the base of the succession is early to middle Wisconsinan in age (Hicock and Armstrong, 1983). However, as older last interglacial (Sangamonian) deposits have been identified near Victoria (*Muir Point Formation*; Alley and Hicock, 1986), it is possible that such deposits exist but remain unrecognized in the Nanaimo Lowland. Such deposits are beyond the range of radiocarbon dating. Calibrated radiocarbon dates used to correlate the stratigraphic units in the study area (Table 1) are shown in Figure 9.

Mapleguard Sediments – Dashwood Drift – penultimate glaciation

The oldest Pleistocene deposits positively identified in the Nanaimo Lowland are bedded sand, silt, clay and minor gravel that underlie glacial deposits at the base of a few sea cliffs northwest of Qualicum Beach. Their origin was thought to be either fluvial, deltaic or marine (Fyles, 1963; Hicock, 1980). Fyles (1963) called these deposits *Mapleguard sediments* and thought that they were nonglacial, predating the penultimate glaciation. Nevertheless, based on pollen assemblages and clast provenance Mapleguard sediments are now considered more likely to be outwash deposited at the onset of the penultimate glaciation (Hicock, 1980; Hicock and Armstrong, 1983; Ryder and Clague, 1989). Mapleguard sediments are up to 10 m thick along the sea cliffs but Fyles (1963) reported more than 20 m in auger borings.

As noted, a few sites on southern Vancouver Island have non-glacial fluvial and marine sediments older than Dashwood Drift (*Muir Point Formation*; Hicock, 1980, 1990). The sediments record climatic conditions over 100 ka ago at least as warm as today based on pollen analysis (Hicock, 1990). As of yet, there are no known occurrences of Muir Point Formation in the Nanaimo Lowland.

Dashwood Drift was deposited during the penultimate glaciation. It includes a single till, 3 to 9 m thick, bounded by glaciofluvial, ice-contact and glaciomarine to marine sediments (Hicock and Armstrong, 1983). The age of this glaciation is thought to be early Wisconsinan because this diamicton is overlain by glaciomarine silt and silty sand containing many marine shells which date beyond the range of radiocarbon (Clague, 1980; Fig. 8). At the Dashwood type section (~5 km northwest of Qualicum Beach), 10 m of glaciomarine sediments are overlain by cobbles and gravel interpreted as a beach lag with a paleosol (Alley, 1979). Fyles (1956) originally included these glaciomarine sediments in his 'Quadra sediments', but Armstrong and Clague (1977) reassigned them to Dashwood drift when they defined the 'Quadra Sand' unit.

Cowichan Head Formation – Olympia Nonglacial Interval

Nonglacial fluvial, estuarine and marine sediments are commonly found between the Dashwood Drift and the overlying Vashon glacial deposits. These stratified sediments were originally part of the Fyles' (1963) Quadra sediments, but are now included in the Cowichan Head Formation (Clague, 1976) deposited during the Olympia nonglacial interval.

Armstrong and Clague (1977) divided the formation into a lower marine member of clayey silt and sand, and an upper member of estuarine and fluvial sandy silt and gravel, rich in fossil plant remains. At Dashwood the Cowichan Head Formation consists of 9 m of organic-rich silt, gravel and peat with minor sand. The basal silts have casts of marine shells in places, whereas, the upper organic material consists of detrital woody fragments, grasses, mosses and sedges. There is at least 2.4 m of compact peat, probably deposited in a boggy floodplain (Alley, 1979). Radiocarbon dates from the Cowichan Head Formation range from 25.8 to 40.5 ka ^{14}C BP (Armstrong and Clague, 1977). Although Alley (1979) suggested that the nonglacial interval may have began > 51 ka ^{14}C BP, based on the nonglacial nature of the upper Dashwood Drift marine sediments described by Armstrong and Clague (1977).

The Cowichan Head Formation appears to represent a conformable sequence recording a transition from glacial to nonglacial conditions following the Dashwood glaciation. Initial sedimentation probably occurred into glacioisostatically depressed lowlands following deglaciation, but continued uplift during the ice-free period allowed terrestrial lowlands to expand into Georgia Depression as the basin filled in. Fossil pollen and beetle assemblages suggest that the climate fluctuated between conditions similar to present and cooler than present (Armstrong and Clague, 1977). The terrestrial part of the Cowichan Head Formation at Dashwood is older than 39 ka ^{14}C BP (Alley, 1979). The Cowichan Head Formation reflects a relatively warm period correlative to Marine Isotope Stage 3.

Quadra Sand – Fraser Glaciation

Thick horizontally and cross-stratified, well-sorted sand with minor silt and gravel overlies Cowichan Head Formation. In places the sediment has been described as "white sand". Lower portions of Quadra sand have wood and peat lenses. Fyles (1963) considered these sands to be part of the underlying nonglacial unit, which he collectively called 'Quadra sediments'. Nonetheless, now this unit is interpreted to be outwash deposited during the transition from non-glacial to glacial conditions at the onset of the *Fraser Glaciation* (Armstrong and Clague, 1977; Clague 1976b, 1977). In general the Quadra sands can be regarded as proglacial outwash formed subaerially and extending across and along the margins of present-day Strait of Georgia. The type section is on Quadra Island (Clague, 1977). Clague (1981) envisioned a "prograding apron or blanket down the axis of the Georgia Depression". In places distal outwash was dissected by meltwater from the approaching ice and re-transported farther down basin. Because the outwash was deposited progressively as the ice advanced down the basin, its age is diachronous and overlapping with the underlying Cowichan Head Formation. The basal radiocarbon age of the Quadra sand decreases from north to south. It is 28.8 ka ^{14}C BP, near Comox, 27.1 ka ^{14}C BP at Dashwood (Alley, 1979), 18.3-18.7 ka ^{14}C BP east of Vancouver and 15 ka ^{14}C BP near Seattle, the southern limit of the outwash (Clague, 1976b). As a consequence no isochronous lithostratigraphic boundary exists between the Fraser Glaciation and the Olympic non glacial interval. In parts of the Nanaimo Lowland Quadra sand is generally found below 100 m above sea level and can exceed 75 m in thickness.

Vashon Drift – Fraser Glaciation

Vashon Drift includes surface till and various ice-proximal deposits and moraines overlying Quadra sand on the lowland, considered to be from the last glaciation (Fyles, 1963). Vashon deposits usually unconformably overlie Quadra sand attesting to the erosive action of the advancing ice. The maximum thickness of Vashon till overlying Quadra sand is 30 m, Fyles (1963) noted 60 m of Vashon till at the Dashwood cliffs where the Quadra had been eroded. On the lowland the tills tend to be sandy diamictons except within some valleys where the matrix is more clayey. The lithological composition of the drift reflects Coast Mountain and Georgia Depression sources (like the underlying Quadra sand) rather than from Vancouver Island Ranges, but till in the Englishman River valley is an exception in that it contains an abundance of local lithologies. Fyles (1963) thought that a local mountain glacier occupied the valley. It may be that this was due to a local resurgence of glaciation (a post Vashon stade), as has been reported in the Fraser Lowland (Lian and Hickin, 1993).

Georgia Depression was covered by Cordilleran ice after about 17-18 ka ^{14}C BP. The maximum extent of the Cordilleran Ice Sheet in Puget Lowland occurred between 14.4-15 ka ^{14}C BP, with retreat north of Seattle by 13.6 ka BP. In Georgia Depression the lowlands were undergoing deglaciation ~13ka ^{14}C BP (Clague, 1980).

Vashon Drift includes eskers, kame terraces, and ice-contact fans and deltas deposited by meltwater streams during early deglaciation. The streams initially would have flowed along the margins of the retreating Cordilleran and local glaciers, with some deltas or terraces building into short-lived ice-dammed lakes. As the Cordilleran ice occupying Georgia Depression thinned, the coastal lowland was inundated by the sea to at least 150 m above current sea level.

Capilano Sediments – Late Fraser Glaciation to Postglacial

As the ice melted away, the upper complex of late glacial sediments included in Vashon Drift transitioned into *Capilano Sediments.* These deposits are considered to be postglacial but still affected by rapid emergence and influxes of glacial meltwater during early deglaciation. Relative sea level fell from elevations of ~150 to 50 m in the first thousand years since deglaciation, eventually reaching a minimum 15 m below present sea level about 11.3 cal ka BP. Sea level has remained near present since 6 cal ka BP (Hutchinson et al., 2004).

Consequently, early Capilano Sediments are coarse glaciofluvial outwash gravels and sands, with minor diamictons, and become more distal with time. Thick glaciomarine and marine sediments were deposited in isostatically depressed coastal areas. Fluvial terraces formed in valleys and deltas prograded into the falling sea where sediment supply was adequate. Sparse vegetation during the early postglacial contributed to rapid aggradation in river valleys and lowlands. Continued uplift led to entrenching and terracing of late glacial and older deposits and vegetated slopes reduced the level of aggradation. In general, Capilano Sediments have a maximum thickness of about 25 m, but they can be thicker within contemporary valleys. In places of the lowland Capilano outwash directly overlies Quadra sand, the Vashon drift having been eroded away.

Salish Sediments – Postglacial – Modern

Geomorphic processes that are active today deposit Salish Sediments. In the Nanaimo Lowland these sediments are related to modern sea, river and lake levels, and recent mass wasting (cf. Armstrong and Brown, 1953). In general, sediments up to 5 m above present base levels are regarded as Salish, whereas the higher sediments are regarded as Capilano or older. In reality, however, the separation by elevation between the two units is not clear because sea level, hence local base level, has been stable near present sea level for the last six thousand years (Hutchinson et al., 2004). Most significant Salish sediments are channel and floodplain deposits on the floors of river valleys and deltas.

Summary of Stratigraphic Subdivisions

Table 2 shows the subdivision of Quaternary deposits in the Nanaimo Lowland. The basic sedimentary characteristics of each lithostratigraphic unit and corresponding depositional environment is provided. Approximate ages are given in thousands of radiocarbon years before present and the equivalent calibrated age (in thousands of years). The time spread of the diachronous boundaries shown is limited to east-central Vancouver Island.

Surficial Materials of the Study Area

Figure 10 (at the back of this report) shows a detailed surficial geology map of the study area, encompassing 634 km^2. The mapping protocol was as follows: Delineation of the surficial units was done by interpretation of aerial photographs (digital orthophotos from the Regional District of Nanaimo), composite satellite images, and NTDB digital elevation model. Additional stratigraphic information was derived from BC Ministry of Environment water well database, BC aggregate resource potential database (Massey, et al., 1998), soils maps (Jungen, 1985), and the seismic reflection survey and bore holes collected during this GSC study

Table 2. *Subdivisions of the Late Quaternary deposits and events, east central Vancouver Island.*

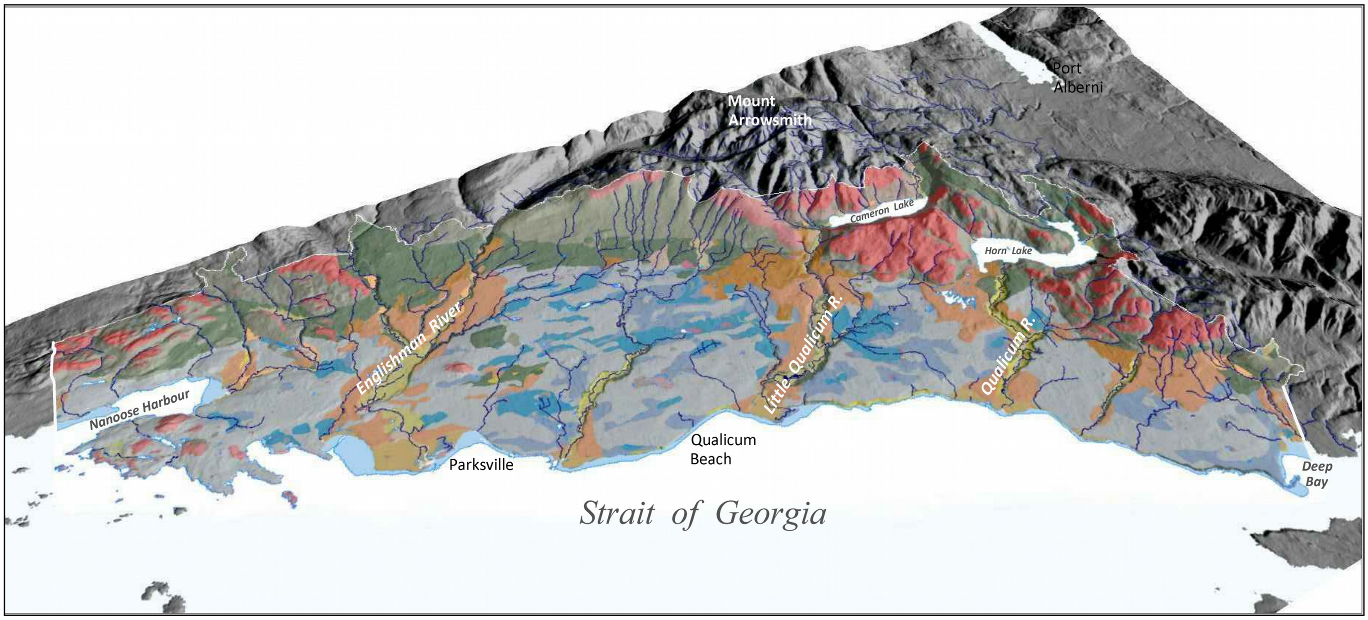
Radiocarbon age		Stage/substage	Climatostratigraphy	Lithostratigraphic Unit	Environment of Deposition and Principal Materials
ka BP	ka cal BP	Holocene	Postglacial	Salish Sediments	Swamp / Organic deposits: organic matter and mud Slope deposits: Alluvial fans of poorly sorted gravels; landslide debris, colluvium Lacustrine: fine-grained sediments deposited in lakes Marine: Littoral sediments, sand, gravel and silt at the present shoreline Fluvial: deltaic and channel floodplain, stratified gravel, sand and silt
10	11.6	Late Wisconsinan	Postglacial	Capilano Sediments	Slope deposits: Alluvial fans of poorly sorted gravels; landslide debris, colluvium Glaciofluvial to fluvial: stratified sand and gravel, postglacial deltatic sediments and channel flood plain deposits. Glaciomarine to marine: stoney silt, sand and clay, contains marine shells and rare wood; diamictons in places.
13	15.6	Late Wisconsinan	Fraser Glaciation	Vashon Drift	Glaciofluvial / ice contact: poorly sorted gravels, sands and silts; stratified; Kame and kame deltas Glacial: sandy to clayey diamicton, till; in places lenses of stratified sediments
18	21.8	Late Wisconsinan	Fraser Glaciation	Quadra Sand	Glaciofluvial: stratified sand, minor gravel and silt, well-sorted, in places organic rich near base
27.1	31.1	Mid Wisconsinan	Olympia Nonglacial Interval	Cowichan Head Formation	Marine to fluvial: Pebble-gravel, peat with pebbles and wood
40	43.6	Mid Wisconsinan	Olympia Nonglacial Interval	Cowichan Head Formation	Marine: Clay, stony clay, silt, shells; basal laminations in places laminated
>50					
beyond the range of radiocarbon dating		pre-Wisconsinan	penultimate glaciation	Dashwood drift *(including Mapleguard sediments)*	Glaciomarine: stoney silts and clay with sand lenses and shells Glacial: sandy to silty diamicton, till containing silt and gravel lenses

(results to be reported elsewhere; Crow et al., 2014; Knight et al., 2014). The stratigraphic framework developed by Fyles (1956, 1963) was followed as much as possible, but with the revision of the Quadra Sediments described by Clague (1983), and Mapleguard Sediments by Hicock (1980). Most of the fieldwork and ground verification was concentrated along road access, exposures along stream banks and coastal cliffs.

In general surficial unit boundaries were based on surface expression and topography with field checking. Most distinct boundaries were defined by specific landforms, however many of the surficial units are thin and discontinuous with lateral gradations of facies, and even within facies there are lateral gradations in texture. Where access was not possible, or the area was heavily forest covered, the unit boundaries are approximate and represent gradual transitions. Likewise, the stratigraphy exposed along the rivers is usually not continuous so that some units were extrapolated along some river valleys. In most places a thin veneer of slope wash obscures the stratigraphy and the stratigraphy is inferred from intervening exposures.

As noted above, most of the deposits are closely linked to the past glacial history of Nanaimo Lowland. Figure 11 shows the relative proportions of the main surficial units exposed at the surface of the mapped area. Note that important aquifers and aquitards such as the Quadra Sands and pre-Vashon sediments respectively comprise only a small fraction of the material exposed at the surface. Significant surface recharge would be restricted to alluvium and glaciofluvial deposits covering some 18% of the total area.

The stratigraphic framework described in the previous section was confirmed by numerous stratigraphic exposures throughout the study area, although the whole stratigraphic column is not exposed in any one place. Moreover, seismic data shows that in areas of the lowland below ~100 m surface elevation the bedrock contact lies up to 90 m below present sea level. In general the seismic reflection survey and bore hole drilling undertaken by the GSC during the course of this study has largely confirmed the stratigraphy of the unconsolidated sediment. Figure 12 shows summary logs of three boreholes drilled in the study area with radiocarbon dated samples (see Appendix I for fossil reports). The Cochrane and Spider boreholes record the transition from the



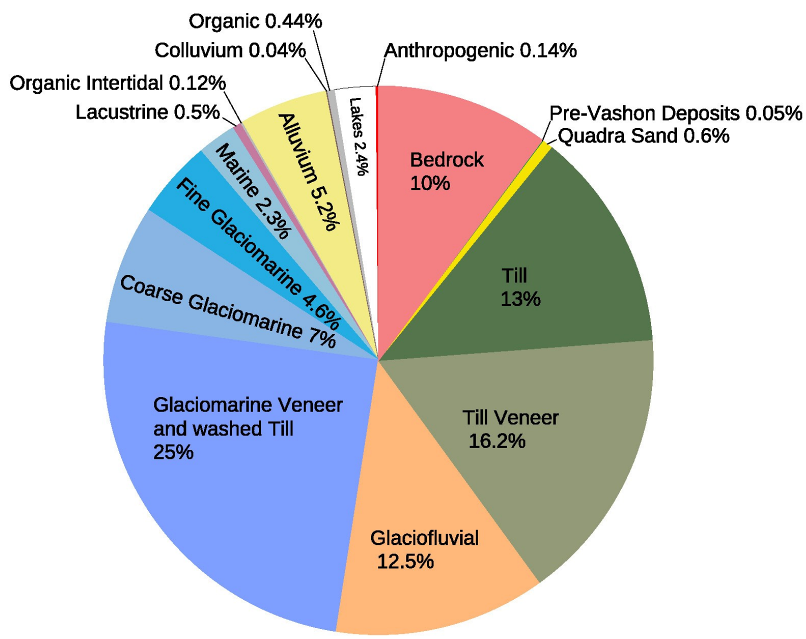


Figure 11. *Relative proportion of surficial materials exposed at the surface in the study area. The perspective map view is to the southwest (see also Fig. 10).*

Dashwood glaciation to Cowichan Head non-glacial conditions, and then followed by deposition of Quadra Sand marking the onset of Vashon glacial conditions. The Cochrane borehole further records glaciomarine conditions as the Vashon ice retreated. All the boreholes are capped by gravels of winnowed till and glaciomarine sediment.

Pre-Vashon Deposits

As defined above, pre-Vashon deposits include the penultimate glaciation unit Mapleguard (advance outwash)-Dashwood drift and the overlying non-glacial Cowichan Head Formation. Pre-Vashon deposits are only exposed in sea cliffs and steep river valleys, although the similarity of Dashwood and Vashon drifts would make these sediments indistinguishable at the surface without dating control. Even where exposed in sections, pre-Vashon deposits are usually obscured by slope wash and colluvium. Each unit is commonly

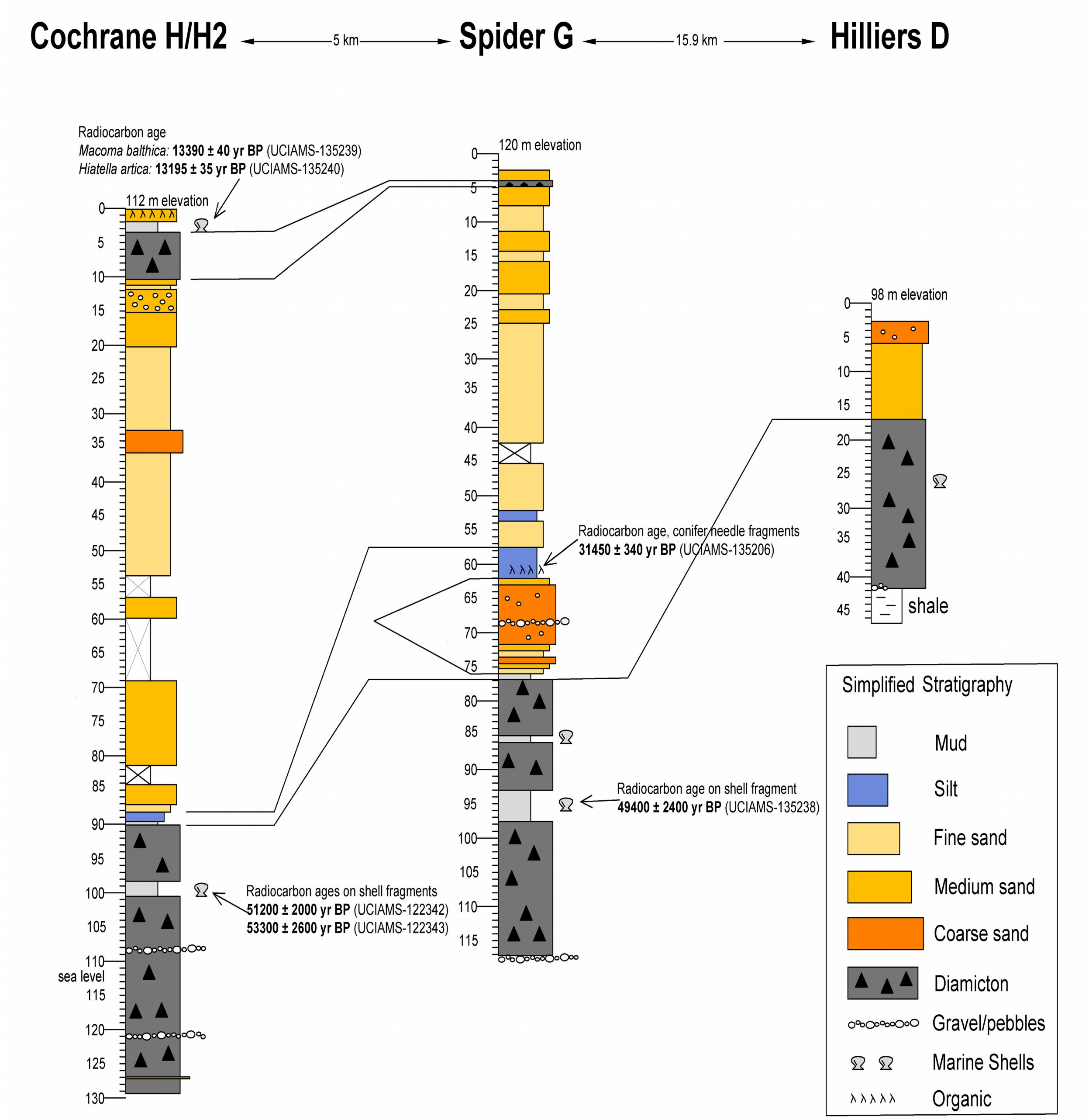


Figure 12. *Lithostratigraphic logs of boreholes drilled in the study area by the GSC with radiocarbon dates (see Table 1). Lithostratigraphy for Cochrane and Spider from Knight et al. (2014). Locations are shown in Fig. 8.*

less than 10 m thick, however the recent bore holes and seismic surveys indicate that the thickness of Dashwood drift may be over 50 m thick. In general Dashwood drift consists of dense, stratified to massive diamictons with scattered unsorted clasts of pebble to boulder size. The upper part of the Dashwood unit contains marine fossils and is interpreted as a glaciomarine diamicton attesting to its deposition by retreating tidewater glaciers.

The Cowichan Head Formation overlies the upper Dashwood glaciomarine sediments. The lower member of the Cowichan Head Formation is composed of marine sand and mud and is overlain by organic rich gravel, sand and silt of fluvial and estuarine character (Fig. 12; Armstrong and Clague, 1977).

Quadra Sand

Although surface exposures of Quadra Sand are limited in extent, the unit is widely

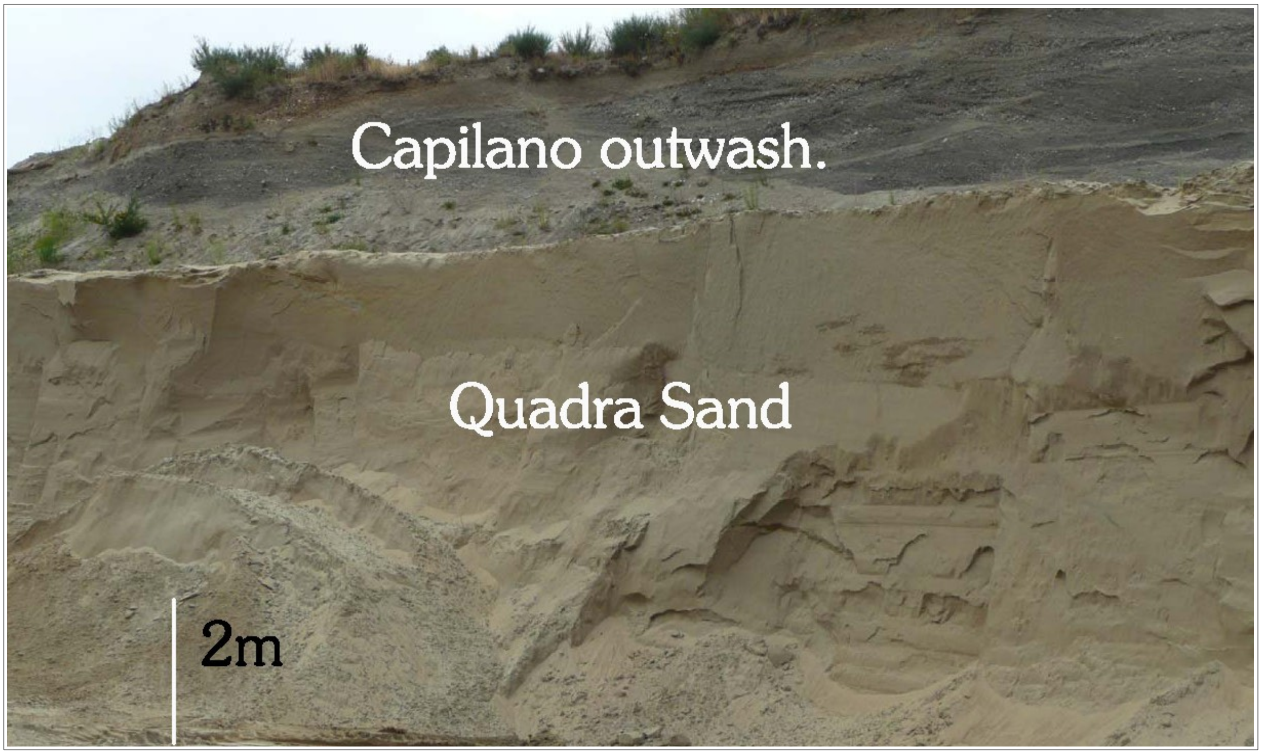


Figure 13. *Well sorted proglacial Quadra Sand underlying coarser Capilano postglacial outwash.*

Figure 14. *Vashon Drift exposed at a 28 m section on the Englishman River. The basal 11 m is a clast-poor, dense grey massive diamicton forming 2 m thick layers bound by shear planes and thin stratified diamictons. The basal unit is overlain by a 10 m thick glaciomarine unit of clast-rich stratified diamictons with cobbles and boulders up to 1 m in diameter. Apparent fabrics are horizontal. The glaciomarine diamicton is conformably overlain by 3.5 m of massive, clast-poor mud that is rhythmically bedded in the lowest 1 m. The top of the section is capped by 3.5 m of brown horizontally stratified sands (Capilano Sediments).*

distributed throughout the study area underlying Vashon till and outwash. The sand is commonly exposed along road cuts, river cut banks and coastal cliffs and boreholes that show thicknesses locally exceeding 50 m. Interpretation of the a laterally continuous, low relief seismic reflector indicates that Quadra Sand may be up to 80 m thick in the north eastern part of the study area where it's base extends well below sea level (unpublished data, A. Pugin). Quadra Sand mainly overlies Cowichan Head Formation where the contact is sharp, but in places Quadra Sand can overlie older sediments or bedrock. As noted, this well-sorted and crossbedded sand records the diachronous progradation of outwash in front of a glacier advancing into Georgia Depression, likely in a marine delta setting (Fig. 13).

Vashon Drift

Glacial deposits from the last stade are collectively called Vashon Drift and are comprised of massive to stratified diamictons with varying amounts of unsorted pebbles, cobbles or boulders scattered throughout the matrix. The colours range from dark grey to olive brown. Where dense and massive, the diamicton is interpreted as basal till deposited directly by the glacier. In places massive diamictons also enclose marine shells, indicating sedimentation in a marine environment and interpreted to be by floating ice (Figs. 12, 14).

Stratified diamictons characterized by a matrix of thinly interstratified sand, pebbles or mud are also common in the study area. In general, they indicate an abundance of subglacial water or subaqueous conditions in proximity to a glacial margin. In places the diamictons contain shells attesting to ice-proximal deposition in a marine environment when the thinning glaciers became buoyant and calved into the sea. Elsewhere the stratified diamictons have massive beds of rounded pebbles, cobbles and boulders indicating the recycling of preexisting gravel deposits (e.g. Fig.15). The gravels were

Figure 15. *Gravelly facies of Vashon Drift. Interstratified diamicton and massive matrix supported gravel exposed along French Creek at the Qualicum Beach airport. The 5 m thick unit has a sandy matrix enclosing mainly well-rounded pebbles, cobbles and occasional boulders. The drift overlies at least 5 m of light brown Quadra Sand at the base of the section.*

probably initially deposited in front of former ice margins and were likely subsequently reworked in subaqueous debris flows.

As noted above, Vashon till may reach 60 m in thickness (Fyles, 1963), but in most upslope Vashon glacial deposits to Capilano postglacial deposits. Of course minor fluctuations of the ice margins would lead to a complex interstratification of the units and sediment deformation from glacial overriding or melting out of buried glacial ice (Fig. 16).

Figure 16. *Ice-contact stratified gravel forming a gravel cored ridge east of Little Qualicum Falls. Extensional faulting indicates buried glacial ice that has melted out. However rapid infilling of depressions by coarse gravel indicates abundant sediment-laden meltwater. The faulted gravels are underlain by plain-bedded sands with pebbly stringers that may be equivalent to Quadra Sand usually found at lower elevations. A sandy diamicton overlies most of the deformed gravels in this area recording either the initial Vashon advance or a subsequent re-advance (red scale bar indicates 1m).*

places the massive diamicton is found as an upper till only 2-4 m in thickness. On broad low-relief areas of the study area the till is usually capped by a thin layer of loose brown gravel that, below 150 m in elevation, is most likely the result of the till being winnowed as the sea regressed from the area. The washed areas were mapped as a coarse glaciomarine unit, but broad depressions where the surface was siltier were mapped as fine glaciomarine.

Near the marine limit the retreating glaciers ice margins stabilized and large volumes of glaciofluvial sediment was deposited into the sea. Consequently, near the marine limit there was a lateral transition from

Final deglaciation of the coastal lowland marked the transition from Vashon to Capilano sedimentation. This transition is well demonstrated by extensive gravel deposits near Spider and adjacent lakes at the mouth of a major valley at Horne Lake (Fig. 17). These deposits, first described by Fyles (1956, 1963), record a delta formed at the margin of a glacier in contact with the high postglacial sea. The lakes occupy a depression formerly occupied by the glacier tongue, whereas thick outwash deposits lie seaward of the depression at higher elevations. A radial pattern of sinuous eskers within the depression suggest that the glacier terminus remained stationary as it ablated. Consequently, thick delta gravels prograded into the high sea beyond the ice margin. This is evidenced by numerous gravel operations and exposures in the surrounding area. Once the glacier completely melted the delta gravels deposited beyond the former ice margin were left perched above the surrounding terrain as shown by the topographic profile (Fig. 17).

the ice-contact delta deposits, up to 140 m of unconsolidated sediment overlies the bedrock. Much of this thick sediment predates the Vashon advance, including up to 60 m of Quadra Sand and possibly 40 m of the penultimate Dashwood till, which overlies bedrock to an elevation 15 m below present sea level.

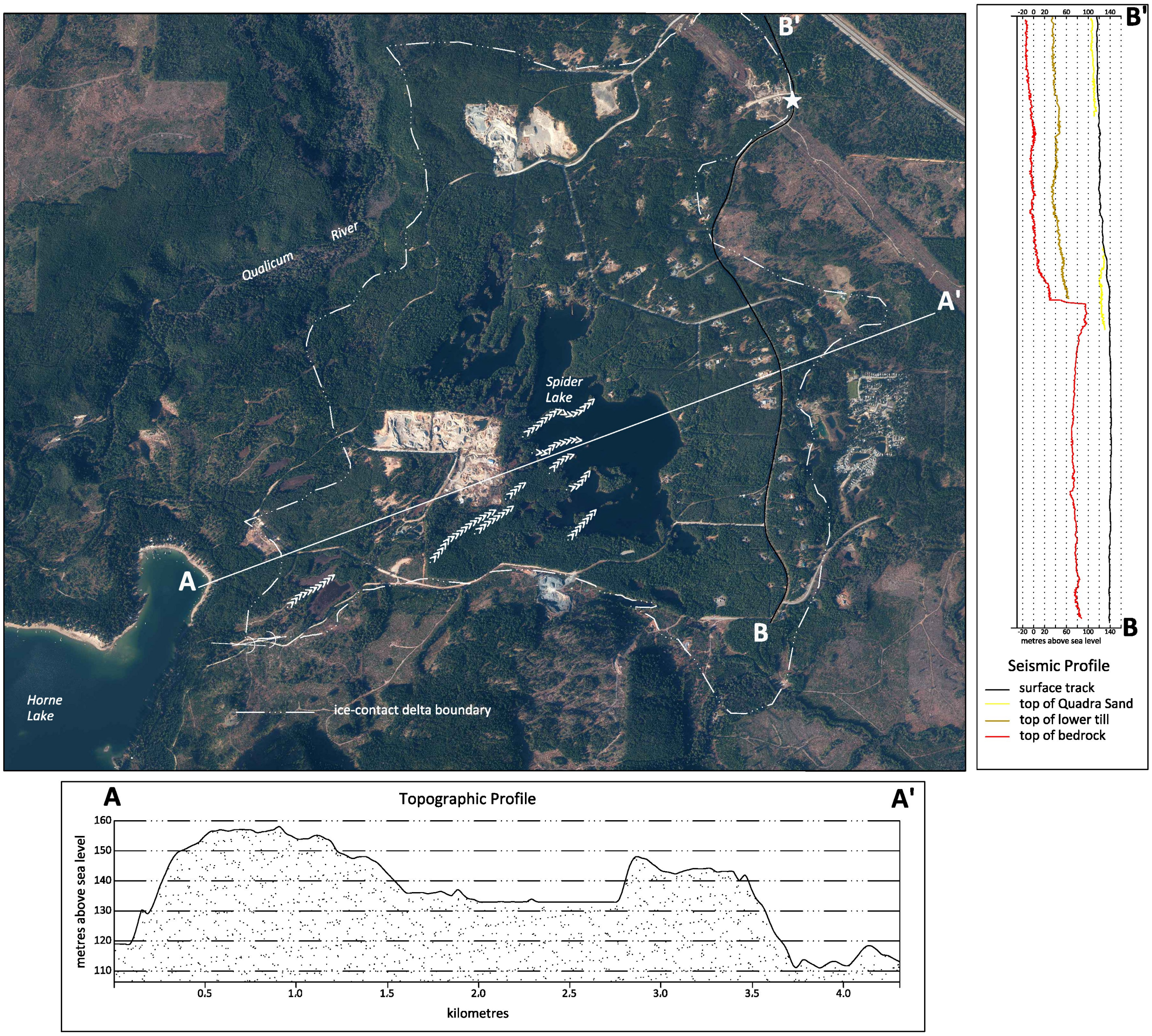


Figure 17. *Extensive glaciofluvial deposits in an ice-contact delta mapped near Spider Lake. Striations near Horne Lake indicate former ice-flow directions during a late stage in glaciation. Prominent eskers form a radial pattern in the lake basin. Topographic and seismic profiles illustrate the extent of the deposits. The star shows the location of the Spider-G borehole.*

The interpretation of seismic reflection data infers at least a 60 m thickness of glaciofluvial gravel overlying bedrock (unpublished data, A. Pugin; Fig. 17). Further to the north, in an area just beyond the limit of

Capilano Sediments

Capilano Sediments were deposited during deglaciation and early postglacial time when base levels where rapidly changing from draining proglacial lakes and, more

Figure 18. *Delta gravel exposing a northeast-dipping foreset beds overlain by 2 m of topset beds west side of Little Qualicum River. Sea level was ~140 m above present at the time (Capilano Sediments); photo by A. Pugin.*

Figure 19. *Capilano Sediments; tabular crossbedding showing the rapid accumulation of glaciofluvial gravels in a delta at ~145 m above sea lea east of Qualicum River and north of Spider Lake (this pit is seen in the upper middle of the air photograph in Fig. 17).*

importantly, the rapid fall in sea level during early deglaciation (Fig. 7). The greatest amount of sediment accumulating took place where sediment-laden meltwater issued from glaciers that persisted in the uplands. Consequently, thick deposits of glaciofluvial outwash were deposited mainly within the valleys as fans and deltas prograding into the sea. Capilano Sediments at higher elevations where more proximal to the ice margins and in general are coarser with numerous deformation structures reflecting ice-contact conditions (e.g. Fig. 15). At lower elevations, the sediments are more fluvial in character displaying characteristic foreset, topset and bottomset delta sequences (e.g. Figs. 18, 19). Once the region became completely ice-free most of the large-scale coarse deposition ceased, however, recycling of previously deposited glaciofluvial sediment took place as rivers down cut in response to continuously falling sea level and younger terraces were built at ever lower elevations.

In general Capilano fluvial and delta sediments are cross-bedded medium to coarse sand with rounded to well-rounded pebbles and cobbles with occasional boulders. The sediments are loose and range in colour from brown to grey. Capilano sediments also include coarse, poorly stratified alluvial fan deposits that are found at the base of the mountains at the mouths of gullies and valleys. Diamictons deposited by various types of mass wasting on steep slopes on land or in the sea are classed as Capilano colluvium when deposited during early post glacial time, but of course these processes are currently still active and are mapped as Salish Sediments when related to modern base levels.

Figure 20. *Typical Salish sediments found in the modern delta of the Englishman River at Parksville. The river is largely re-transporting older glaciofluvial deposits which are then redistributed by wave action in sea, as seen in the intertidal zone. The image shows a 3 km width.*

Salish Sediments

Modern deposits, including river, lake and marine sediments, as well as mass wasting debris accounts for less than 9 % of the mapped area (Fig. 11). As noted, most deposits up to 5 m above present-day stream and river channels, lake levels, or high tide were mapped in this category. However, in places much of the sediment is derived from older Capilano deposits (e.g. Fig. 20). In general, coarse alluvium is the most important in terms of ground water sources and surface recharge areas.

Summary

Groundwater on the east coast of Vancouver Island occurs within a complex mixture of unconsolidated sediments and fractured bedrock, and for many communities well water is the only source of potable water. An understanding the distribution of unconsolidated sediments over the lowland provides key information for managing this resource. The contemporary landscape in much of Canada has been greatly affected by Pleistocene glaciations and most accumulation of thick sediments and their dispersion can be explained by the glacial history of an area. To gain a better understanding of the hydrogeology the Nanaimo Lowland, this report describes its surficial geology, particularly by detailed mapping from from Deep Bay to Nanoose Harbour. The resulting surficial geology map incorporates Pleistocene stratigraphy, seismic reflection surveys, boreholes, and lithological information from field sites and water well data.

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Appendix

I. Descriptions of Radiocarbon dated samples prepared by A. Telka, Paleotec Services, Ottawa, Ontario.