# The Holocene to Modern Fraser River Delta, Canada: Geological History, Processes, Deposits, and Natural Hazards

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## ABSTRACT

The Fraser River Delta (FRD) is a major sedimentary system and is home to one of Canada's largest metropolitan areas, Metro Vancouver. It is also an ecologically important region that is culturally significant to several First Nations groups. In this review, we summarize the state of knowledge about the geological evolution of the FRD and link hydrodynamic processes with sedimentary products across the continuum of environments from the river to the delta slope. We discuss the implications of sedimentation for natural hazards and highlight knowledge gaps. This review also serves as background for continued research on the FRD.

The FRD consists of four main zones: river, delta plain, tidal flats, and delta slope. The river zone includes the Fraser River and its various distributary channels from the landward limit of tidal modulation to the terminus of the distributary channels at the seaward limit of the tidal flats. The delta plain borders the modern Fraser River's distributary channels. Intertidal marshes and tidal flats rim the seaward portion of the delta plain and include both "active" and "abandoned" areas. Active tidal flats are situated on the western margin of the FRD and receive sediment directly from the Fraser River; these include Roberts Bank and Sturgeon Bank. Abandoned tidal flats receive virtually no sediment from the Fraser River and occur along the southern boundary of the FRD at Boundary Bay and Mud Bay. The tidal flats transition seaward into more steeply dipping foresets of the subaqueous delta slope. South of the Main Channel the upper delta slope is predominantly sand, and north of the Main Channel the upper delta slope is predominantly mud. The lower delta slope both south and north of the Main Channel consists of mud, and these sediments grade into flat lying, muddy sediment at the base of the Strait of Georgia.

The FRD experiences a range of natural hazards including subsidence and flooding, earthquakes, liquefaction, and tsunamis. Many parts of the FRD are subsiding, which amplifies the effects of rising sea level. Approximately 250 km of dikes along the river, distributary channels, and landward side of tidal flats protects the populated delta plain from river floods and storm surges. Rare subduction-related earthquakes and large crustal and subcrustal earthquakes produce sudden land level changes that can trigger tsunamis, submarine slope failures, and/or liquefaction of unconsolidated delta sediments. With increasing knowledge of the sedimentation on the FRD and its evolution, it may be possible to devise novel methods to protect the populated FRD from some of the worst impacts of these hazardous events.

## 1. INTRODUCTION

Deltas sit at the nexus of fluvial and marine environments and are a storage place and staging ground for sediment, pollutants, and organic carbon that is transported from the continent to the shelf and deep sea. Deltaic sedimentary accumulations record complex physical, chemical, and biological processes and interactions, and serve as an archive of environmental conditions and events that influence both land and sea. Approximately 340 million people live on deltas globally (Edmonds et al., 2020), and distributary channels crossing delta plains are important shipping lanes that supply food and goods to cities (Haasnoot et al., 2012; Syvitski and Saito, 2007). Deltas are also significant diversity hot spots for flora and fauna (Glenn et al., 2001; Ward et al., 1999), but the combined effects of human activity, changing climate, and rising sea level have negatively impacted these important systems by increasing their vulnerability to storms, flooding, and erosion (Syvitski, 2008; Syvitski et al., 2009; Szabo et al., 2016; Tessler et al., 2015; Vörösmarty et al., 2015). Given the global significance of deltas, system-scale geological studies are necessary to reveal how fluvial and marine processes interact to determine coastal morphology and sedimentation patterns, including their future trajectories. Synthesis studies have recently been undertaken for some of the world's large deltas (e.g., Bentley et al., 2016; Blum and Roberts, 2012; Guo et al., 2021; Khan et al., 2021; Nittrouer et al., 2021; Paszkowski et al., 2021; Sestini, 1989), but are still lacking for many systems, including the Fraser River Delta. Such syntheses are crucial for developing a global catalog of deltas and their variations.

The Fraser River Delta (FRD) in British Columbia, Canada, is one of the largest delta systems in North America (Fig. 1A). It comprises the unceded territory of several First Nations of the Coast Salish people. Archeological evidence suggests that the region presently occupied by the delta has been inhabited by Indigenous people for at least 9,500 years, which pre-dates progradation of the delta to its present limits (Lepofsky et al., 2009; Matson and Coupland, 1995; Murray, 2008). The FRD partly underlies the metropolitan area of Vancouver (the third largest city in Canada), which along with the surrounding region is home to over 2.6 million people. The delta also hosts Canada's largest port, through which goods valued at more than $240 billion annually are traded with 170 countries (Davis and Hutton, 2004). Vancouver International Airport, Canada's second largest, is situated on the FRD's delta plain and serves ~26 million passengers and 300,000 flights annually. Consequently, understanding environmental challenges, geological processes, and natural hazards is necessary for sustaining and improving both the quality of life and economies of British Columbia and Canada (Groulx and Mustard, 2004).

The tidal wetlands of the FRD are an ecological crucible on the Pacific coast of North America. Millions of migratory birds gather for spring breeding or overwinter in the area (Adams and Williams, 2004; Butler and Campbell, 1987). Hundreds of millions of juvenile Pacific salmon reside in the lower Fraser River (the estuary; Pyper and Peterman, 1999) and millions of adult salmon spawn along the banks of the Fraser River annually. As well, tidal flat and delta plain ecosystems host robust marine, brackish, and freshwater plant communities (Schaefer, 2004).

Due to the ecological and societal importance of the FRD, a substantial body of literature has amassed through decades of research on the hydrodynamic processes, sedimentology, stratigraphy, and natural hazards of the system. However, a synthesis does not exist of the linkages between sedimentary processes and deposits and the implications for natural hazards. In the past few years an acute need has arisen to better understand the geological history, sedimentary processes, and architecture of the FRD to accurately predict the impacts of future climate change and sea-level rise on the delta. For example, protecting the delta plain from inundation due to rising sea level using “living dikes” (e.g., Readshaw et al., 2018) not only requires broad knowledge of the sedimentary strata underlying the delta plain, but also of how the sedimentary system evolved in response to changing forcing conditions. In this regard the past is the key to the present, and the present is our starting point for predicting the future.

In this review we summarize the state of knowledge of the geological evolution and Holocene sedimentary system of the FRD. We link hydrodynamic processes with their corresponding sedimentary products across the continuum of environments from the river to the delta slope, and we discuss the implications of sedimentation and delta evolution for natural hazards. This summary serves as background for continued research on the FRD in the context of both climate change and anthropogenic modification. The work is also intended to enable comparisons of the FRD to other major deltas globally for which synthesis studies already exist.

## 2. SYSTEM AND SETTING

### 2.1 Drainage Basin and Physiography

The Fraser River, with a catchment area of ~230,000 km$^2$, is the largest river on the Pacific Coast of Canada (Fig. 1A; Mathews and Shepard, 1962). Its headwaters are located in the Rocky Mountains near the Alberta-British Columbia border, and the main stem flows undammed for ~1,375 km. In its lower reaches, the river flows across the Fraser Lowland and discharges into the Strait of Georgia (the northern arm of the Salish Sea).

We use a broad definition of the Fraser River Delta in this paper, which departs from the definition used in many past studies. Previously, the FRD was considered to encompass only the exposed delta plain west of the apex at New Westminster (Fig. 1B). Herein, we consider the FRD to have an areal extent of about 1,000 km$^2$ and to extend from the landward limit of tides on the delta plain (Yaalstrick Island) to the seaward limit of the gentle delta slope at water depths of ~350 m (Fig. 1B). The fluvio-tidal transition in the Fraser River and adjacent upper region of the delta plain are situated at elevations between 4 and 6 m above mean sea level and extend along a relatively narrow corridor that borders the Fraser River from Sumas Mountain in the east to Surrey Highland in the west (Fig. 1B and C). The upper region of the delta plain is not discussed herein because there is a dearth of information about the sedimentary deposits below it. The remainder of the FRD is subdivided into four broad categories: **Fraser River** (including distributary channels), **delta plain** (subaerial delta), **tidal flats** (intertidal and shallow subtidal delta), and **delta slope** (subaqueous delta; Fig. 1B; Table 1).

Where it crosses the FRD, the Fraser River and its distributaries are divided into four zones based on the influences of brackish water and tides. Landward of tidal influence is the river zone (freshwater and non-tidal). The fluvio-tidal transition zone (FTT) occurs where river levels are modulated by tides. The FTT includes, from east to west: 1) the freshwater and tidal subzone (FTT–Fresh); 2) the freshwater to saltwater transition subzone (FTT–Transitional); and 3) the sustained brackish-water subzone (FTT–Brackish; Fig. 1B; Table 1). Seaward of New Westminster, the Fraser River bifurcates into two main distributaries: Main Channel and North Arm. Farther downstream and north of Lulu Island, the North Arm bifurcates again, with the Middle Arm flowing south of Sea Island. Similarly, the Main Channel splits south of Lulu Island to form Canoe Pass (Fig. 1A). The distributaries west of New Westminster are impacted by tides and are inundated by brackish water. The degree of tidal influence and brackish water incursion decreases landward (eastward) and varies as a function of river discharge and tidal stage; hence, the division between the FTT–Brackish and FTT–Transitional subzones is gradational and shifts spatially both daily and seasonally.

The delta plain (DP) comprises the subaerial delta and includes both lower (west of New Westminster) and upper (east of New Westminster) regions. As mentioned previously, the upper region is not discussed further and we focus solely on the western expression (or lower region) of the delta plain, including the floodplain (DP–Floodplain) and peatlands (DP–Peatland; Fig. 1B; Table 1).

A distinctive feature of the FRD is the broad (5–7 km wide) tidal flats that fringe the delta on its western and southern margins (Fig. 1B and C). On the western margin the break between the tidal flats and delta slope is placed at the 5 m bathymetric contour (Table 1). Roberts Bank and Sturgeon Bank are mainly intertidal (and partly subtidal) flats located south and north of Main Channel, respectively. Together these flats extend for 27 km from Point Roberts Highland to Burrard Highland (Fig. 1B), and this region is referred to as the "active" region because river discharge and river-derived sediment have a major impact on sedimentation on the flats. Point Roberts Highland separates the active delta region from a 13 km-long, "inactive" part of the FRD that includes the sand-dominated tidal flat in Boundary Bay and attached mud-dominated tidal flat in Mud Bay. The tidal flats at Boundary Bay and Mud Bay are referred to as inactive because they receive virtually no sediment from the Fraser River (Engels and Roberts, 2005; Kellerhals and Murray, 1969). The much smaller Serpentine and Nicomekl rivers deliver a small volume of sediment to Mud Bay mainly.

The delta slope (DS) lies seaward of the tidal flats along the active delta front and starts at about the 5 m bathymetric contour. It dips westward to the base of the Strait of Georgia in water depths of up to ~350 m (Fig. 1B and C; Table 1). The slope gradient ranges from 0.5° to 23°, with an average of ~2°; it is steepest in shallow water (10–150 m contour) and decreases gradually towards the floor of the Strait of Georgia (Mosher and Hamilton, 1998). A series of gullies and canyons incise the DS. The largest canyon is the Sand Heads Sea Valley, which lies off the Main Channel, and is incised up to 21 m into the upper delta slope (Fig. 2B; Ayranci and Dashtgard, 2016; Evoy et al., 1993; Hart et al., 1992a; Hart et al., 1992b; Hill, 2012). Several active slope gullies that incise from 2–5 m are present adjacent to the Sand Heads Sea Valley

(Fig. 2A; Hill, 2012; Hill and Lintern, 2022), and other abandoned and partially reworked gullies are located outboard of the mouths of abandoned distributary channels (Carle and Hill, 2009).

### 2.2 Hydrodynamics and Sedimentation

The mean annual discharge of the Fraser River is ~2,700 $m^3 s^{-1}$ (at Hope BC; Dashtgard et al., 2012); however, daily flows range from ~1,000 $m^3 s^{-1}$ to 15,000 $m^3 s^{-1}$ (Fig. 3A–B; Kostaschuk et al., 1998). High discharge (above ~5,000 $m^3 s^{-1}$) is driven by seasonal snowmelt in the river catchment and is referred to as the freshet. Peak freshet flows typically occur between late May and mid-June (Fig. 3A and B). Base flow conditions (below ~2,800 $m^3 s^{-1}$) prevail through the rest of the year. The Main Channel carries about 85% of the river flow, and the other three distributaries carry about 5% each (Fig. 1A; Northwest Hydraulic Consultants, 2008).

Tides at the mouth of the Fraser River are mixed semi-diurnal, with a mean amplitude of ~3.0 m and a neap-spring range of 2.1–4.9 m at Sand Heads (Fig. 3D–E). A landward-tapering wedge of marine water (tidal prism) extends from the Strait of Georgia up the distributary channels. The upstream limit of the tidal prism is controlled by river discharge and channel depth, and hence varies between distributaries and annually. During spring high tide and low river flow (between ~1,000 and 5,000 $m^3 s^{-1}$), the saltwater wedge extends up to 30 river km (a river km is the distance upstream along the thalweg of the channel; Venditti and Church, 2014) up the Main Channel (Ages, 1979; Hughes and Ages, 1975; Kostaschuk and Atwood, 1990) and 16 river km up the North and Middle arms. Under moderate flows (~5,000–7,000 $m^3 s^{-1}$), the saltwater wedge extends only a few kilometers up the Main Channel (Milliman, 1980). When flow exceeds ~8,000 $m^3 s^{-1}$, the saltwater wedge does not enter the Main Channel even during spring high tides (Kostaschuk and Atwood, 1990). Depending on river flow conditions, a tidally controlled rise of the river surface extends from 70 river km to ~102 river km inland from the Strait of Georgia (to Yaalstrick Island; Fig. 1A; Venditti and Church, 2014).

Large waves generated during storms approach mainly from the northwest and west, with a secondary approach vector from the southeast (Fig. 3C; Ayranci and Dashtgard, 2016). These waves impact sediment distributions in the intertidal and upper subtidal zones and rarely overtop dikes. As climate change drives sea-level rise, flooding of the delta plain because of dike-overtopping during storms and spring high tides is expected to increase without human intervention (Houser and Hill, 2010a). Strong storms with high sustained wind speeds (Fig. 3C) are concentrated mainly in the winter months.

On average, the Fraser River delivers ~17 x $10^9$ kg $year^{-1}$ (range: 12–30 x $10^9$ kg $year^{-1}$) of sediment to the Strait of Georgia (Milliman, 1980), of which approximately 35% is sand and the remainder is silt and clay (Kostaschuk et al., 1998; McLean and Tassone, 1990). Johannessen et al. (2003) estimate that 550 x $10^6$ kg $year^{-1}$ of organic carbon is also carried into the Strait of Georgia by the Fraser River. Under base flow conditions, sediment transported to the delta slope is dominantly mud. Under high flow conditions more than half of the transported sediment is sand (McLean and Tassone, 1991). Sand is temporarily deposited on the delta slope at the mouths of the distributary channels and on the tidal flats (Houser and Hill, 2010a; McLaren and Tuominen, 1996). A substantial proportion of that sand is subsequently transported offshore by sediment gravity flows and slope failures (Ayranci et al., 2012; Hill et al., 2008; Kostaschuk et al., 1995; Kostaschuk et al., 1992). Mud either bypasses the river mouth entirely and is carried seaward in hypopycnal surface plumes that are ~5–10 m thick (Hill et al., 2008) or settles by convection that is modulated by seasonal and tidal discharge patterns (Ayranci and Dashtgard, 2020; Hill and Lintern, 2021). During freshet, the surface plume commonly extends west from the mouth of the Main Channel across the southern Strait of Georgia, and north past Vancouver into southern Howe Sound and Burrard Inlet (Pawlowicz et al., 2017). During spring high tides and base flow conditions, the saltwater wedge traps mud in the distributary channels, forming a turbidity maximum zone (Kostachuk and Luternauer, 1989; Kostaschuk, 2002; Kostaschuk et al., 1989) and abundant mud is deposited in the channels, on the tidal flats, and on the delta slope (La Croix and Dashtgard, 2014; Sisulak and Dashtgard, 2012).

## 3. QUATERNARY EVOLUTION AND STRATIGRAPHY

### 3.1 Pleistocene Context

The FRD is located in a mountainous region that was repeatedly enveloped by the Cordilleran ice sheet during the latest Pliocene and Pleistocene (Clague, 1989; Jackson Jr. and Clague, 1991). When fully formed, the Cordilleran ice sheet and its satellite glaciers covered almost all of British Columbia, southern Yukon Territory, and southern Alaska and extended south into the northwestern conterminous United States (Fig. 4). In western British Columbia, ice streamed down fjords and valleys in the coastal mountains and covered large areas of the Pacific continental shelf. Glaciers issuing from the southern Coast Mountains and the Vancouver Island Ranges coalesced over the northern Salish Sea to produce an outlet glacier, the “Puget Lobe” (Waitt Jr. and Thorson, 1983). At the last glacial maximum, ~17,000 years ago, the area that is now the FRD was covered by about 2,000 m of ice (Fig. 4).

Glaciation profoundly modified the landscape of British Columbia (Mathews, 1989). Bedrock in what is now the northern Salish Sea was deeply eroded into northwest-trending ridges and troughs with 200–1,000 m of relief (Clague et al., 1983; Clague et al., 1998). Much of the sediment produced by glacial erosion was transported beyond the periphery of the ice sheet, although large amounts were deposited in coastal lowlands such as the Fraser Lowland.

Deglaciation of southwest British Columbia began shortly after 17,000 years ago and was complete by 12,000 years ago (Clague, 1981). Deglaciation was interrupted near the end of the Pleistocene when glaciers stabilized at pinning positions at the front of the Coast Mountains and in the eastern Fraser Lowland and shifted about those positions for 1,500–2,000 years. Notably, the western Fraser Lowland was deglaciated shortly after 15,000 years ago, but the glacier-margin stabilized in what is now the Abbotsford/Chilliwack area, where it advanced and retreated several times between 14,000 and 12,000 years ago (Fig. 5; Armstrong, 1981; Clague et al., 1997a; Kovanen, 2002). At least one of the advances occurred during the globally recognized Younger Dryas Chronozone.

The lithosphere was displaced downward during growth of the last Cordilleran ice sheet (Clague and James, 2002; Clague et al., 1983; James et al., 2000). As deglaciation progressed, the zone of rapid isostatic uplift migrated in step with receding glacier margins (Clague, 1983). The rate of uplift in each region decreased exponentially with time and rebound was largely complete a few thousand years after deglaciation (Clague et al., 1982; James et al., 2000). By ~6,000 years ago relative sea level stabilized near its present datum (Fig. 6A).

## 3.2. Holocene Delta Stratigraphy

### *3.2.1 Delta architecture and chronostratigraphy*

Most of our understanding of the Holocene depositional architecture of the FRD is derived from seismic reflection, borehole, and cone penetrometer studies carried out from the 1970s to 1990s (Clague et al., 1998; Hunter et al., 1998; Hutchinson et al., 1995; Luternauer et al., 1986; Monahan, 1999; Monahan et al., 1993a; Mustard and Rouse, 1994; Pullan et al., 1989;

Roberts et al., 1985; Williams, 1988; Williams and Luternauer, 1991; Williams and Roberts, 1989; Williams and Roberts, 1990). A prominent disconformity, representing the glacially eroded Tertiary bedrock surface, is present at sub-bottom depths ranging from 200 to 1,000 m (Clague et al. 1998). It is overlain by several hundred metres of Pleistocene diamict, sand, and gravel deposited in glaciomarine and marine environments. The top of the glaciomarine / marine unit is an irregular surface with up to 300 m of relief that defines a second unconformity upon which up to 300 m of Holocene sediment accumulated (Fig. 7; Clague et al. 1998). However, only ~200 m of the Holocene sedimentary package is related to the FRD.

Holocene delta deposits are characterized by classic progradational and downlapping clinothems, with topset, foreset, and bottomset components (Fig. 8; Clague et al., 1991; Jol and Roberts, 1988; Jol and Roberts, 1992; Pullan et al., 1998; Pullan et al., 1989). The topset includes tidal flat, tidal marsh, floodplain, distributary channel, and peat bog deposits that thin westward from ~20 m at Annacis Island to less than 4 m near Roberts Bank (Fig. 9; Clague et al., 1983; Clague et al., 1998; Monahan et al., 1993a; Monahan et al., 1993b). The westward thinning of topset deposits reflects the progressive subsidence of older deposits and subsequent infilling of topographic lows during rising sea level (Clague et al., 1983; Williams and Roberts, 1989; Williams and Roberts, 1990). The topset can exceed 20 m in thickness where distributary channels scour into the underlying foresets of the delta slope. Borehole data show that the lower part of the delta topset is mainly 8–20 m thick (and ranges up to 30 m thick) and consists of fining-upward, fine- to medium-grained sand successions that together form a continuous sand sheet (Fig. 9; Clague et al., 1998; Hutchinson et al., 1995; Monahan et al., 1993a; Monahan et al., 1993b; Monahan et al., 1995; Williams and Luternauer, 1991). The sand sheet has been interpreted as the deposits of a migrating distributary channel network (Monahan et al., 1993a); however, the thickness of the unit is comparable to the thickness of the sand-dominated upper delta slope and tidal flats suggesting at least part of the unit preserves older upper delta slope and tidal flat deposits. The uppermost unit in the topset succession is peat and organic-rich and laminated clayey silt that ranges in thickness from 1 m inland of the tidal flats to more than 10 m at New Westminster (Fig. 9; Clague et al., 1983; Williams, 1988; Williams and Roberts, 1989). This unit contains the 7,700-year-old Mazama tephra and forms the domed peat bog at Burns Bog (Clague et al., 1983; Hebda, 1977).

Underlying the topset is up to ~165 m of dipping foreset strata deposited on the delta slope (Fig. 8; Clague et al., 1991; Monahan et al., 1993a; Pullan et al., 1998; Pullan et al., 1989). The foresets comprise mainly bioturbated mud and sand (Ayranci and Dashtgard, 2013; Ayranci and Dashtgard, 2016; Ayranci et al., 2014; Christian et al., 1994; Dallimore et al., 1995). Erosionally based fining-upward sand and mud beds are interpreted as sediment gravity flow deposits (Ayranci et al., 2012; Lintern et al., 2016; Stacey, 2014), and coarsening-upward packages are thought to record annual and interannual deposition seaward of the river mouth. The present-day annual and interannual sediment volume deposited on the delta slope ranges from 0.5–2 x $10^6$ $m^3$ $year^{-1}$ (Hill, 2012; Hill and Lintern, 2021; Lintern et al., 2016). The foresets are sandier at shallow water depths and become muddier offshore (Ayranci and Dashtgard, 2016).

Radiocarbon dates of organic material recovered in boreholes indicate that delta foresets built past Annacis Island by 9,000 years ago and the west side of Burns Bog by 7,000 years ago (Figs. 1, 9–11; Williams and Roberts, 1989). By ~6,000 years ago, the delta had prograded west to Point Roberts Highland (Fig. 1A), which until then was an island in the Salish Sea. The onlap of the FRD onto Point Roberts Highland largely terminated the delivery of sediment to Boundary Bay (Hutchinson et al., 1995). Since ~6,000 years ago and following closure of the tidal channel between Point Roberts and the FRD, the locus of deposition switched from southward to westward (Clague et al., 1998). Delta-slope foresets transition seaward into bottomsets representing both distal deposits of the Fraser River and sediment redistributed in the marine realm.

### *3.2.2 Delta evolution resulting from relative sea-level change and sedimentation*

Delta architecture was influenced by relative sea-level (RSL) changes through the Holocene (Fig. 6A). The most recent compilation of relative sea-level data for the FRD indicates an initial rapid postglacial RSL fall in response to isostatic uplift near the Last Glacial Termination, with RSL reaching a minimum of -20 m between ~12,000 and ~10,000 years ago (Fig. 6A; Figure 5 in Shugar et al., 2014). RSL then rose to a few metres below its present level by ~6,000 years ago. The rise in RSL is reflected in the ascending trajectory of the delta hinge point – the inflection between the flat-lying topset and seaward-dipping foresets (Figs. 9 and 10; Williams and Roberts, 1989). The stepped nature of this ascending trajectory is interpreted by Williams and Roberts (1989) to record possible stillstands and accelerations of RSL; however, there is no evidence for such stillstands in the empirical sea-level curve of Shugar et al. (2014) suggesting that the steps may be related to autocyclic changes within the delta, such as channel switching.

Based on the analysis of Williams and Roberts (1989), the delta prograded most rapidly (~6.5 m year$^{-1}$) into the Strait of Georgia during the early Holocene (~9,000–8,000 years ago) when the delta's depositional front was confined by Pleistocene highlands (Figs. 6B and 10). The rate slowed to approximately 3.8 m year$^{-1}$ between 6,200 and 5,800 years ago and further decreased to 2.4 m year$^{-1}$ over the past 2,250 years.

Other researchers compared marine chart contours to estimate historic progradation/erosion of the delta. Johnston (1921) estimated that between 1859 and 1919 the average rate of advance across the entire western delta front was 3 m year$^{-1}$ with the strongest progradation north of the Main Arm and negligible progradation to the south. By contrast, Mathews and Shepard (1962) suggested that between 1929 and 1959, the delta prograded at a rate of 8.5 m year$^{-1}$ near the mouth of the Main Channel. Stewart and Tassone (1989) analyzed data from 1929 to 1979 and calculated a progradation rate of 8.6 m year$^{-1}$. None of these predicted progradation rates are supported by modern survey data which suggests that Roberts and Sturgeon banks have not prograded significantly over historic time scales (Fig. 6B). Indeed, there are clear indications of erosion of the upper slope of Roberts Bank, including outcropping strata and mobile bedforms (Carle and Hill, 2009), and a linear (rather than asymptotic) seaward-dipping profile in the upper delta slope (Fig. 12). This disconnect between calculations from chart data and modern surveys may be related to dredging of the channel in recent decades.

Present-day progradation is confined mainly to the area extending 1 km or so around the mouth of the Main Channel (Hill, 2012). Annually repeated multibeam surveys of the mouth indicate several metres of accumulation at the lip of the delta and at the head of the northernmost tributary canyon of the Sand Heads Sea Valley. Just to the south, slope failures at the lip have opened a new tributary canyon (Hill, 2012 and more recent unpublished surveys).

Sedimentation rates on the delta slope are low, averaging 0–2 cm year$^{-1}$ on both the lower extent of foresets on the southern DS and on bottomsets across the entire DS, and up to 13 cm year$^{-1}$ on the upper extent of foresets seaward of the Main Channel (Hart et al., 1998). At the bottom of the Strait of Georgia, below 300 m water depth, up to 22 cm year$^{-1}$ of sediment can accumulate locally through event-style deposition (Ayranci and Dashtgard, 2020) although the long-term fate of these sediments is unknown.

### 3.4 Quaternary Surficial Sediments

Pleistocene glaciations and subsequent Holocene sea-level changes and growth of the FRD left behind a complex mosaic of surface sediments across the Lower Mainland of British Columbia. These deposits were mapped by the Geological Survey of Canada in the 1970s and 1980s (Armstrong, 1980a; Armstrong, 1980b; Armstrong and Hicock, 1979; Armstrong and Hicock, 1980). Herein, we show a simplified map of the Holocene deposits to demonstrate the distribution of the eight major sedimentary units, one anthropogenic unit, as well as two other units which underlie the FRD (Fig. 13; Table 2). The eight major geological units include: (1) peatland sediment, (2) overbank sediment, (3) alluvial slope sediment, (4) mountain stream sediment, (5) marine shoreline sediment, (6) fluvial and deltaic channel sediment, (7) lake sediment, and (8) aeolian sediment. The anthropogenic unit is landfill, and the other two underlying units are Pleistocene glacial and glaciomarine sediment and pre-Quaternary basement (Fig. 13; Table 2). These units are the foundations upon which domestic and commercial construction occurs and roads and highways are built. They are also the surface expression of the underlying geology of the FRD (including adjacent areas).

## 4. CONTEMPORARY SEDIMENTARY PROCESSES AND DEPOSITS

### 4.1 River and Fluvio-Tidal Transition (River, FTT–Fresh, FTT–Transitional, and FTT–Brackish)

Sedimentary processes shift progressively from river-dominated at the landward end of the FTT to mixed fluvial and tidal at the mouths of the distributary channels (Fig. 1B). Tidal influence increases seaward through the channels (Dashtgard and La Croix, 2015; Dashtgard et al., 2012; La Croix and Dashtgard, 2015). Because river flow varies seasonally and increases up to 15-fold from base flow to freshet (Fig. 3A–B), tidal effects on river flow, and by extension sedimentation, are greatest during the low-flow season (La Croix and Dashtgard, 2014; Sisulak and Dashtgard, 2012).

The relative influence of tides differs between distributary channels and is largely proportional to the volume of water flowing through them (Fig. 1A). The Main Channel carries about 85% of the flow, hence tides and associated brackish-water influence is subdued in that channel relative to other distributaries (Dashtgard and La Croix, 2015; Dashtgard et al., 2012; La Croix and Dashtgard, 2014; La Croix and Dashtgard, 2015). Canoe Pass (5%), Middle Arm (5%), and North Arm (5%) are more strongly impacted by tides and brackish water (Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2015; Sisulak and Dashtgard, 2012).

At the mouth of the Main Channel, water salinity reaches up to 26 parts per thousand (ppt) during base flow and 0 ppt during freshet (Ages, 1979; Ages and Woolard, 1976; Hughes and Ages, 1975; Kostaschuk and Atwood, 1990; Kostaschuk et al., 1989). Salinity tapers landward to 0 ppt throughout the full season at ~30 river km upstream (near New Westminster; Fig. 1A). Salinity in the Main Channel is also 0 ppt through the high flow season (freshet). In the smaller distributaries, such as the North and Middle arms, water salinity reaches as high as 26 ppt under base flow conditions and 19 ppt during freshet (Ages, 1979; Ages and Woolard, 1976; Chapman, 1981; Chapman and Brinkhurst, 1981; Hughes and Ages, 1975; Johnson and Dashtgard, 2014; Kostaschuk and Atwood, 1990; Kostaschuk et al., 1989).

Shifts in hydrodynamic forcing impart a conspicuous pattern in surface sediment distribution within channels. In the river upstream of tidal influence (i.e., “River”; Fig. 1; Table 1), channel sediments comprise ~20–30% sand and ~70–80% gravel (Fig. 14; Venditti and Church, 2014). At the transition downstream into the tidally influenced reach of the Fraser River (i.e., Yaalstrick Island, landward end of the FTT), there is a marked decrease in gravel (rarely up to 20%) and an increase in sand (60–90%). The approximate average grain size ($AGS_{avg}$) of mud through the FTT is 0.02 mm (medium silt), and the $AGS_{avg}$ of sand is 0.3 mm (medium sand). Mud increases downstream through the FTT, with silt and clay comprising up to 40% of channel sediment in the FTT–Brackish subzone (Dashtgard et al., 2012; Venditti and Church, 2014). Fine-grained sediment (silt and clay) accumulates primarily in intertidal portions and the downstream ends of channel bars, in side-channels, and on channel floors near the mouths of distributary channels (Fig. 15; La Croix and Dashtgard, 2015). There is a locus of mud deposition on channel bars near New Westminster where the Fraser River bifurcates (Fig. 16; La Croix and Dashtgard, 2014). In the FTT–Brackish subzone, most channel bars exhibit a mud-sand-mud profile from upstream to downstream (i.e., bars have a mud-sand-mud longitudinal distribution; Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2015).

Vertical sedimentary successions are also linked to hydrodynamics within channels and these successions contain partial records of hydrodynamic shifts controlled by river flow and tides. (c.f., Sisulak and Dashtgard, 2012; Johnson and Dashtgard, 2014; La Croix et al., 2014; Dashtgard and La Croix, 2015; Dashtgard et al., 2012; La Croix and Dashtgard, 2014, 2015; Smith, 1985). Channel-bar successions in the FTT–Fresh subzone are dominantly sand with subtle, small-scale fining-upward profiles of ripple cross-laminated to cross-bedded sand that record variations in river discharge (Fig. 17E–F). Successions in the FTT–Transitional subzone consist mainly of mud or mixed sand and mud, and successions fine upward; they record both tidal and river discharge cyclicity in a brackish-water setting (Fig. 17C–D). Sand layers preserved in vertical successions in the FTT-Transitional subzone are ripple cross-laminated and occur in either upper subtidal / lowermost intertidal positions or towards the base of the channel. Muddy deposits reflect impedance of river flow by tidal incursion and potentially mud flocculation in brackish water (La Croix and Dashtgard, 2015; Sutherland et al., 2014). Typical sedimentary successions of channel bars in the FTT–Brackish subzone show predominantly cross-bedded to ripple cross-laminated sand or are mixed sand and mud that either fines upward or has no obvious vertical grain-size trend (Fig. 17A–B). These successions record both tidal cycles and seasonal and annual variations in river discharge, as well as the influence of brackish-water incursion up channels.

### 4.2 Delta Plain (DP–Floodplain and DP–Peatland)

The delta plain (DP) includes the floodplain and peatlands (Table 1). The floodplain is at or near mean sea level (some parts are up to 1 m below mean sea level; Fig. 1C), and the floodplain is protected by an extensive network of dikes that prevent flooding during high tides, storms, and high river discharge. The natural state of the floodplain, which existed prior to diking, was an area periodically inundated by flood water (landward, generally > 1 m above mean sea level; Fig. 1B–C and 13) or saltwater during exceptionally high tides and storm surges (seaward, generally <1 m above mean sea level; Luternauer et al., 1998).

Near-surface sediment in the floodplain is ~2–3 m thick and comprises dominantly horizontally layered organic silt and clay; these sediments are derived from Fraser River flood waters (Figs. 9–10 and 13; Table 2; Armstrong and Hicock, 1979; Armstrong and Hicock, 1980; Luternauer et al., 1998). Peatland on the delta plain includes domed areas of peat up to 5 m thick that have elevations high enough to avoid regular flooding/saltwater incursion (up to 5 m above the floodplain). Peatlands are characterized by accumulative plant growth atop generally poorly drained sediment and with hindered organic decomposition (Fig. 13; Table 2; Armstrong, 1980a; Armstrong, 1980b; Armstrong and Hicock, 1979; Armstrong and Hicock, 1980). Peat deposits range from sphagnum- to sedge-dominated depending on geographic location and the degree of soil drainage (Hebda, 1977; Lowe and Bustin, 1985; Styan and Bustin, 1983).

### 4.3 Tidal Flats (TF–Tidal Marsh, TF–Sturgeon Bank, TF–Roberts Bank, TF–Boundary Bay, TF–Mud Bay)

The tidal flats category comprises three zones (Table 1): tidal marsh, active tidal flats (Sturgeon and Roberts banks), and inactive (abandoned) tidal flats (Boundary and Mud bays; Fig. 1A). The tidal marsh is the vegetated portion at the landward end of the tidal flats. The term "active" is applied to tidal flats adjacent to the Fraser River and its distributaries. The active tidal flats receive sediment from the river and are periodically covered by freshwater during high river-discharge events. Inactive, or "abandoned" tidal flats are separated from the Fraser River by Point Roberts Highland (Fig. 1B). They receive virtually no sediment from the Fraser River and experience only polyhaline to euhaline water (18–32 ppt).

#### *4.3.1 Tidal marshes (TF–Tidal Marsh)*

Historical accounts, maps, and charts indicate that, prior to construction of the dikes in the twentieth century, much of the delta coastline was characterized by tidal marsh, and these marshes formed at the transition between the delta plain and the unvegetated tidal flats (Church, 2017; Hayes, 1947; Vancouver, 1798). Areas of tidal marsh remain in front of the dikes on Sturgeon Bank, Roberts Bank, Boundary Bay, and Mud Bay (Fig. 1B and 18; Church and Hales, 2007; Hales, 2000; Kellerhals and Murray, 1969; Swinbanks and Murray, 1981). The tidal marshes on Sturgeon Bank and Roberts Bank (active tidal flats) are characterized by brackish vegetation zoned by elevation that includes bulrush, sedge, and cattail (*Schoenoplectus americanus, Carex lyngbyei, S. maritimus*, and *Typha* sp.; Adams and Williams, 2004; Bode, 2019; Hutchinson, 1982). These species also record freshwater influence from the Fraser River. The absence of a major distributary channel in Boundary Bay and Mud Bay (abandoned tidal flats) results in more saline conditions in the tidal marshes, which is reflected in more typical saltmarsh vegetation (*Distichlis spicata, Triglochin maritima, Atriplex patula*, and *Sarcocornia pacifica*; Bode, 2019; Yamanaka, 1975).

Comparison of historic air photos indicates that the marsh on Sturgeon Bank and northern sections of Roberts Bank expanded in area from 1932 (16 x $10^6$ $m^2$) to 1994 (24 x $10^6$ $m^2$) and then remained relatively stable until 2004 (Fig. 18; Church and Hales, 2007; Hales, 2000). Most expansion of the marsh occurred near the Fraser River distributaries where they transect the tidal flats. However, this trend appears to have reversed and the marsh has retreated significantly in recent years (Balke, 2017; Marijnissen, 2017; McDonald, 2018). Marsh is absent along the southern portion of Roberts Bank, except for an artificially maintained saltmarsh located behind the dike, and in most parts of Boundary Bay. Wood preserved in buried peat beds approximately 1 km seaward of the dyke in Boundary Bay was radiocarbon dated at 4,350 ± 100 years ago (Fig. 19; Kellerhals and Murray, 1969), and old marsh deposits were encountered below 10 cm of sand approximately 430 m from the dyke (Fig. 19A; Dashtgard, 2011a). The radiocarbon age and old marsh deposits below the tidal flat indicate that Boundary Bay is being actively transgressed and that 4,000 years ago the tidal marsh was much more extensive.

### *4.3.2 Active tidal flats (TF–Sturgeon Bank, TF–Roberts Bank)*

Sediment supplied to the active tidal flats is derived mainly from the Fraser River's distributary channels and especially the Main Channel (Ayranci et al., 2012; Hart et al., 1998; Houser and Hill, 2010a; McLaren and Ren, 1995; McLaren and Tuominen, 1996). Canoe Pass and Middle Arm (each ~5% of river discharge) flow freely across the tidal flats, and hence, can distribute sediment to the flats without obstruction (Fig. 20); however, their total sediment volumes are low. The Main Channel and North Arm are both trained by jetties on one side where they cross the tidal flats and this results in most of their sediment load bypassing the flats (McLaren and Tuominen, 1996). Sediment supplied to areas of the tidal flats near the jetties is limited to fine sediment advected in suspension back onto the flats during high tide and from the surface plume at the mouth of the distributary channel. The paucity of sediment reaching the active delta tidal flats is exacerbated by dredging in the Main Channel, South Arm tidal channel, and rarely the North Arm (Fig. 1A). Between 1997 and 2007, ~2.0 x $10^6$ $m^3$ $year^{-1}$ of sediment was removed from these three channels (Fraser River Estuary Management Program, 2006; 2007). Dredging results in more sediment being trapped in the river and less reaching the tidal flats. Recently, parts of the jetty between the Main Channel and Sturgeon Bank were removed in an attempt to increase sediment delivery to Sturgeon Bank (www.raincoast.org; accessed April 4, 2023). The success of this program is uncertain at this time.

Sediment supply to the active tidal flats is influenced by asymmetric tidal currents on the delta slope, which carry plume sediment in a net northward direction ("downdrift") of the Main Channel (Barrie et al., 2005; Hart and Barrie, 1995; McLaren and Tuominen, 1996). Sediment on the tidal flats is advected from the surface plume and remobilized by tidal currents on the rising tide, and then transported offshore during falling tides (Ayranci et al., 2012; Hill et al., 2008). Sediment on the outer tidal flats is also mobilized and moved onshore by large storm-waves (Fig. 20; Houser and Hill, 2010a).

The jetty that trains the Main Channel, dredging, and net northward tidal flow have significantly altered delivery of sediment to the active tidal flats and is reflected in their shore-normal profiles (Figs. 12 and 20E–F). The tidal flats seaward of Westham Island form the northern end of Robert Bank and are situated between Canoe Pass to the south and Main Channel to the north. The Main Channel is not trained along its southern margin and, consequently, the intertidal and subtidal flats are widest here, reaching nearly 8 km seaward of the dike. The tidal flat profile off Westham Island reflects progradation of the delta at the mouth of the Main Channel. Southern Roberts Bank, south of Canoe Pass, receives little sediment from the Fraser River because of net northward tidal flow, and this is reflected in the absence of a tidal marsh, evidence of erosion on the delta slope (Carle and Hill, 2009), an erosional profile at the transition of the tidal flats to the delta slope (relative to the Westham Island profile, Fig. 20E), and evidence of sediment accumulation in the intertidal zone (again relative to Westham Island). Hence, the outer part of Roberts Bank is interpreted to be wave-influenced and possibly experiencing net erosion. Similarly, Sturgeon Bank shows a shore-normal profile with a smoother tidal flat surface suggesting modest sediment accumulation (less than Roberts Bank, but more than Westham Island; Fig. 20F). Wave erosion on the outer margin of the tidal flats is also suggested by the steeper profile relative to Westham Island, although the width is less than on Roberts Bank.

Both Sturgeon and Roberts Banks are mud-dominated within approximately 500 m of the tidal marsh ($AGS_{avg}$ = 0.045 mm; coarse silt), and the mud transitions seaward into dominantly medium-grained sand ($AGS_{avg}$ = 0.3 mm) that extends to the outer limit of the subaqueous flats (5 m water depth; (Figs. 12, 20E–F, and 21B; Dashtgard, 2011b; Hart et al., 1998). Due to northward alongshore sediment transport, sediment on the north side of jetties and other manmade structures, such as Deltaport and Steveston Jetty, is typically finer grained than on the south side of these structures (Dashtgard, 2011b). The active tidal flats of Sturgeon and Roberts banks show several interesting geomorphological features including wave-formed bars (Fig. 20A–B) and small-scale creek networks (known locally as “mumblies”; Fig. 20B, D). A topographically higher profile on Roberts Bank occurs in association with the small-scale creek networks and is probably related to biofilm binding sediment together (Williams et al., 2009).

### *4.3.3 Abandoned tidal flats (TF–Boundary Bay, TF–Mud Bay)*

Boundary Bay appears to receive most of its sediment from erosion of the sandy bluffs on the east side of Point Roberts Peninsula and from wave reworking of the subaqueous delta slope (Figs. 12 and 19). Waves and tides are the primary drivers of sediment transport. Waves approach Boundary Bay from the southeast (Fig. 3C). Tidal currents flow into the bay from the southwest and circulate counter-clockwise (Murty and Roberts, 1989). The east margin of Boundary Bay is flood-tide dominated, whereas the western margin is ebb-tide dominated (Kellerhals and Murray, 1969; Swinbanks and Murray, 1981), and tidal currents are strongest along the western margin and within tidal channels (Murty and Roberts, 1989). Mud Bay is the embayed, northeast extent of Boundary Bay and is sheltered from incoming waves (Dashtgard, 2011a; Kellerhals and Murray, 1969).

The Fraser River flowed into Boundary Bay before onlapping Point Roberts ~6,000 years ago (Clague et al., 1998), and Boundary Bay was part of the actively accreting delta front until that time (Fig. 11). The width of the intertidal and shallow subtidal flats at Boundary Bay are comparable to those at Westham Island (Figs. 12 and 19B), but the subtidal profile shows evidence of sediment erosion between ~4,500 m and 8,000 m from the dike (Fig. 19B). The tidal flat profile at Boundary Bay is attributed to wave erosion caused by storm waves that approach from the southeast (Fig. 3C; Ayranci et al., 2012; Houser and Hill, 2010a). In conjunction with evidence of erosion of the marsh in Boundary Bay (see section 4.3.1), the whole system appears to be undergoing slow erosion and landward retreat attributed to low sediment supply to this part of the delta.

Boundary Bay is dominantly sandy with <5% mud, and sediment coarsens seaward from very fine-grained ($AGS_{avg}$ = 0.12 mm) to fine-grained sand ($AGS_{avg}$ = 0.2 mm; Fig. 21A; Dashtgard, 2011a). Wave-sheltered Mud Bay is mud-dominated ($AGS_{avg}$ = 0.045 mm; coarse silt; Dashtgard, 2011a; Kellerhals and Murray, 1969; Northcote, 1961). Mud also extends up both the Nicomekl and Serpentine rivers (Fietz et al., 2021). Minor gravel deposits are present in the southwest part of Boundary Bay where they form a series of north-prograding beach ridges (Dashtgard, 2011a; Engels and Roberts, 2005). The inactive tidal flats of Boundary Bay and Mud Bay have several important geomorphological features such as tidal creeks, wave-formed bars, and pioneer marsh colony mounds (Fig. 19A).

Interestingly, Boundary Bay shows a domed profile where the flats are colonized by eelgrass (middle flats; Fig. 19B). The domed profile of the flats in the eelgrass-colonized zone is interpreted as an accumulation of sand due to baffling of waves, wave-forced currents, and tidal currents and subsequent settling of the coarsest suspended sand grains. As storm waves approach from the southeast, they attenuate across the flats (e.g., Dashtgard, 2011a; Houser and Hill, 2010b; Swinbanks and Murray, 1981) and interact with tidal currents that also decrease in strength landward (Dalrymple and Choi, 2003; Pritchard and Hogg, 2003). Together these landward-weakening processes transport increasingly finer grained material with coarser material dropping out of suspension as hydraulic energy decreases (e.g., Masselink and Short, 1993). This is manifested in the landward decrease in grain size landward across Boundary Bay and the accumulation of mud where there are no wave-forced currents (Mud Bay).

## 4.4 Delta Slope

### *4.4.1 Sedimentation processes on the delta slope*

In contrast, to Roberts and Sturgeon banks, the break in slope between the delta slope and tidal flats at Boundary Bay occurs at ~8.5 m depth (Fig. 19B). Little work has been done on the delta slope deposits in Boundary Bay, thus they are not discussed further. Sediment on the delta slope landward of Roberts Bank and Sturgeon Bank is dispersed by tidal currents (Hill and Lintern, 2021), and also in the upper ~20 m by waves (Ayranci and Dashtgard, 2016; Hill and Davidson, 2002). Sand is transported offshore from the tidal flats during ebbing tides (Ayranci et al., 2012; Hill et al., 2008).

Near surface and intermediate water-depth currents are out of phase by several hours, indicating a distinct stratification of the water column (Hill and Lintern, 2021; Pawlowicz et al., 2007). In the upper part of the water column, currents are driven by surface tides, whereas below approximately 70 m depth currents are driven by internal tides. Peak current speeds decrease with depth so that the lower delta slope is an area where fine sediment falls from suspension. At greater depths again, sediment may be resuspended and transported in suspension via currents generated by seasonal deep-water renewal events that push dense Pacific Ocean water into the Strait of Georgia (Ayranci and Dashtgard, 2020; Masson, 2002).

Net sediment redistribution is northward on the upper delta slope resulting from strong north-directed flood tides and weaker south-directed ebb tides (Ayranci et al., 2012; Barrie et al., 2005; Hart and Barrie, 1995; Hill et al., 2008; Kostaschuk et al., 1995; McLaren and Tuominen, 1996; Thomson, 1981). On the upper ~100 m of the delta slope, peak tidal current velocities exceed the critical threshold for erosion of previously deposited material (Hill et al., 2008; Kostaschuk et al., 1995), and sediment resuspension and winnowing processes impact depositional patterns. Specifically, subaqueous dunes and outcrops of older strata on the updrift slope indicate net erosion down to at least 100 m water depth (Carle and Hill, 2009), while the downdrift slope shows net deposition at all depths.

Turbidity currents with the capacity to destroy submarine cables and move observation platforms occur periodically in submarine channels and on the open delta slope off the mouth of Main Channel (Lintern et al., 2016; Mckenna et al., 1992). Repeat multibeam surveys and cores acquired from the levees of the Sand Heads Sea Valley (Fig. 2B) indicate that large overtopping turbidity currents are generated from both slope failures and hyperpycnal flows on interannual time scales, and that the valley formed mainly after the Main Channel was stabilized by the Steveston Jetty in the early 20th century (Hill, 2012; Stacey, 2014). Unconfined turbidity currents have been observed on the open slope in the vicinity of the Main Channel and are likely related to the formation of the smaller slope gullies (Fig. 2A; Hill and Lintern, 2022). These unconfined flows likely dissipate a few kilometres down slope; they are still observed at water depths of 110 m but probably do not continue to much greater depths.

### *4.4.2 Sediments on the delta slope (DS–Updrift, DS–Downdrift)*

The sedimentary processes active on the DS result in a clearly asymmetric grain-size distribution of surficial sediments (Fig. 21C; Ayranci et al., 2014; Barrie and Currie, 2000). South of the Main Channel (DS–Updrift subzone), surface sediments in the upper DS are dominantly sand and silty sand (~73% sand overall; $AGS_{avg}$ = 0.052–0.1 mm; coarse silt–very-fine sand; Ayranci et al., 2014). The sedimentary succession on the upper DS–Updrift comprises thick laminated sand and silty sand beds with uncommon soft-sediment deformation (Fig. 22A). In the lower DS–Updrift subzone, surface sediment comprises silt and sandy silt, with up to ~30% sand ($AGS_{avg}$ = 0.024 mm; medium silt; Ayranci and Dashtgard, 2013; Ayranci and Dashtgard, 2016; Barrie and Currie, 2000; Pharo and Barnes, 1976). The corresponding sedimentary succession comprises mainly bioturbated silt or bioturbated interbedded sand and silt (Fig. 22B; Ayranci and Dashtgard, 2016; Evoy et al., 1994; Evoy et al., 1997).

North of the Main Channel (DS–Downdrift subzone), surface sediments of the upper DS are more homogenous, and consist of highly bioturbated silt and sandy silt (~20–30% sand; $AGS_{avg}$ = 0.014–0.023 mm; fine silt to medium silt; Ayranci et al., 2014). The lower downdrift DS comprises mainly intensely bioturbated silt ($AGS_{avg}$ = 0.012 mm; fine silt) (Fig. 22C and E; Ayranci and Dashtgard, 2013; Ayranci and Dashtgard, 2016; Barrie and Currie, 2000; Pharo and Barnes, 1976). The sedimentary succession in the upper DS–Downdrift subzone comprises thick-bedded, bioturbated silt and sandy silt, which pass seaward into intensely bioturbated silt beds of the lower DS–Downdrift subzone (Fig. 22D and F; Ayranci and Dashtgard, 2016).

## 5. Delta Change, Coastal Management, and Natural Hazards

Many studies have assessed natural hazards associated with the low-lying, geologically young, and heavily populated Fraser Delta plain. We briefly review the hazards here.

### 5.1 Subsidence and Flooding

The Fraser River Delta is subject to ongoing, albeit localized slow subsidence, which, with tectonic and isostatic vertical movements being close to zero (James et al. 2009; Shugar et al. 2014), amplifies relative sea-level rise. InSAR, leveling and GPS data reveal that the dominant controlling factor of recent deltaic subsidence is consolidation of the thick Holocene sedimentary pile (Mazzotti et al., 2009; Samsonov et al., 2014). The Pleistocene highlands bordering the FRD show no appreciable vertical motion, whereas parts of the delta plain are subsiding at rates up to 3 mm $year^{-1}$, although this is localized to mainly developed urban areas on the delta plain (Fig. 23). Subsidence of 1–2 mm $year^{-1}$ translates into an additional 8–15 cm of subsidence-induced relative sea-level rise by the end of the century (Mazzotti et al., 2009; Samsonov et al., 2014), and this is in addition to rising sea level associated with warming of the atmosphere. Consequently, many parts of the lower delta plain lie will soon below the upper limit of tides and will be increasingly vulnerable to frequent flooding without improvement of the existing dike network.

The Fraser River Delta plain is protected from river floods and storm surges by ~250 km of dikes (Fig. 24) that were built during the early part of the last century and strengthened following the second largest recorded Fraser River flood in June 1948. Improvements to the river and sea dikes after the 1948 flood were funded under a joint Federal-Provincial flood risk reduction program. What remains uncertain is the extent to which existing dikes will prevent flooding if there is a re-occurrence of the largest recorded flood (1894) which extensively inundated the delta plain.

The risk of flooding is being slowly amplified by sea-level rise. Mean sea level along Salish Sea shorelines has increased at an average rate of 1–2 mm year$^{-1}$ over the past century and is now exceeding 3 mm year$^{-1}$ (Clague, 2022). Scientists predict that global mean sea level will be 0.3–0.65 m higher relative to 2005 by 2100 (Horton et al., 2020) with the result that low-lying coasts around the world will be inundated and eroded (Tessler et al., 2015). There will be large regional and global differences in the rate and magnitude of sea-level rise (see Clague, 2022 for a discussion), but a higher average sea surface in the Strait of Georgia will increase the risk of flooding on the FRD. Only ~4% of dikes currently stand higher than 60 cm above the 1894 flood level (Northwest Hydraulic Consultants, 2015).

Higher sea levels and associated flooding will also increase groundwater levels, soil salinity, and erosion, and this will impact agricultural land on the FRD, of which 40% is situated on vulnerable parts of the delta plain (Northwest Hydraulic Consultants, 2017). Sensitive intertidal environments on the seaward side of the dikes (i.e., tidal marshes) that rim the delta (Figs. 1B, 18–20) will also be impacted. The tidal marshes are habitat for waterfowl migrating along the Pacific Flyway (Adams and Williams, 2004; Butler and Campbell, 1987), and salmonid fry entering the Salish Sea from the Fraser River (Pyper and Peterman, 1999).

Because of the hardened nature of the coastline (i.e., diked shoreline), rising sea level will result in "coastal squeeze" as accommodation space for marsh and upper intertidal environments is reduced (Hill et al., 2013). Sediment aggradation in marshes is required to keep pace with sea-level rise to prevent changes in marsh ecosystems. Modelling studies suggest that marsh accretion can track sea level rise at rates <0.5 mm year$^{-1}$, but as sea-level rise accelerates, extensive marsh loss will occur (Hill et al., 2013; Kirwan and Murray, 2008).

### 5.2 Earthquakes and seismically induced liquefaction

The Fraser River Delta is situated inboard of an active subduction zone and in a region with active crustal faults, and hence, it is susceptible to major earthquakes (Fig. 25). Megathrust earthquakes (magnitude 8 or larger) have occurred along the Cascadia subduction zone (boundary between the North America Plate and Juan de Fuca Plate) at intervals ranging from <100 years to >1,000 years through the Holocene (Atwater, 1996; Atwater and Hemphill-Haley, 1997; Clague, 1997). These events produce sudden changes in land levels, tsunamis, and shaking along the outer coasts of British Columbia, Washington, Oregon, and northern California (Atwater, 1996; Atwater and Hemphill-Haley, 1997; Clague and Bobrowsky, 1994; Darienzo and Peterson, 1990; Darienzo et al., 1994; Nelson et al., 1996). In addition, over the past 175 years, there have been nine, large (>6.7 $M_w$) crustal and in-slab (subcrustal) earthquakes within the North American and Juan de Fuca plates in northwestern Washington State and southwestern British Columbia (Fig. 25A; Clague, 1997; Clague and Bobrowsky, 1994; Rogers, 1994). Several of these earthquakes were locally damaging, although there is no direct evidence that any impacted the FRD (Rogers, 1994).

Engineers and earth scientists expect that the water-saturated granular sediments of the FRD will liquify during a future strong earthquake. In particular, geotechnical studies (e.g., Finn, 1996; Fraser Delta Task Force, 1991) show that the shallow sand sheet that underlies much of the delta plain is susceptible to earthquake-induced liquefaction, and sand dikes and sand blows found in several shallow excavations on the delta indicate this has happened in the past (Clague et al., 1997b). There is uncertainty about the specific locations and areal extent of liquefaction of FRD sediments during either a megathrust earthquake, which would likely have a source over 200 km from the FRD, or a moderate to large earthquake at depth within the North America or Juan de Fuca plates. A shallow crustal earthquake (i.e. $M_w$ 6–7 with an epicenter within about 50 km of Vancouver) would induce widespread and severe liquefaction of shallow sands within the FRD (Clague et al., 1997b), although the probability of a shallow-crustal earthquake close to Vancouver is low (Fig. 25).

In the event of a liquefaction-inducing earthquake, the spatial pattern of liquefaction would be highly variable. The intensity of shaking would differ with differences in the thickness of Holocene deltaic sediments and the source location and character of the event. Geophysical studies and coring indicate that the depth to the base of the deltaic sequence in Richmond ranges from less than 20 m to more than 200 m (Fig. 7; Hunter et al., 1998), and amplification of seismic energy is probable due to deep basin effects and where deltaic sediments onlap Pleistocene sediments in southern Vancouver and western Surrey (Fig. 1B).

Damage from earthquake shaking and liquefaction should be minimized by strong building codes, which, in the Fraser Delta region are based on frequently updated seismic hazard models (Halchuk et al, 2019). In addition, neighbourhood-level seismic risk assessments have been used to develop recommendations related to infrastructure, building codes, and community-based planning, response, and recovery strategies; this is done to manage social and financial impacts (Hastings and Hobbs, 2022).

Earthquakes can also cause submarine slope failures, which threatens infrastructure built at the edge of the Roberts Bank delta slope. Slide-generated tsunamis are another potential outcome of large earthquakes, which we describe in more detail below.

### 5.3 Tsunamis

The last great earthquake at the Cascadia subduction zone occurred in January 1700 (Atwater et al., 2005; Satake et al., 1996). It generated a large tsunami that produced damaging run-up along the outer coasts of southern British Columbia, Washington, Oregon, California, and Japan. Numerical modelling of a similar Cascadia subduction zone tsunami indicates it would attenuate greatly as it moved eastward through the Juan de Fuca Strait and northward through the southern Gulf Islands and into the northern Salish Sea. For the FRD, the tidal flats at Boundary Bay would experience a wave resonance effect that might increase maximum wave heights to 2 m. Tsunami waves impacting the tidal flats at Roberts Bank and Sturgeon Bank and the adjacent delta slope would probably only be ~1 m (Cherniawsky et al., 2007). If a tsunami arrived at high tide, it would overtop the protective sea dikes along the west side of Richmond (Fig. 24) and would run some distance up the Main Channel of the Fraser River (distance dependent on Fraser River stage at the time of the tsunami).

In terms of damage, even small tsunamis can be dangerous. Tsunami waves only 1 m in height travel at sufficiently high velocities and with sufficient energy to damage wharves and dislodge pleasure craft from their anchorages. Give the number of houseboats and pleasure craft anchored in the channels near the mouth of the Fraser River, substantial damage might result from even a greatly attenuated tsunami.

Two other possible sources of tsunamis are a large seafloor-displacing earthquake on a fault beneath the Strait of Georgia and a submarine landslide sourced on the Fraser Delta slope. A few recently active fault zones have been mapped in the Salish Sea (e.g., Skipjack Island fault zone, Devils Mountain fault zone), and these pose potential earthquake and tsunami risks for coastal waters (Barrie and Greene, 2018; Greene et al., 2018). Modelling studies suggest that slope failure of delta-front sediments smaller than ~0.1 km$^3$ will not produce any significant waves (Dunbar and Harper, 1993), and this is supported by observations of the 1985 submarine landslide with a volume of over 0.1 km$^3$, which did not generate a tsunami (Mckenna et al., 1992).

### 5.4 Coastal Management

The terrestrial and aquatic components of the Fraser River Delta comprise a patchwork of productive ecosystems fed by marine- and watershed-sourced nutrients (Hoos and Packman, 1974; Schaefer, 2004; Williams et al., 2009). The FRD has been anthropogenically modified extensively over the past century, although it retains many elements of a natural system. In addition to the engineered dikes along all Fraser River distributary channels (Fig. 24), navigation through the Main Channel is maintained by regular sand dredging to ensure ships can reach Annacis Island and New Westminster. An average of ~2.0 x 10$^6$ m$^3$ year$^{-1}$ of sand is removed through dredging (Fraser River Estuary Management Program, 2006; 2007), and this has contributed to coastal erosion by altering sedimentation patterns (Armstrong, 1990; Barrie and Currie, 2000) and adversely affecting ecosystems (Schaefer, 2004).

Causeways that cross the tidal flats and a sewage disposal line that extends seaward of Iona Island have also greatly altered natural sediment distribution, enhanced seabed erosion, and increased the risk of slope failure (Barrie and Currie, 2000; Luternauer et al., 1998). Moreover, overbank sediment accumulation on the delta plain has effectively been shut off by dikes, and this is contributing to localized subsidence (Fig. 23; Lambert et al., 2008; Mazzotti et al., 2009; Samsonov et al., 2014).

In response to climate-related sea-level rise and associated recession of coastal marshes, a number of studies have sought to understand patterns and rates of change in marsh distribution across the FRD, as well the potential drivers of change (Balke, 2017; Bode, 2019; Hales, 2000;

Marijnissen, 2017; McDonald, 2018). One potential solution being explored is the implementation of a network of vegetated dikes (i.e., "living dikes"; Readshaw et al., 2018), which have been employed globally as a nature-based coastal management strategy (see Temmerman et al., 2023). New coastal infrastructure proposals are now subject to extensive environmental assessment and review at both the federal and provincial levels in order to identify and mitigate impacts on ecosystems and Indigenous communities, as well as develop practical adaptive management practices.

## 6. Knowledge Gaps with Implications for Delta Management

Both natural processes and human activity have impacted the evolution of the Fraser River Delta and its modern sedimentary regime. Anthropogenic development on the delta is competing with the need to preserve ecosystems, and this requires integrated management solutions to ensure that the FRD can withstand future changes in sea level, erosion, and morphodynamics. The synthesis of the sedimentary history, sediment dynamics, and natural hazards of the FRD presented herein provides the most up-to-date scientific basis for informed decision-making, but there are societally important knowledge gaps that require further research.

Nicholls et al. (2007) rank Vancouver as one of the top 20 port cities worldwide for which climate, flooding, subsidence, population growth, and urbanization are anticipated to threaten significant assets by 2070 (US$303 billion). Accordingly, there is a shift towards employing ecosystem-based coastal flood protection aimed at restoring and enhancing coastal wetlands to mitigate storm surges and storm waves; this, in turn, enhances the ability of the wetlands to keep pace with rising sea level (Temmerman et al., 2013). However, uncertainty remains as to the efficacy of these solutions, which require site-specific data to accurately assess advantages and limitations of ecosystem-based coastal flood protection (Möller, 2019; Seddon et al., 2020). Implementing “living dikes”, for example, at Boundary Bay (Figs. 1 and 19) requires detailed studies of local- and meso-scale geomorphological processes and sedimentary conditions before adequate construction strategies can be developed. Specific knowledge gaps include an understanding of sediment transport pathways, sediment sources, and rates of sediment accumulation, and how these change along the delta front, especially the tidal flats. Reliable modelling studies will require empirical data for calibration.

Loss of subaerial delta plains (including tidal flats and tidal marshes) due to erosion is a global problem (Vörösmarty et al., 2015) that also affects the FRD, despite the fact that large sections are protected by dikes. Reconnecting delta distributary channels to their floodplains and tidal flats allows sediment to accrete naturally and this has proven successful in a number of cases (e.g., Mississippi River Delta, Rhine-Meuse delta) to offset subsidence and sea-level rise (Day et al., 2007; Smit et al., 1997). Redistributing dredged material to help re-establish and expand intertidal marshes and wetlands has been proposed for the FRD, but present understanding of delta-front morphodynamics is insufficient to optimize sediment placement, forecast sediment transport, and decipher the role of sediment texture on the stability and ultimate redistribution of such material.

Although several studies have looked at the characteristics and community structure of vegetation at the land-water interface along the FRD (e.g., Bradfield and Porter, 1982; Hutchinson et al., 1998; Shepperd, 1981), and in particular the tidal marshes, little is known about how floral and faunal communities will respond to changing climate and rising sea level. Indeed, modelling studies indicate that marsh productivity is a key factor in determining the ability of a marsh to accrete as sea level rises (Kirwan and Murray, 2008). Researchers are increasingly recognizing linkages between sea-level change, floral and faunal ecosystem composition, and geomorphological changes in tidal marshes (Crotty et al., 2020; Feagin et al., 2005). For example, bioturbating (burrowing) animals can alter sedimentary properties and control the geomorphological evolution of deltaic landscapes. Despite the myriad of studies of bioturbating animals and their structures in the FRD (e.g., Ayranci and Dashtgard, 2013; Ayranci et al., 2014; Chapman and Brinkhurst, 1981; Dashtgard, 2011a; Dashtgard, 2011b; La Croix et al., 2015; Swinbanks and Luternauer, 1987; Swinbanks and Murray, 1981), the impact of bioturbation on geomorphological evolution and their effect on the geotechnical properties of the sediments are poorly understood. This is a clear knowledge gap that should be investigated further because of its implications for delta management.

A final knowledge gap is the possible impact of changes in the seasonal and long-term regime of the Fraser River in a changing climate. Significant changes in winter snowpack and glaciers within the watershed are likely as climate warms, but the magnitude and effects of these changes on river and sediment delivery to the Fraser River Delta are not understood, much less their consequences for the complex morphodynamics at play in the distributary channels and at the delta front.

## 7. Conclusions

The Fraser River Delta is one of the largest deltas in North America (Fig. 1). Part of the metropolis of Vancouver, including a major part of it's port and it's international airport sit atop FRD deposits. The FRD is also ecologically crucial for migrating birds, spawning fish, and a diverse terrestrial, brackish, and marine ecosystem, and is culturally significant, having been occupied by several First Nations for at least the past 9,500 years. Despite its importance, a synthesis of research on the hydrodynamic processes, sedimentology, stratigraphy, and natural hazards of the system has not been undertaken, even though these types of studies are necessary to accurately predict the impacts of future climate change and sea-level rise on the delta system.

Following deglaciation and over the past ~10,000 years, the FRD built westward into the Strait of Georgia (Salish Sea). By ~9,000 years ago the delta had reached Annacis Island, and by ~7,000 years ago it reached Burns Bog. By ~6,000 years ago the delta prograded to Point Roberts Highland, eliminating sedimentation into Boundary Bay to the south and restricting it to the northern Salish Sea to the west. Progradation was controlled, in part, but relative sea level which reached a minimum of -20 m between ~12,000 and ~10,000 years ago. Sea level then rose, reaching its present level by ~6,000 years ago. Delta progradation was most rapid from ~9,000–8,000 years ago due to delta confinement between Pleistocene highlands. Since then, the rate of progradation has decreased steadily with present-day progradation limited to the area immediately around the mouth of the Main Channel.

The FRD is broadly sub-divided into four zones, each with distinctive sedimentary processes, deposits, and stratigraphic architecture: channels, delta plain, tidal flats, and delta slope. Overall, FRD deposits are characterized by classic progradational and downlapping clinothems, with topsets, foresets, and bottomsets whose architecture is a response to relative sea-level changes throughout the Holocene.

Fraser River Delta channels extend from the landward limit of tides to the seaward terminus of the subaerial delta plain and are influenced by both river flow and tides. Upstream of the limit of tidal effects, sediments in the channel are predominantly gravel and sand. Downstream of this limit, in the FTT, daily and seasonal shifts in hydrodynamic conditions results in a rapid decrease in gravel content and a corresponding increase in the proportion of sand within channels. Further seaward, mud content increases, but it accumulates primarily on intertidal channel bars, in side-channels, and on channel floors near the mouths of distributary channels. The thickest and most widespread accumulation of mud is on channel bars new New Westminster).

The subaerial delta plain (DP) borders the modern Fraser River and its distributary channels. Prior to dike construction, periodic river floods that deposited mainly silt and clay on the delta plain (DP–floodplain). Fine-grained DP–floodplain sediments drain poorly, allowing for the accumulation of domed peat bogs (DP–peatland) that cap flat-lying topsets on the eastern delta plain. Intertidal marshes (TF–tidal marsh) and tidal flats rim the seaward portion of the delta plain. Sediment is transported from the mouth of the Fraser River across the active tidal flats (TF–Roberts Bank, TF–Sturgeon Bank) and is redistributed northward by tide-forced currents. These deposits are dominantly muddy along the shoreline and in proximity to the tidal marshes but coarsen seaward into sand. On the abandoned tidal flats (TF–Boundary Bay, TF–Mud Bay), which are effectively cut off from Fraser River sedimentation, sediment is redistributed by waves and tides only and deposits are sandy, except for wave-sheltered areas such as Mud Bay. The tidal flats transition into seaward-dipping foresets of the subaqueous delta slope at 5 m water depth on Roberts Bank and Sturgeon Bank and at 8.5 m water depth in Boundary Bay.

Sediment is transported primarily by tides and currents on the delta slope, but also by waves in shallow water. Tidally asymmetric currents result in net sediment transport to the north on the upper delta slope, which is evident in the distribution of sediments. South of the Main Channel (DS–Updrift), the upper DS is predominantly sand and silty sand. North of the Main Channel (DS–Downdrift), sediments of the upper DS are silt and sandy silt. The lower DS both south and north of the Main channel is floored by silt and sandy silt. The delta slope extends to the deepest parts of the Strait of Georgia and passes gradationally into flat-lying muddy bottomsets.

The FRD is subject to a variety of natural hazards, including subsidence, earthquakes, liquefaction, tsunamis, and flooding. Parts of the delta plain are subsiding at rates of up to 3 mm year$^{-1}$. Subsidence of the FRD amplifies eustatic sea level rise which is now approaching 4 mm year$^{-1}$. To protect the FRD delta plain from river floods and storm surges, ~250 km of dikes have been built along the river and distributary channels, as well as along the landward side of the tidal flats. Significantly, only ~4% of dikes currently stand higher than 60 cm above the 1894 flood level, the largest flood in recent history. Rising sea levels and flooding will also raise groundwater tables, increase soil salinity, amplify erosion, and negatively impact the vulnerable tidal marshes that rim the delta. The hard backstop formed by dikes along the FRD means that sediment aggradation must keep pace with sea-level rise to prevent changes to tidal wetlands and ecosystem function.

The FRD is located along the Cascadia subduction zone, where great subduction-related earthquakes occur at intervals from <100 years to >1,000 years. These earthquakes, as well as large crustal earthquakes, may cause sudden land-level changes, liquefaction of unconsolidated FRD sediments, tsunamis, and/or submarine slope failures.

Dredging is regularly undertaken in the Main Channel and to a lesser extent the other distributaries to maintain navigable channels. Along with causeways built across the tidal flats, dredging is contributing to coastal erosion by shifting sedimentation patterns. In response to the changes in coastal geomorphology and ecosystems, recent efforts have focused on exploring nature-based solutions such as vegetated dike systems. However, knowledge gaps pertaining to sediment transport pathways and rates of sediment accumulation across and along the subaqueous delta are hindering reliable modelling to forecast the future trajectory of the FRD.

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## 10. Table and Figure Captions

Table 1 – Summary of depositional environments (delta categories and zones), sub-environments (subzones), terminology (names), and defining characteristics of the Fraser River Delta. See Figure 1 for geographic locations.

Table 2 – Summary of characteristics of the two major bedrock units, eight major sedimentary units, and one anthropogenic unit that cover the Fraser River Delta and Fraser Lowland. Based on Armstrong (1980a, 1980b) and Armstrong and Hicock (1979, 1980).

Figure 1 – A) Landsat image of the Fraser River Delta in southwest British Columbia, Canada, showing geographical features along the lower Fraser River (yellow), tidal flats (orange), and population centres (white). Blue text defines waterways, and the percentages in blue at the mouths of distributary channels are approximate discharge percentages determined through numerical modeling (Northwest Hydraulic Northwest Hydraulic Consultants, 2008). The inset map shows the 230,000 km$^2$ watershed of the Fraser River, which originates in the Rocky Mountains along the British Columbia-Alberta border. The yellow box in the inset map shows the locations of A), B), and C). B) General zones of the Fraser River Delta used in this paper and described in Table 1. (Image Source: USGS and NASA). The pink lines in B) mark the approximate locations of breaks between the river, FTT-fresh, FTT-transitional, and FTT-brackish subzones, although all boundaries are gradational. The boundary between the FTT-brackish and FTT-transitional subzones in the North Arm is unknown. The highlands are derived from surface geology maps (Armstrong, 1980a, 1980b; Armstrong and Hicock, 1979, 1980). C) Combined elevation and bathymetry map of the Fraser River Delta and surrounding area.

Figure 2 – A) 3D model of the Fraser River Delta emphasizing the system of submarine channels on the delta slope, including the Sand Heads Sea Valley. B) Multibeam bathymetric model showing the morphology of the Sand Heads Sea Valley, on the delta slope just west of the Main Channel.

Figure 3 – A) Hydrograph of flow in the Fraser River at Mission (river km 65) between 1965 and 2018. Maximum (red), mean (green), and minimum (blue) daily discharges are shown. The coloured polygons show the daily suspended sediment load (brown) and daily discharge (light blue) in 1985 as an example of the variability in flow and sediment load (Kostaschuk and Lutternauer, 1989). The dashed black line marks the approximate boundary between high-flow and low-flow discharge (~2,800 m$^3$ s$^{-1}$). B) Ridgeline plot showing mean daily discharge from 1965 to 2018 (data source: wateroffice.ec.gc.ca, accessed March 2, 2023). C) Rose plot of monthly maximum wind speeds and directions recorded at Vancouver International Airport between 1957 and 2013. Percentages of monthly maximum wind speeds >63 km hr$^{-1}$ (minimum wind speed in tropical storms based on the Saffir-Simpson scale; Saffir and Simpson, 1974) are shown by arc thicknesses. Winds exceeded 63 km hr$^{-1}$ in 276 of the 674 months in the 1965-2018 interval (41%; data source:

climate.weather.gc.ca, accessed March 2, 2023). D) Representative daily and (E) monthly tidal cycles experienced at 300 m water depth on the delta slope of the FRD (data source: www.oceannetworks.ca, accessed March 2, 2023). Darker blue indicates spring cycles and lighter blue are neap cycles. One decibar (0.1 Bar) of pressure change records approximately 1.03 m of water level change.

Figure 4 – Depiction of the extent of the Cordilleran ice sheet in western Canada at the Last Glacial Maximum ~17,000 years ago. Modified after Clague (1994).

Figure 5 – Glaciers terminating on the isostatically depressed and marine-inundated western Fraser Lowland during deglaciation (i.e., just before the Fraser River began to prograde westward towards Pitt Meadows at ~10,000 years ago). Modified after Clague and Turner (2003).

Figure 6 – A) Comparison of relative sea-level curves for southwest British Columbia from Mathews et al. (1970), Clague et al. (1982), Williams and Roberts (1989), and Shugar et al. (2014). B) Lateral progradation and vertical aggradation rates for the Fraser River Delta. Modified after Williams and Roberts (1989).

Figure 7 – 3D model of the paleo-land surface in the Fraser Valley and Fraser River Delta region prior to delta progradation (i.e., pre-Holocene) based on the thickness of modern sediments (modified from Ayranci (2022) with data from Hunter and Christian (2001).

Figure 8 – Seismic reflection profile showing flat lying delta plain topset strata overlying seaward dipping delta slope foreset strata (modified from seismic line 900 in Pullan et al. (1989). The line of section (southwest-northeast) is oblique to the direction of progradation (south).

Figure 9 – Cross-sections displaying stratigraphy of topset sediments beneath Lulu Island. Section A–B is dip-oriented and shows the topset thinning to the west from near Annacis Island to Roberts Bank. The lower part of the delta topset is up to 20 m thick and comprises fining-upward cycles of sand that together form a near-continuous sand sheet (Sections G–H and I–J). Coloured polygons are our interpretation of how deposits relate to subzones defined in Table 1 (modified from Williams and Roberts, 1989).

Figure 10 – Generalized lithostratigraphic and geochronologic model for the Fraser River Delta from ~9,000 years ago guided by radiocarbon dating of peats and tephra layers. Colours indicate how deposits relate to subzones in Table 1 and correlate closely to the colour scheme in Figure 9. Figure is modified from Williams and Roberts (1989).

Figure 11 – Paleogeographic reconstruction of the Fraser River Delta as it prograded into the Strait of Georgia during the Holocene. Modified from Clague et al. (1991)

Figure 12 – Cross-shore profiles of the Fraser River Delta tidal flats and upper delta slope and their interpretations. Profiles are derived from LiDAR data.

Figure 13 – Surficial geology map of the British Columbia Fraser Lowland, including the Fraser River Delta. Compiled and modified from Armstrong (1980a, 1980b) and Armstrong and Hicock (1979, 1980).

Figure 14 – Grain-size percentages of channel-bed sediments in the Fraser River from Hope to Sand Heads. Grain-size percentages shown on the vertical axis are the average of multiple samples taken across the river channel and do not resolve cross-channel variations in sediment proportions. The dashed lines mark the approximate breaks between the Fraser River, FTT-Fresh, FTT-Transitional, and FTT-Brackish zones (modified from Venditti and Church, 2014).

Figure 15 – Maps showing the sand and mud percentages on bars and the channel base at various positions through the fluvial-tidal transition in the Fraser River. A–B) FTT–Fresh subzone. C–E) FTT–Transitional subzone. F–I) FTT–Brackish subzone. Data from Johnson and Dashtgard (2014), La Croix and Dashtgard (2015), and Sisulak and Dashtgard (2012).

Figure 16 – Fence diagram showing the cumulative sand and mud percentages on channel bars in the fluvio-tidal transition (FTT zone) in the Fraser River. Note the locus of mud deposition near where the river bifurcates into the Main Channel and North Arm. Modified from La Croix and Dashtgard (2014).

Figure 17 – Lithological descriptions of vibracores taken from channel bars in the the fluvio-tidal transition (FTT zone) in the Fraser River. A) Middle Arm, FTT–Brackish subzone. B) Canoe Pass, FTT–Brackish subzone. C) Annacis Channel, FTT–Transitional subzone. D) Surrey, FTT–Transitional subzone. E) Forth Langley, FTT–Fresh subzone. F) Matsqui Island, FTT–Fresh subzone. Modified from La Croix and Dashtgard (2015).

Figure 18 – Historical extent of salt marshes on Sturgeon Bank, Roberts Bank, and Westham Island from the 20th and early 21st centuries, as mapped by Hales (2000) and Church and Hales (2007) using air photos. The maps show that the salt marsh area increased from the 1930s to 1994 and has remained stable since 1994.

Figure 19 – A) LiDAR-generated DEM of the tidal flats in Boundary Bay, highlighting the major geomorphic and biophysical features including. tidal creeks, wave-formed bars, ebb deltas, the high tide sand prism, and present-day and interpreted historical extents of marshes. The location of the radiocarbon-dated peat bed reported by Kellerhals and Murray (1969) is indicated, and the red line marks the line of transect shown in B). Vertical reference datum is CGVD2013. B) Shore-normal profile of Boundary Bay versus Westham Island. Differences in the two profiles are highlighted to infer areas of net sedimentation and net erosion in Boundary Bay. Storm-wave base is between 10 and 20 m (Hill and Davidson, 2002). The inset map shows the position of A and

the two profiles in B. Mean high tide (MHT) is +1.5 m and mean low tide (MLT) is -1.4 m.

Figure 20 – Lidar-generated DEM of Sturgeon and Roberts banks, highlighting their major geomorphological and biophysical features. Westham Island forms the northern half of Roberts Bank. A–D) Features include tidal creeks, wave-formed bars, small-scale creek networks ("mumblies"), and pioneer marsh colony mounds. Vertical reference datum is CGVD2013. E) Shore-normal profiles of southern Roberts Bank and Westham Island. Differences in the two profiles are highlighted to infer areas of net sedimentation and erosion on southern Roberts Bank. F) Shore-normal profiles of Sturgeon Bank and Westham Island. Differences in the two profiles are highlighted to infer areas of net sedimentation and erosion in southern Sturgeon Bank. Inferred net erosion in both E) and F) is relative to the shape of the outer Westham Island profile. Mean high tide (MHT) is +1.5 m and mean low tide (MLT) is -1.4 m.

Figure 21 – Maps showing percentages of sand and mud across the tidal flats and delta slope of the Fraser River Delta. A) TF–Mud Bay and TF–Boundary Bay subzones. B) TF–Sturgeon Bank and TF–Roberts Bank subzones. C) DS–Updrift and DS–Downdrift subzones. D) 3D model of the Fraser River Delta showing percentages of sand and mud. Data from Barrie and Currie (2000), Dashtgard (2011a, 2011b), and Ayranci and Dashtgard (2013).

Figure 22 – Lithological descriptions of piston cores taken from the delta slope of the Fraser River Delta. A) Upper portion of the DS–Updrift subzone. B) Lower portion of the DS–Updrift subzone. C) Upper portion of the DS–Downdrift subzone. D) Lower portion of the DS–Downdrift subzone. E) Upper portion of the DS–Downdrift subzone. F) Lower portion of the DS–Downdrift subzone. Modified from Ayranci et al. (2016).

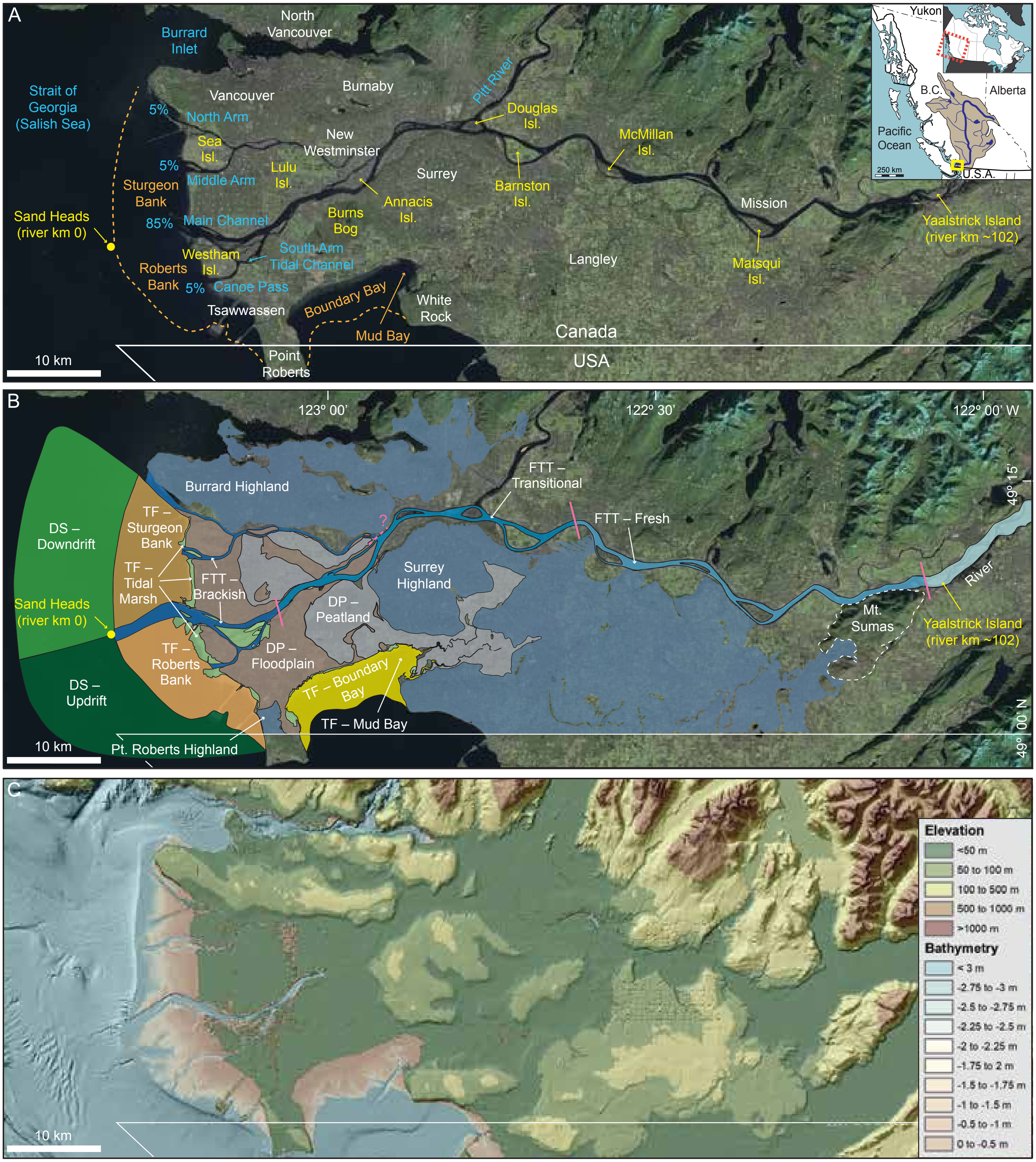
Figure 23 – Uplift and subsidence rates in the region of the Fraser River Delta determined by inSAR, leveling, and GPS relative to the ITRF2000 (international terrestrial reference frame). The green arrows and ellipses indicate horizontal velocity at the GPS sites relative to the easternmost site (i.e., BCMR), meaning that the regions denoted by the squares (GPS datapoints) are moving towards the regions defined by the ellipsoids at a rate of 2 +/- 1 mm year$^{-1}$. The colour map represents inSAR-derived data and filled circles are leveling data points. YVR—Vancouver International Airport; D.P.—Delta Port; T.F.—Tsawwassen ferry terminal. Figure 1 from Mazotti et al. (2009). Reproduced with permission from the Geological Society of America.

Figure 24 – Distribution of flood protection structures around the Fraser River Delta and adjacent areas. Map colours indicate ground surface elevations above sea level (m.a.s.l). From https://openmaps.gov.bc.ca).

Figure 25 – A) Earthquakes >$M_W$ 6.7 in the Pacific Northwest since 1847. B) Earthquakes $M_W$ >6.0 in the Pacific Northwest since 1922. Data from http://www.earthquake.usgs.gov (accessed March 2, 2023).

| Delta Category | Zone | Subzone | Name | Defining Characteristics |
|---|---|---|---|---|
| Fraser River (including distributary channels) | Freshwater and non-tidal | | **River** | Fluvial discharge that is not tidally modulated. |
| | Fluvio-tidal transition (FTT) | Freshwater and tidal | **FTT–Fresh** | Fluvial discharge with tidal modulation of water levels and no flow reversals. Completely fresh water (0 ppt) regardless of river stage or tides. |
| | | Freshwater to saltwater transition | **FTT–Transitional** | Fluvial discharge with tidal modulation of water levels, salt wedge, and flow reversals towards seaward end of zone. Salinity ranges from 0 ppt (landward) up to 10 ppt (seaward) during low flow stage and high tide. |
| | | Sustained brackish water | **FTT–Brackish** | Fluvial discharge with tidal modulation of water levels, migrating salt wedge and flow reversals. Salinity ranges from 10 ppt (landward) to 20 ppt (seaward) during low flow stages and high tide. Salinity is typically 0 ppt during freshet. |
| Delta Plain (subaerial delta) | Floodplain | | **DP–Floodplain** | Low-lying, subaerially exposed region. Would be inundated during spring high tides, large floods, or storm surge if undiked. |
| | Bog / Peat Mire | | **DP–Peatland** | Raised peat bog (e.g., Burns Bog) with high groundwater tables and heavily vegetated. Organic burial before decomposition / oxidation. |
| Tidal Flats (supratidal through shallow subtidal delta) | Tidal Marsh | | **TF–Tidal Marsh** | Supratidal to upper intertidal and vegetated sediment on the seaward side of the delta plain. Inhabited by mainly salinity tolerant plants. |
| | Active Tidal Flats | | **TF–Sturgeon Bank** | Roberts Bank. Updrift (south) of Main Channel. River influenced. Extends from tidal marsh limit to approximately 5 m water depth. |
| | | | **TF–Roberts Bank** | Sturgeon Bank. Downdrift (north) of Main Channel. River influenced. Extends from tidal marsh limit to approximately 5 m water depth. |
| | Abandoned Tidal Flats | | **TF–Boundary Bay** | Boundary Bay. Receives limited sediment from the Fraser River (non-river-influenced). Sand dominated. Extends from tidal marsh limit to approximately 8.5 m water depth. |
| | | | **TF–Mud Bay** | Mud Bay. Receives limited sediment from the Fraser River (non-river-influenced). Mud dominated. Extends from tidal marsh limit to where it grades into Boundary Bay. |
| Delta Slope (subaqueous delta) | Updrift Delta Slope | Updrift delta front | **DS–Updrift** | Updrift (south) of Main Channel. Extends between 5 m and 150 m bathymetric contours with an average slope of 2–3°. Strong alongshore tidal current influence. Sand dominated and erosional in places. |
| | | Updrift prodelta | | Updrift (south) of Main Channel. Extends below 150 m bathymetric contour with an average slope of <1°. Strong alongshore tidal current influence. Mud dominated. Grades into Strait of Georgia seafloor. |
| | Downdrift Delta Slope | Downdrift delta front | **DS–Downdrift** | Downdrift (north) of Main Channel. Extends from between 5 m and 150 m bathymetric contours with an average slope of 2–3°. Strong alongshore tidal current influence. Mud dominated. |
| | | Downdrift prodelta | | Downdrift (north) of Main Channel. Extends below 150 m bathymetric contour with an average slope of <1°. Strong alongshore tidal current influence. Mud dominated. Grades into Strait of Georgia seafloor. |

| **Surficial Unit** | **Thickness (m)** | **Mean \| Maximum \| Cumulative Area (km$^2$)** | **Associated with / Overlies** | **Main Lithology** |
|---|---|---|---|---|
| Peatland (DP–Peatland) | Up to 8 | 1.5 \| 140 \| 289 | River / FTT, DP–Floodplain | Peat / organic material |
| Overbank (DP–Floodplain) | Up to 2 | 5.6 \| 71.8 \| 281 | River / FTT | Silt to clayey silt to sandy silt or silty sand |
| Alluvial Slope | Up to 15 | 0.57 \| 4.3 \| 23.3 | River / FTT, DP–Floodplain | Clayey silt and silty clay to sands and gravels |
| Mountain Stream | Up to 15 | 1.4 \| 57.8 \| 139 | Interbedded with River / FTT, DP–Floodplain, or lake | Clayey silt to silty clay to sand to sand and gravel |
| Marine Shoreline (TF) | Up to 2 | 1.5 \| 7.3 \| 10.2 | River / FTT, DP–Floodplain, TF | Sand, muddy sand, gravel |
| Fluvial and Deltaic Channels (River / FTT) | 10–60 | 1.4 \| 115 \| 270 | TF, DP–Floodplain, River / FTT | Sand and gravel to sand with silt interbeds |
| Lake | 5–8 | 14.7 \| 84.6 \| 88.2 | River / FTT | Sand and muddy sand |
| Windblown | 0.05–8 | 0.15 \| 4 \| 6 | Pleistocene glacial/glaciomarine sediments, pre-Quaternary basement rocks | Silt, silty sand, sand |
| Landfill | Highly variable | 0.62 \| 3.1 \| 10 | May overlie any other unit | Sand, gravel, till, crushed stone, and refuse |



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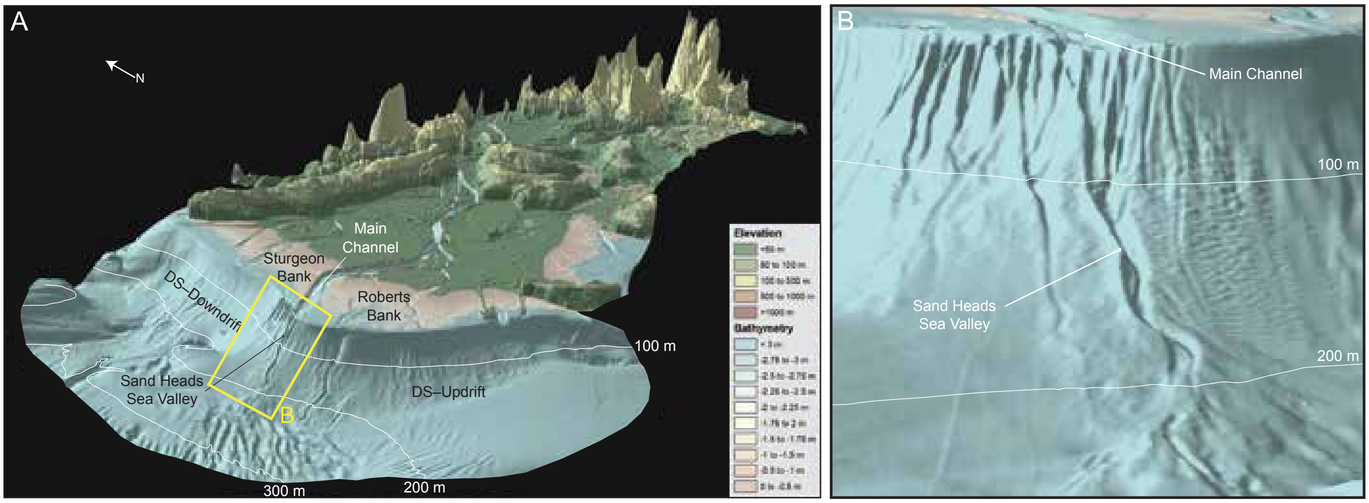

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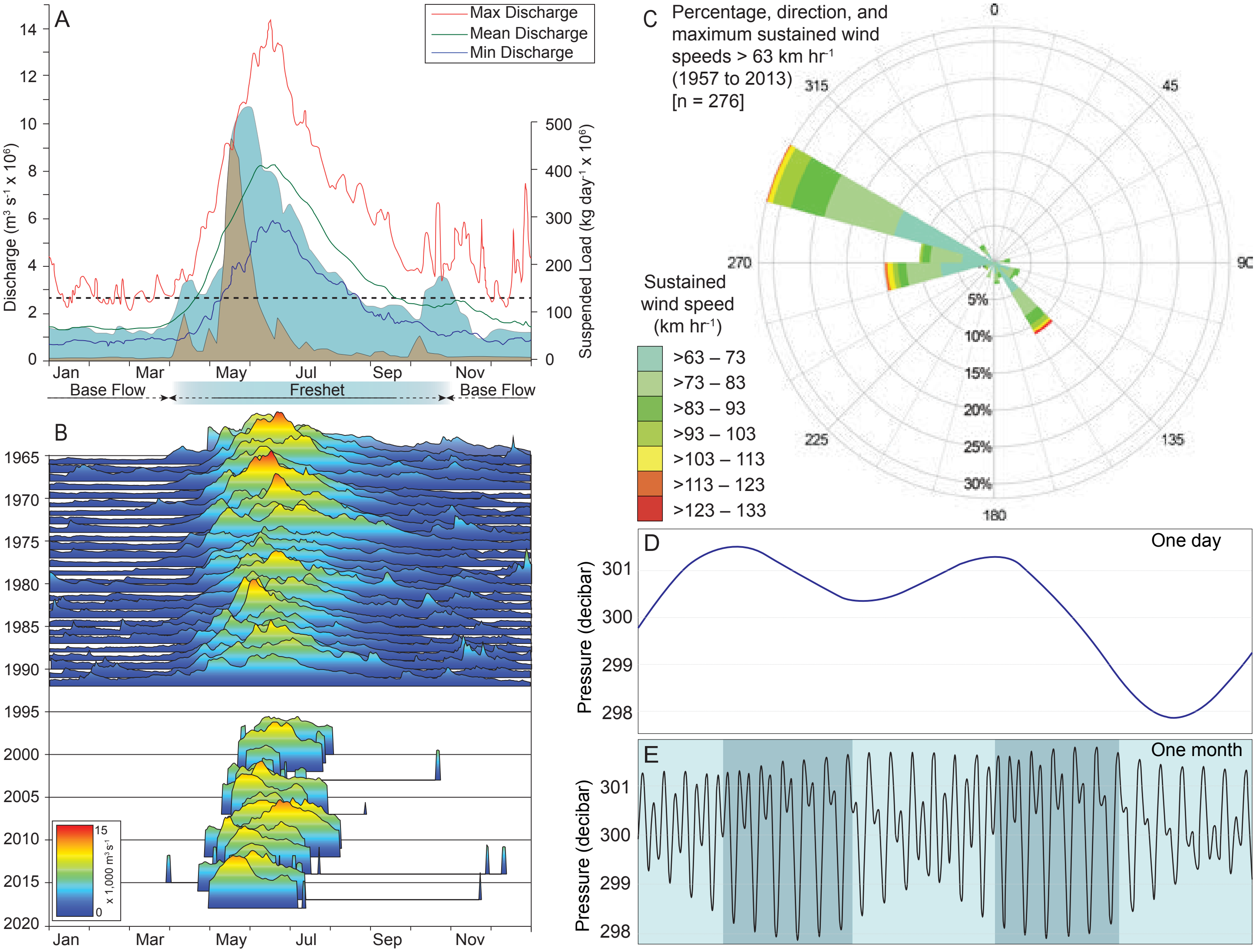

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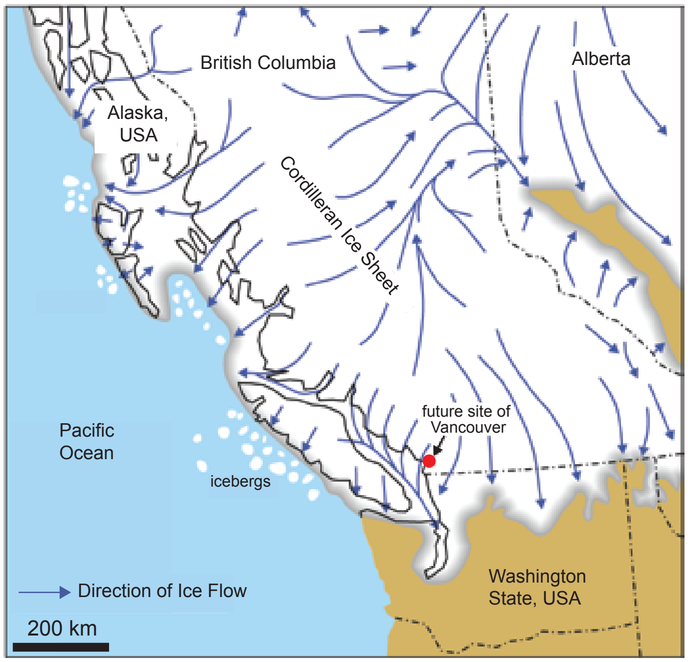

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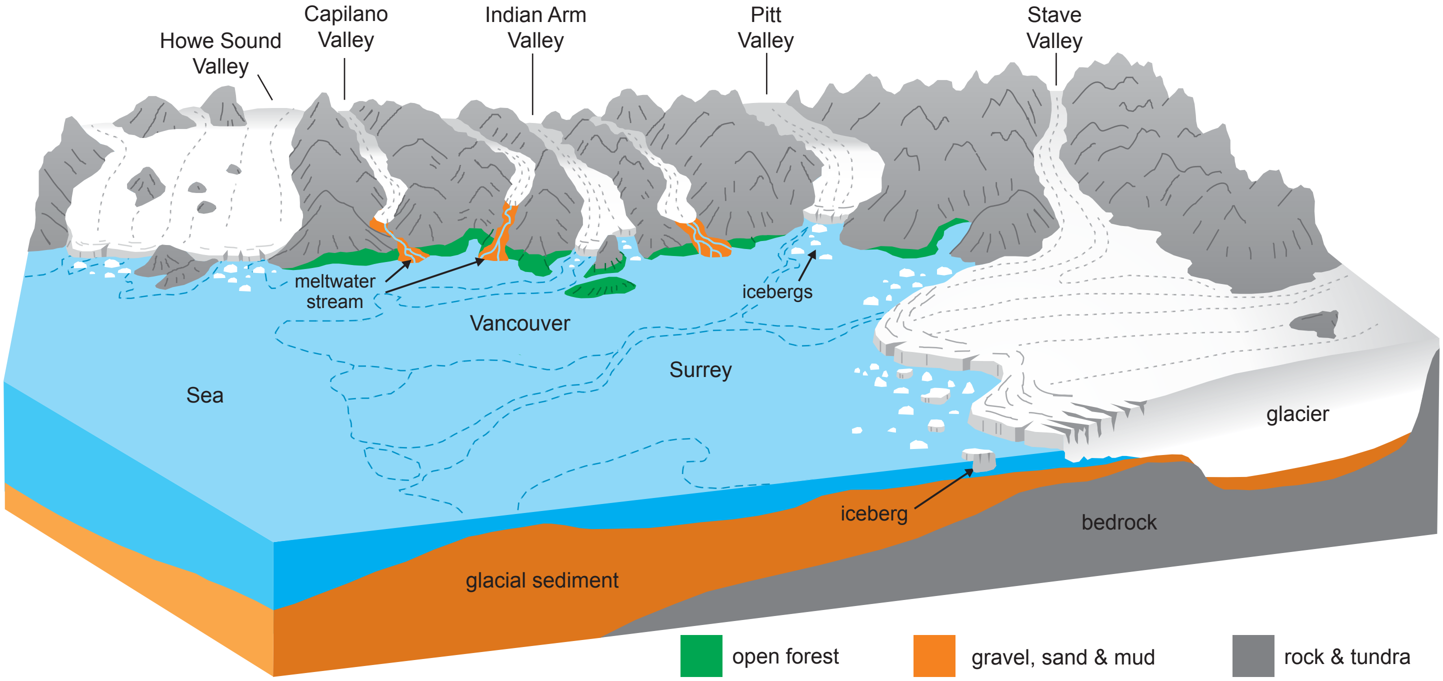

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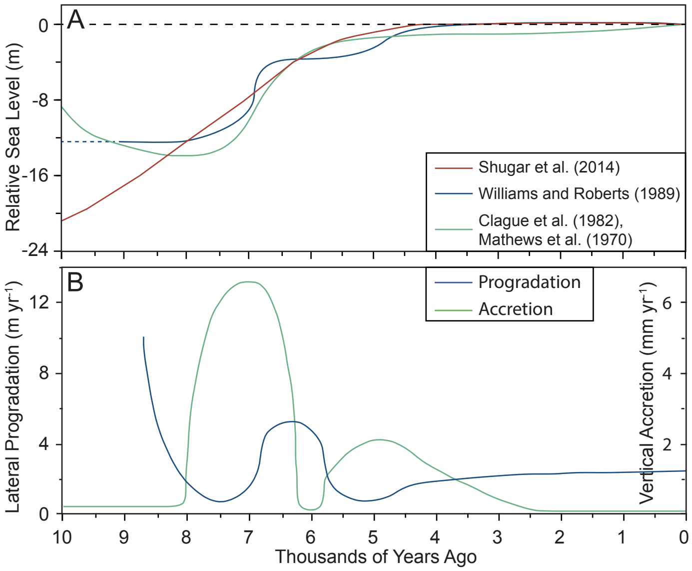

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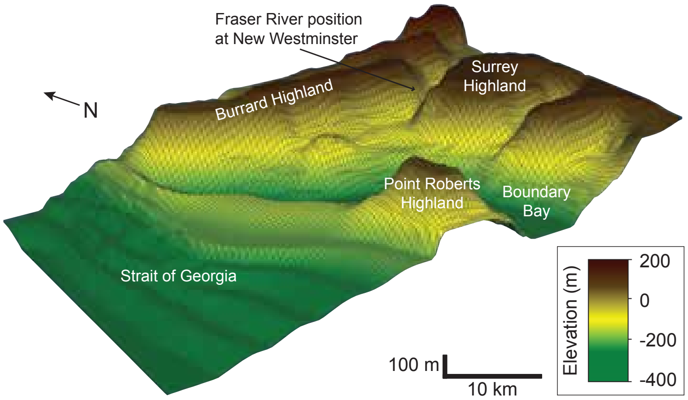

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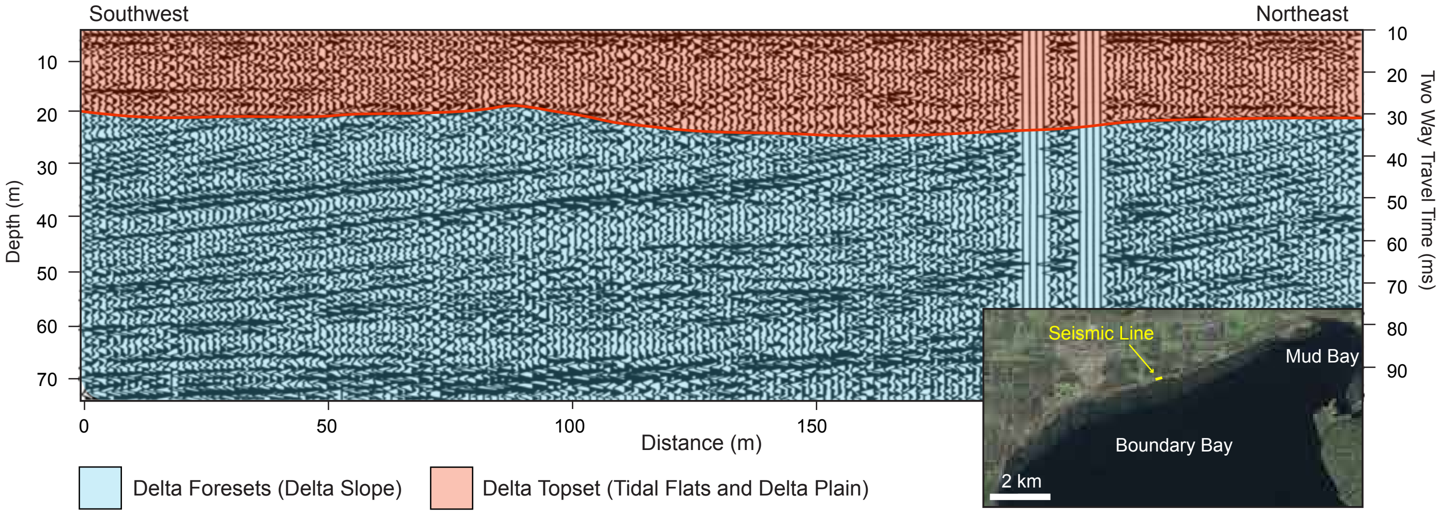

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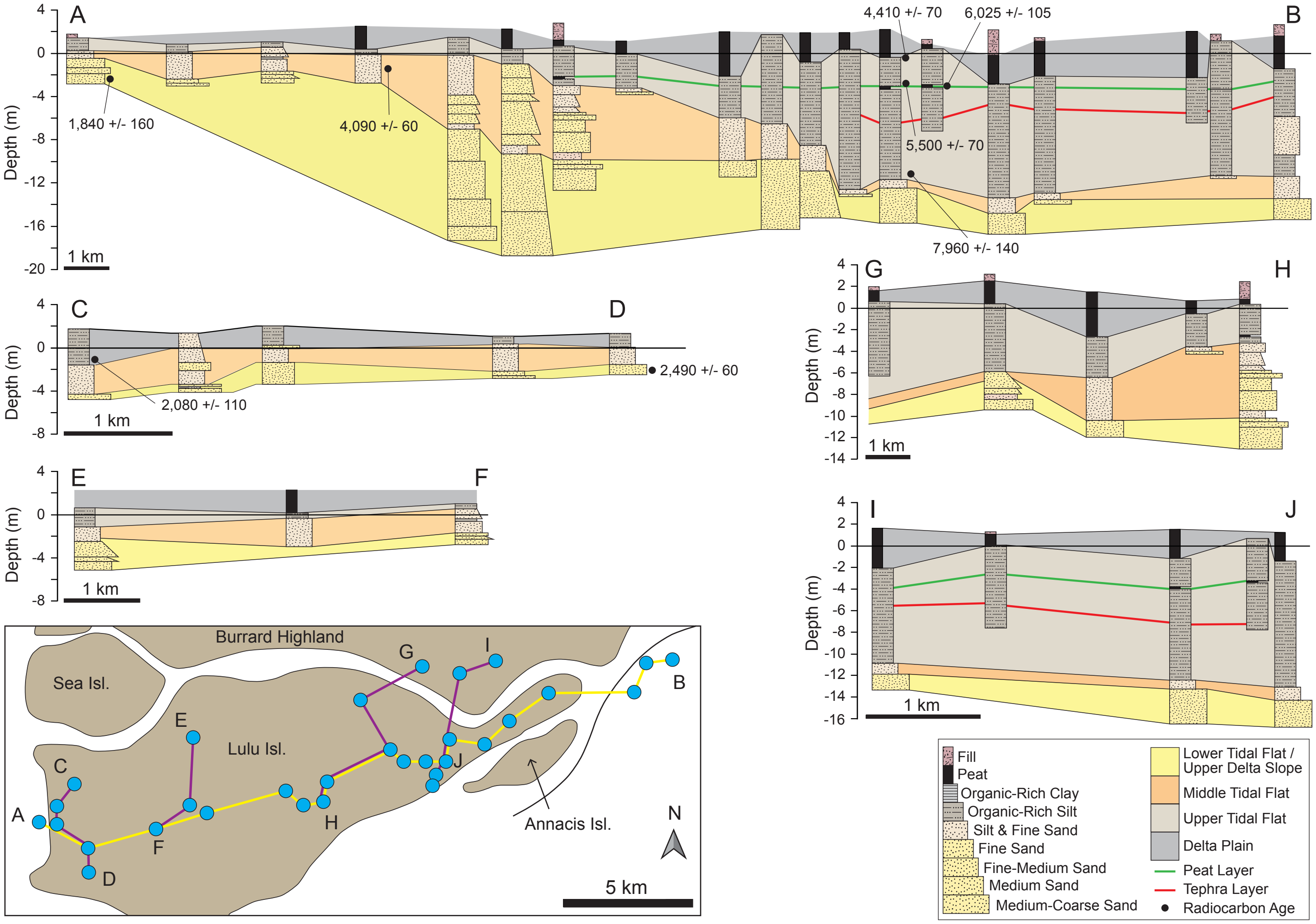

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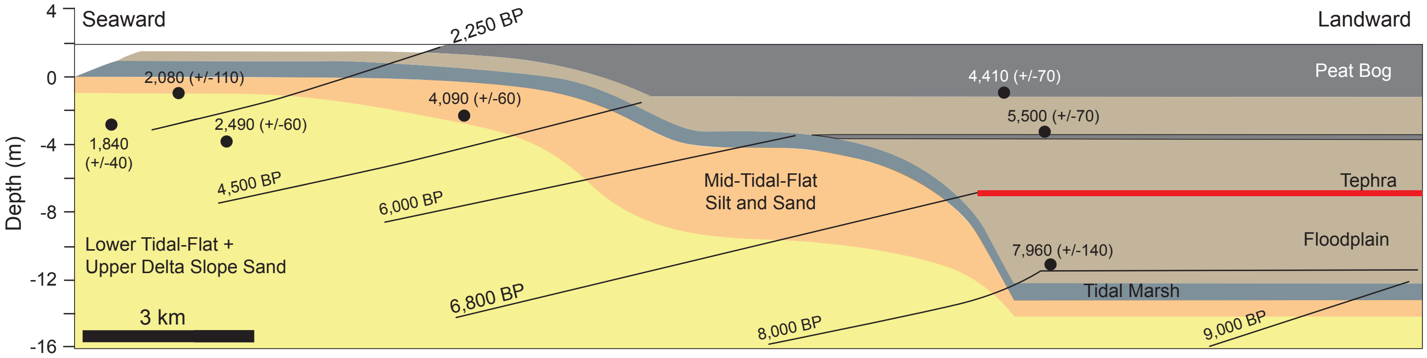

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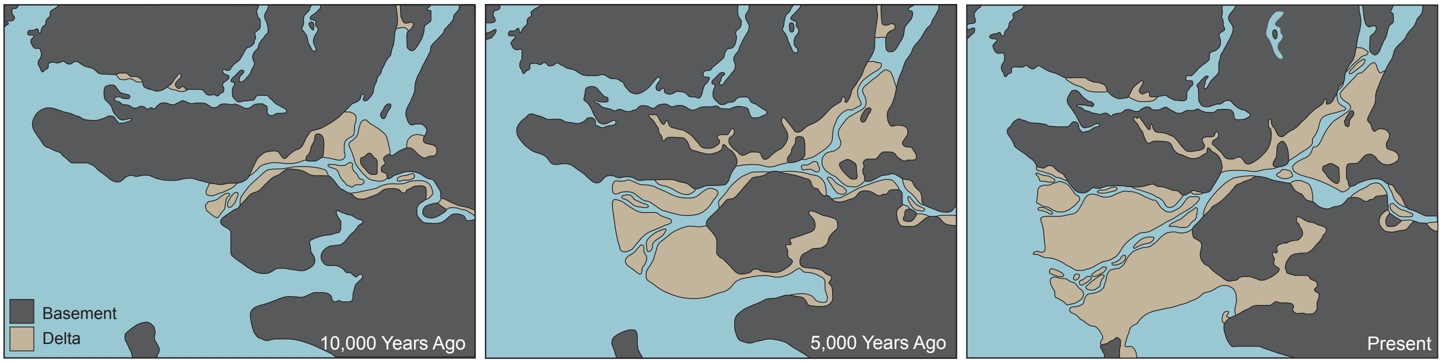

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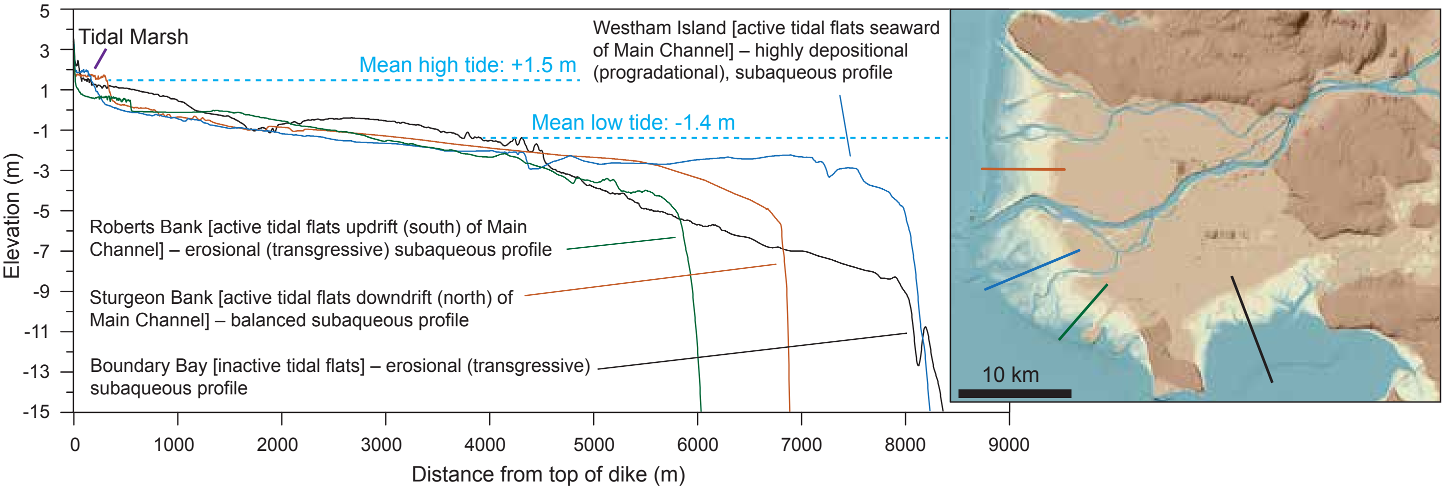

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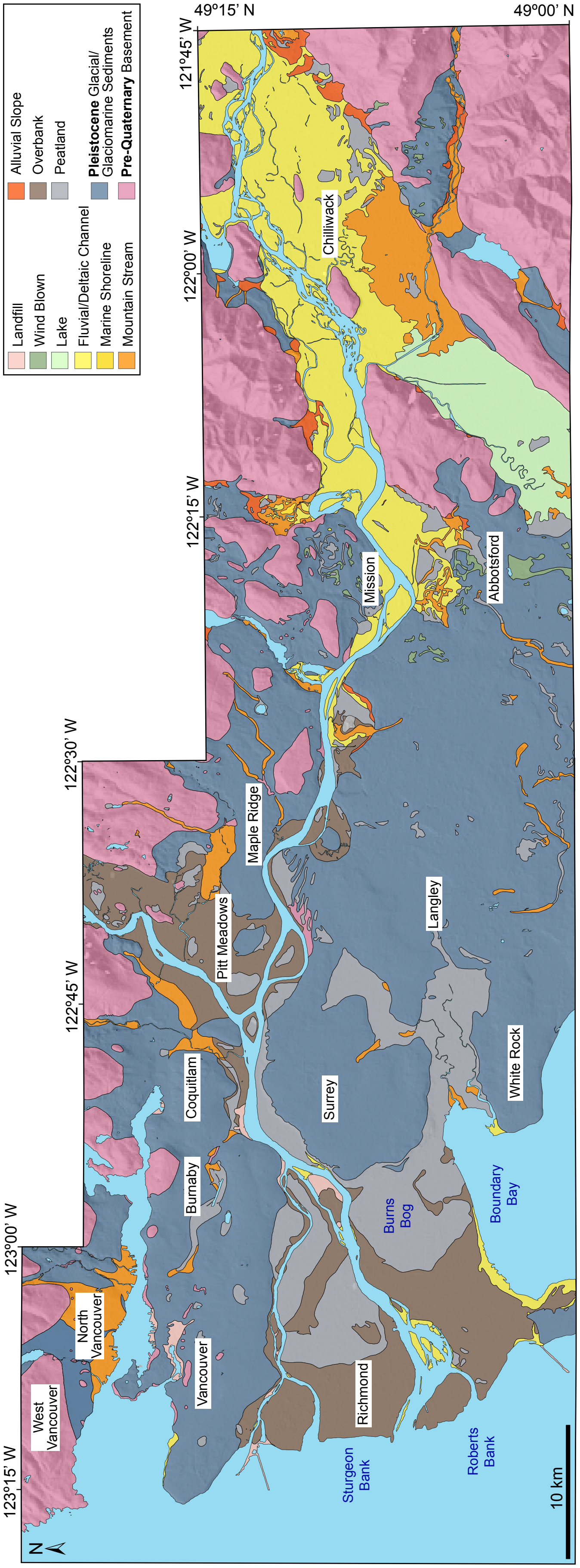

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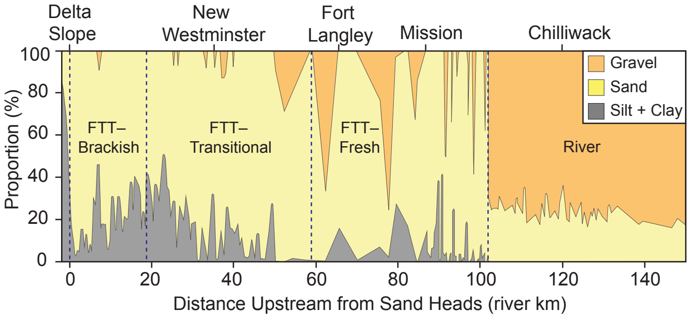

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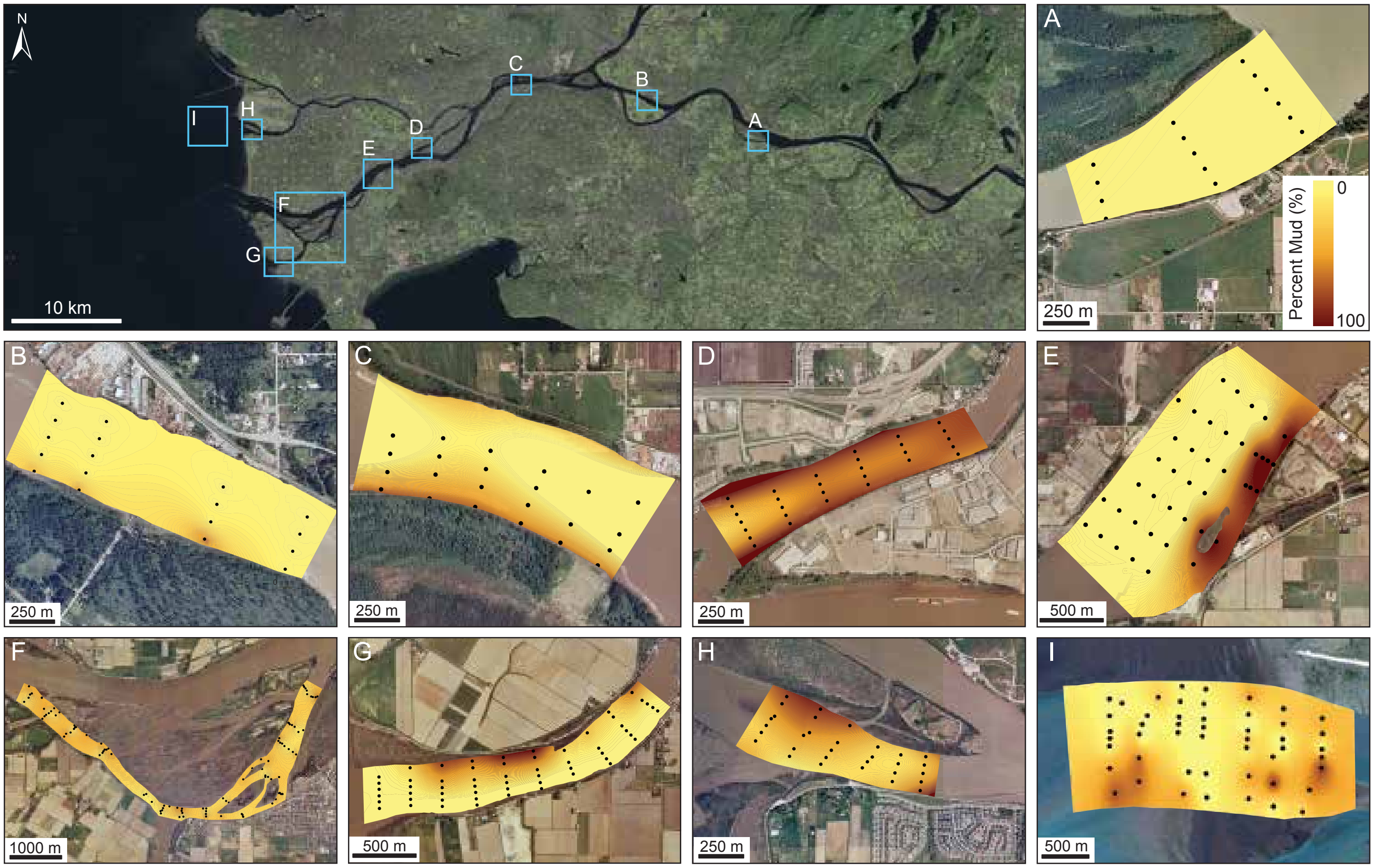

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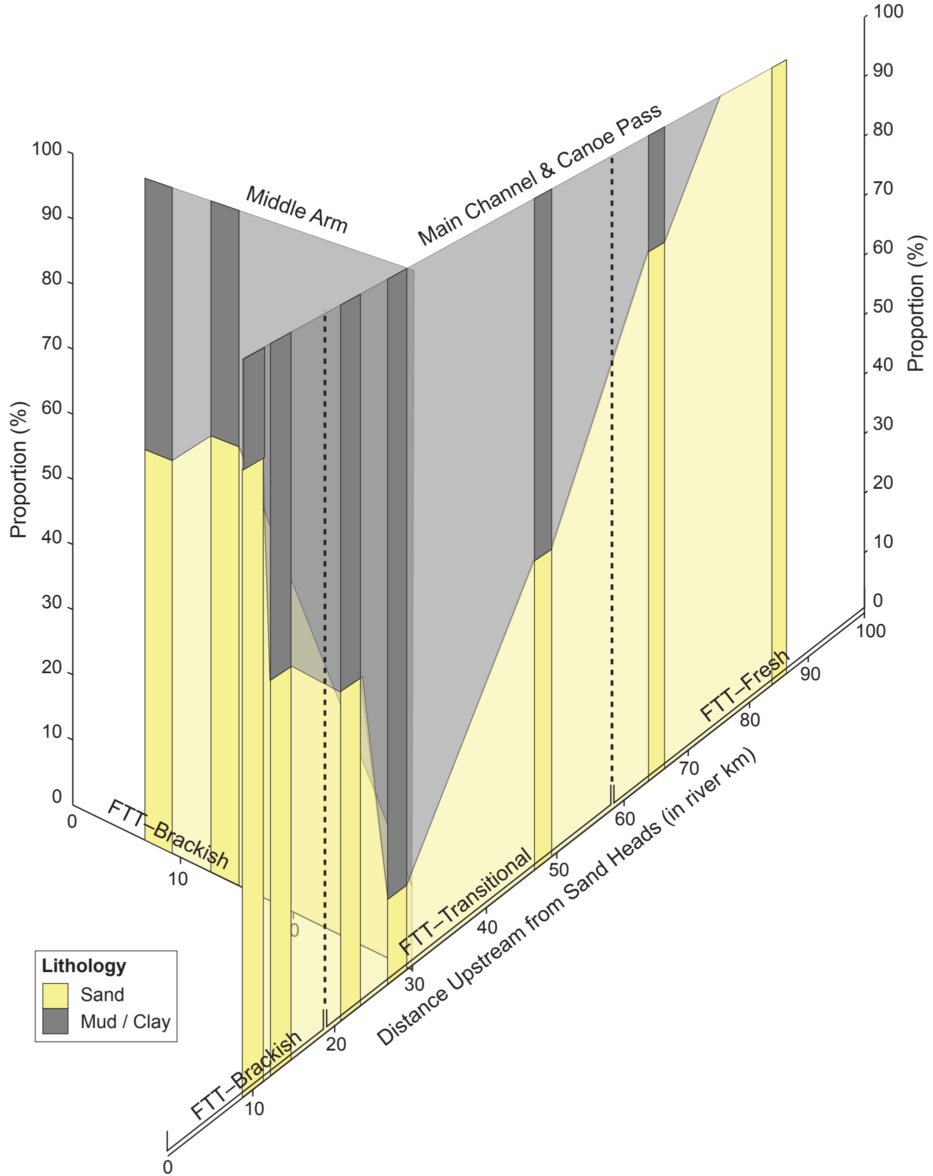

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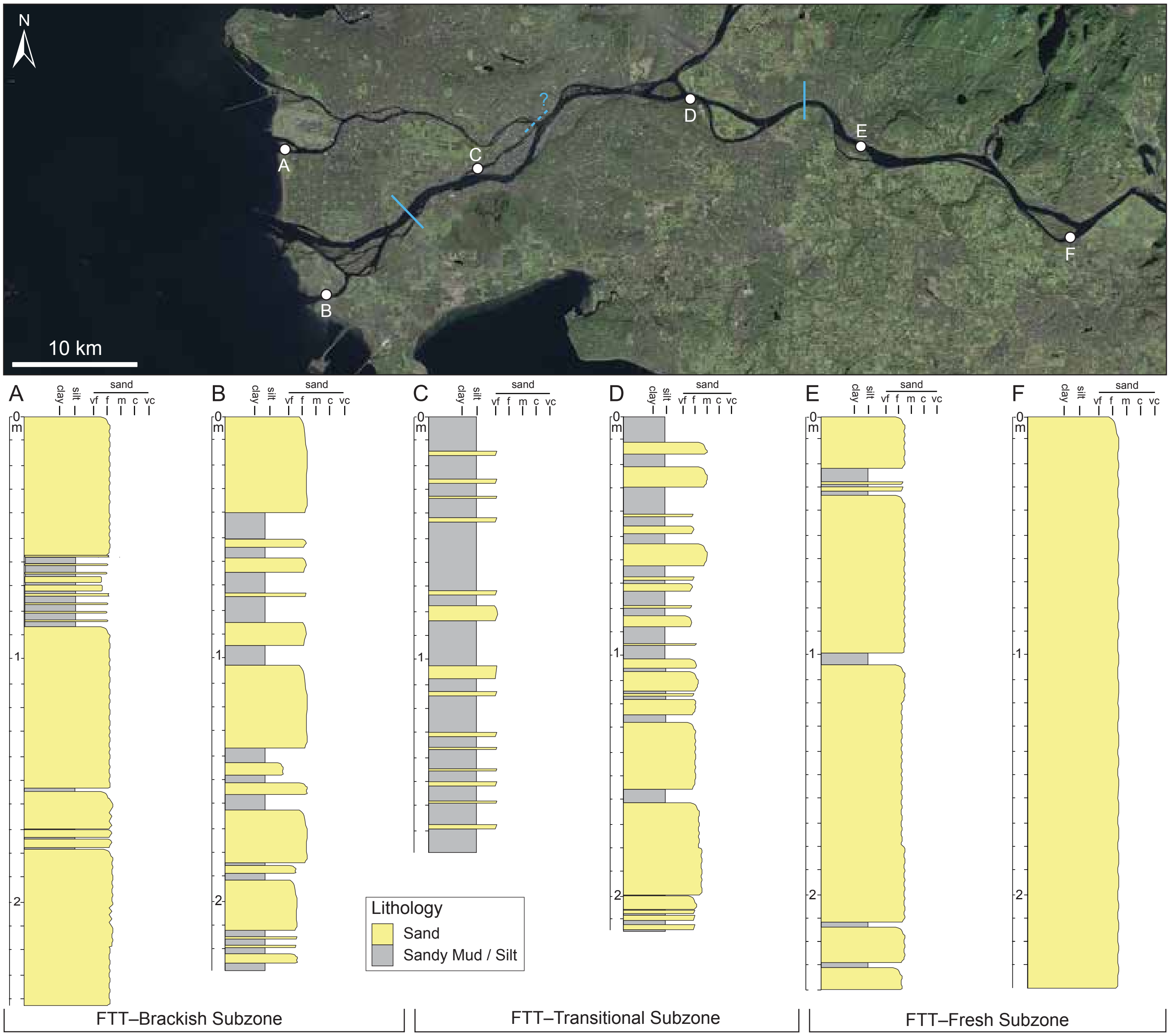

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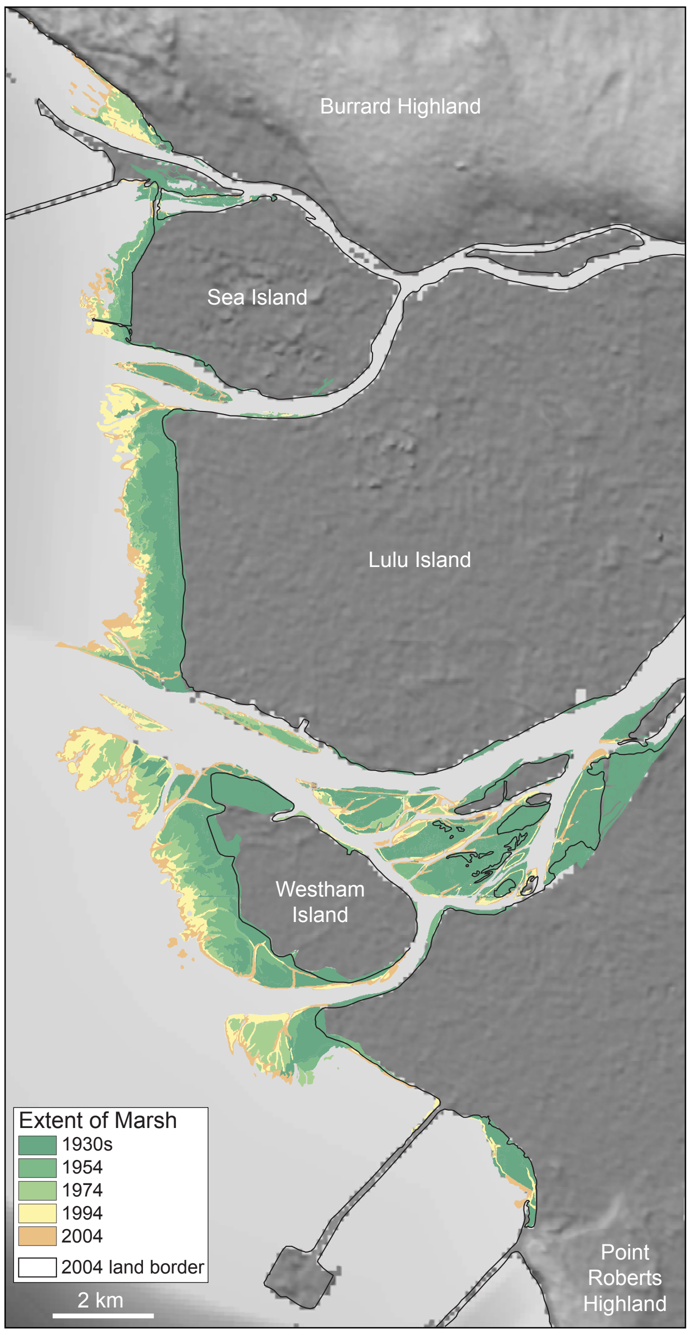

Figure 18 - one column

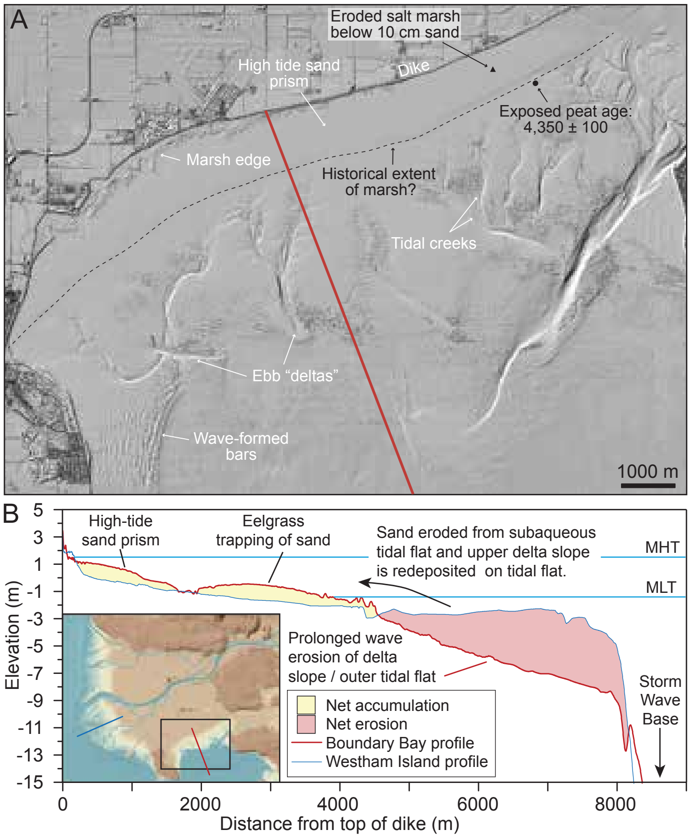

Figure 19 - one column

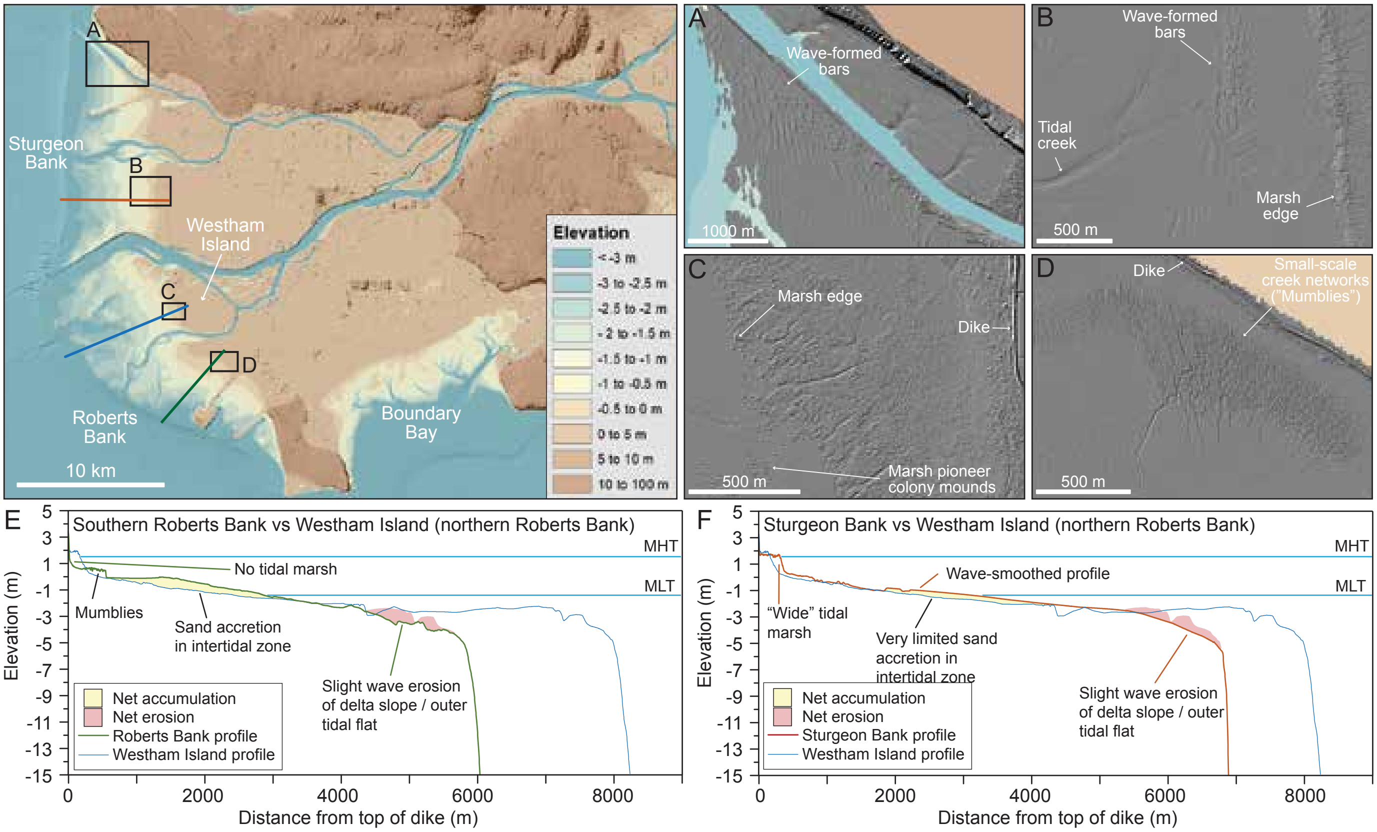

Figure 20 - two column

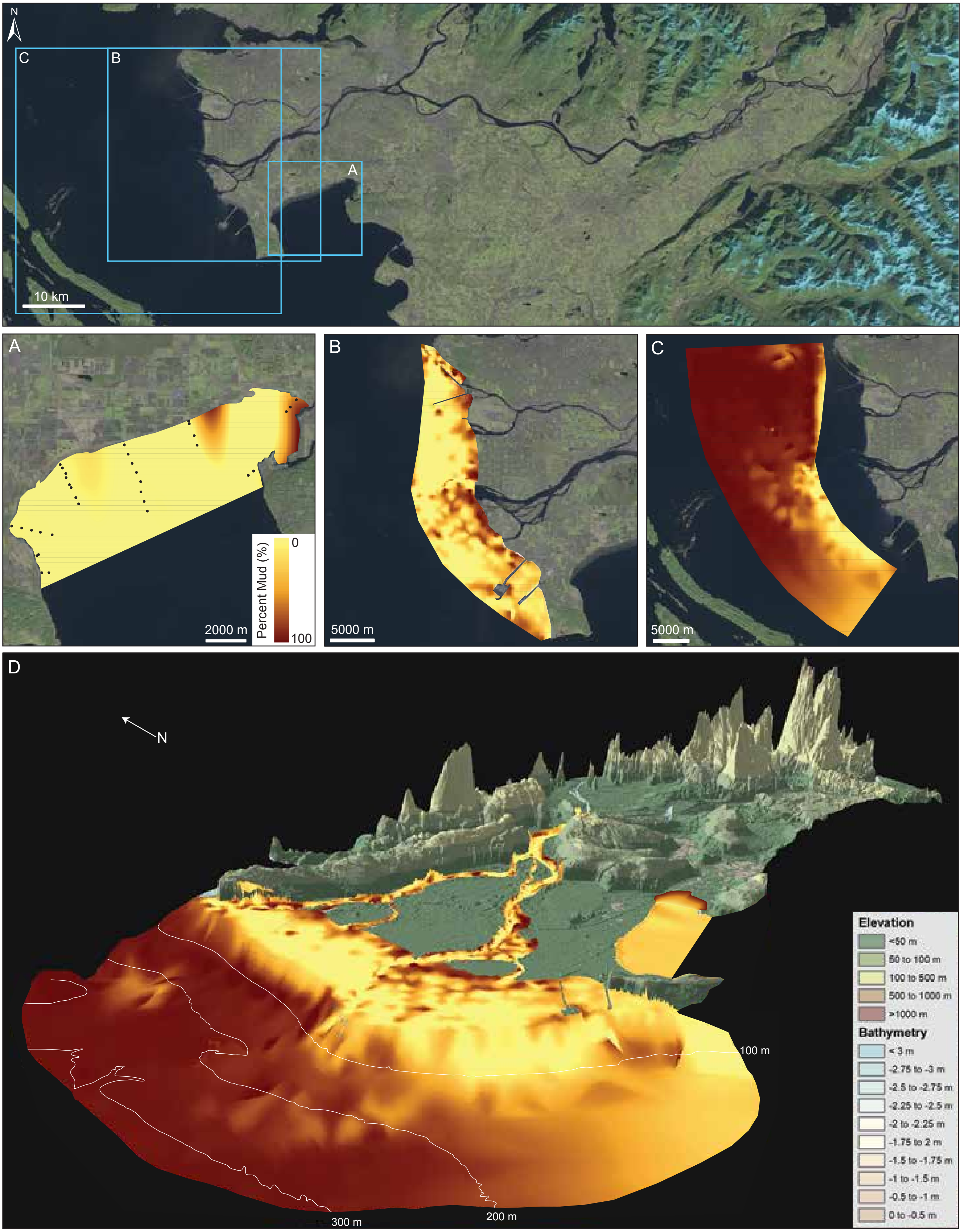

Figure 21 - two column

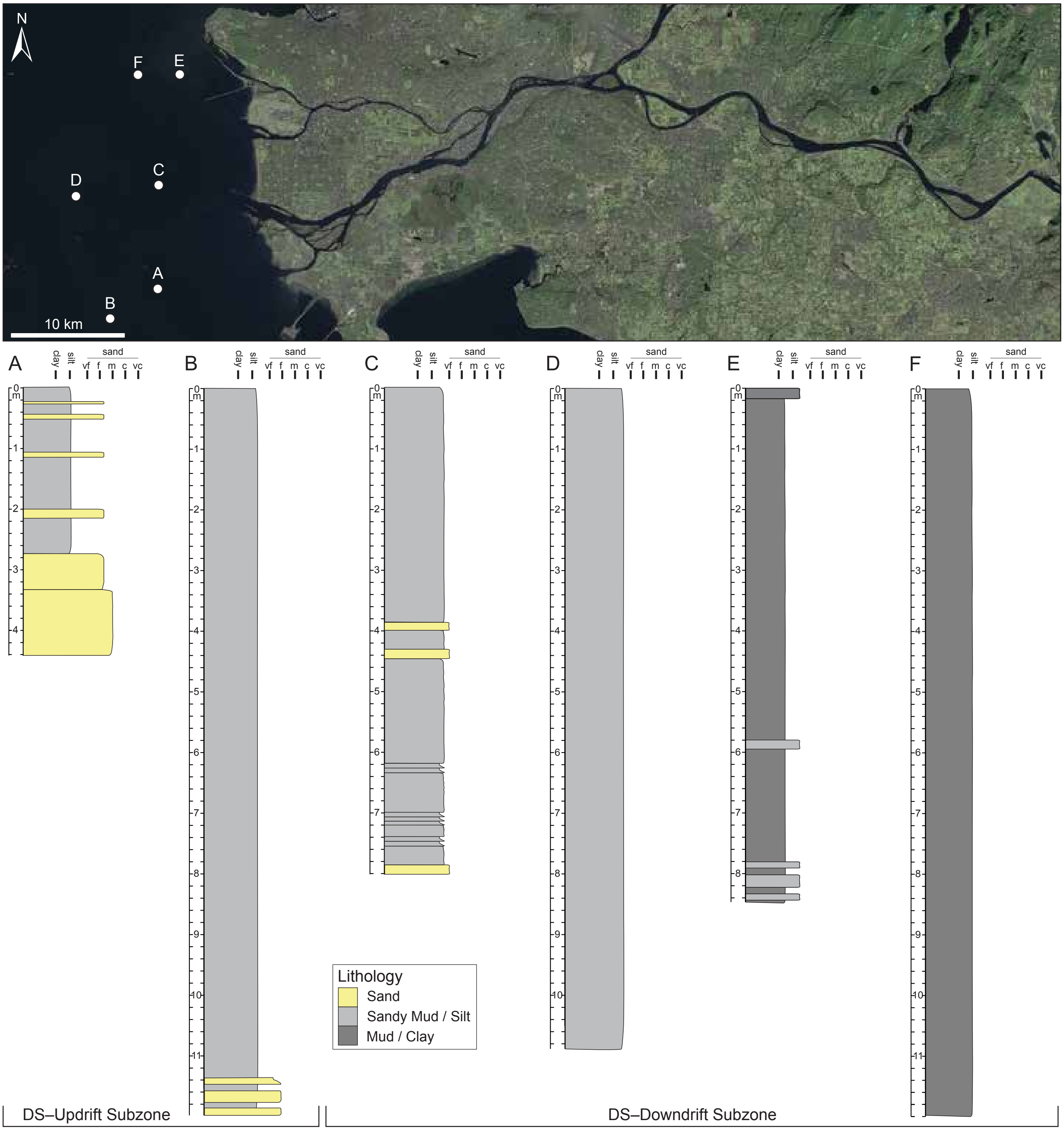

Figure 22 - two column

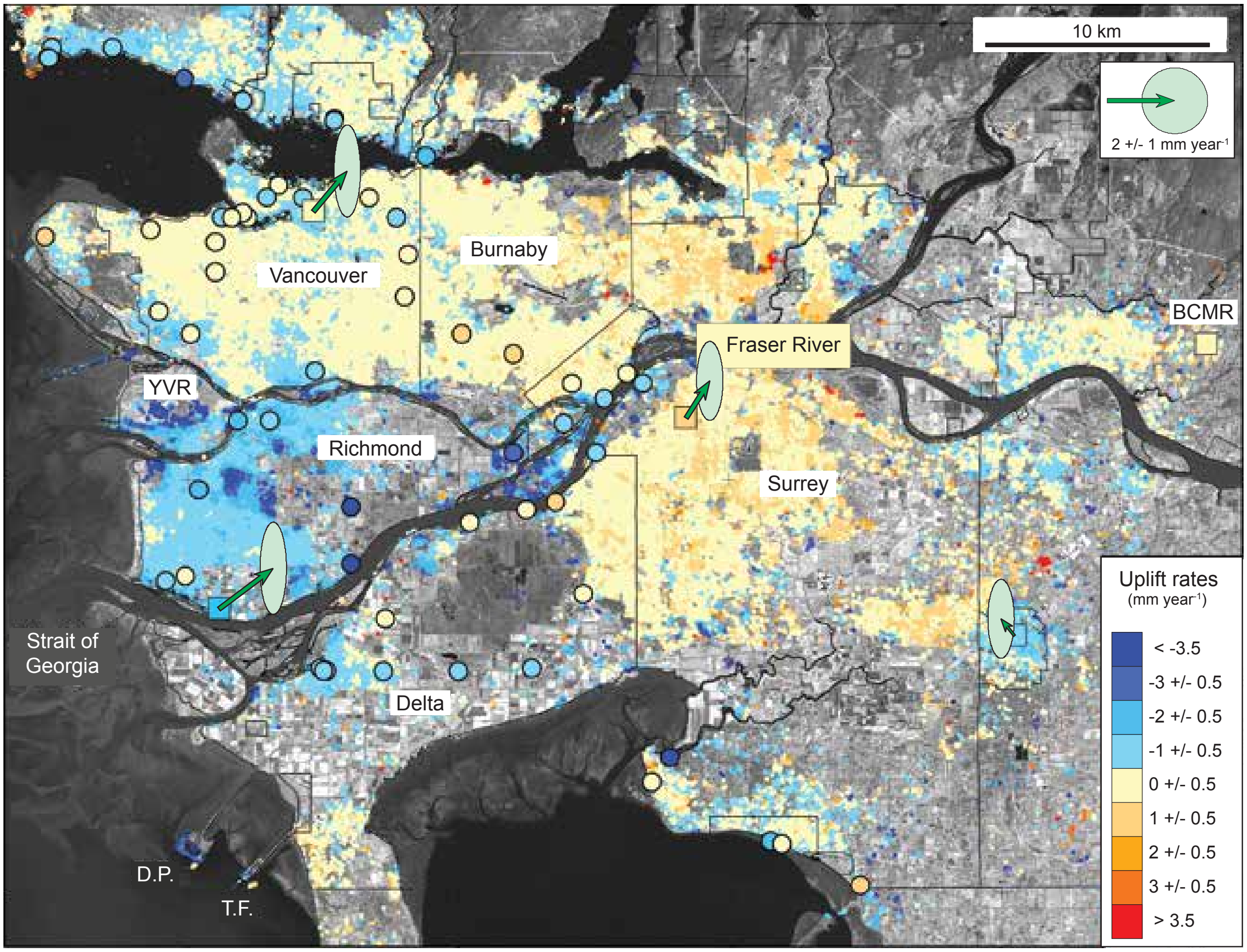

Figure 23 - two column

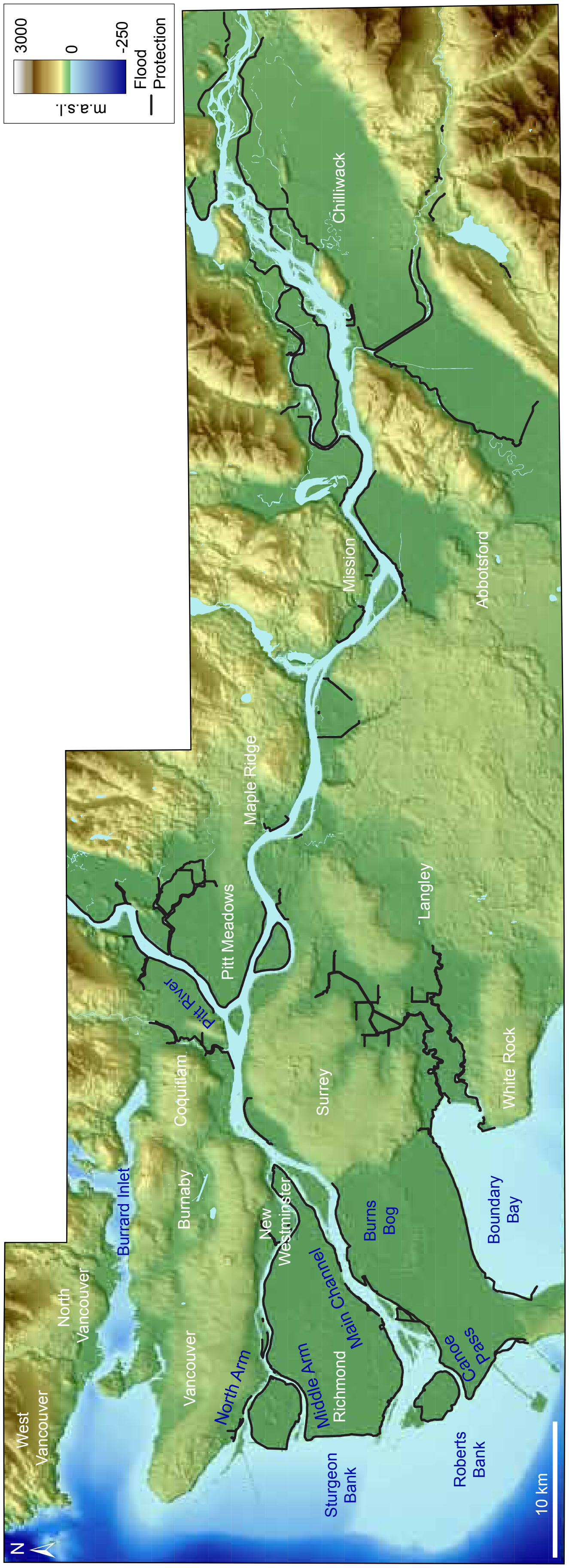

Figure 24 - one column or landscape

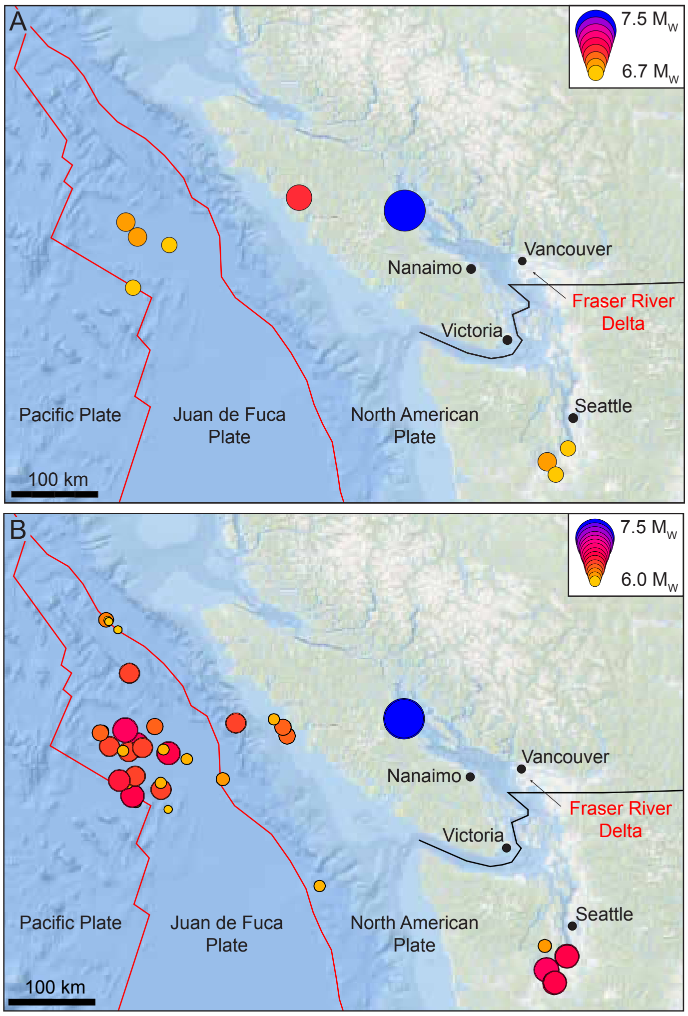

Figure 25 - one column