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

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ABSTRACT

The Fraser River Delta (FRD) is a large sedimentary system and home to Metro Vancouver, situated within the unceded territories of several First Nations. This review provides an overview of the geological evolution of the FRD, connecting hydrodynamic processes with sedimentary deposits across its diverse environments, from the river to the delta slope. The study emphasizes the implications of sedimentation and delta evolution for natural hazards and coastal/delta management, pinpointing knowledge gaps. Comprising four main zones – river, delta plain, tidal flats, and delta slope – the FRD is subject to several natural hazards including subsidence, flooding, earthquakes, liquefaction, and tsunamis. The delta plain, bordering the Fraser River's distributary channels, hosts tidal marshes and flats, including both active and abandoned areas. Active tidal flats like Roberts Bank and Sturgeon Bank receive sediment directly from the Fraser River, while abandoned tidal flats, like those at Boundary Bay and Mud Bay, no longer receive sediment. The tidal flats transition into the delta slope, characterized by sand in the south and mud in the north of the Main Channel. The FRD's susceptibility to hazards necessitates protective measures, with approximately 250 km of dykes shielding the delta plain from river floods and storm surges. Subsidence amplifies the impact of rising sea levels. Earthquakes in the region can induce tsunamis, submarine slope failures, and liquefaction of delta sediments, emphasizing the importance of incorporating sedimentation patterns and delta evolution into management strategies for sustainable urban development, habitat restoration, and coastal defence initiatives.

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 are transported from the continent to the shelf and deep sea. The sedimentary record of deltas records complex physical, chemical, and biological processes and interactions, and serves as an archive of changing environmental conditions and events. 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 (Syvitski and Saito, 2007; Haasnoot et al., 2012). Deltas are also significant diversity hot spots for flora and fauna (Ward et al., 1999; Glenn et al., 2001). Presently, the combined effects of human activity, changing climate, and rising sea level have negatively impacted many deltas by increasing their vulnerability to storms, floods, and erosion (Syvitski, 2008; Syvitski et al., 2009; Tessler et al., 2015; Vörösmarty et al., 2015; Szabo et al., 2016).

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., Sestini, 1989; Blum and Roberts, 2012; Bentley et al., 2016; Guo et al., 2021; Khan et al., 2021; Nittrouer et al., 2021; Paszkowski et al., 2021), but are still lacking for many systems, including the Fraser River Delta.

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 (Matson and Coupland, 1995; Murray, 2008; Lepofsky et al., 2009). The FRD partly underlies the metropolis of Vancouver (the third largest urban area 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 delta plain and serves ~26 million passengers and 300,000 flights annually.

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 (Butler and Campbell, 1987; Adams and Williams, 2004). Hundreds of millions of juvenile Pacific salmon reside in the estuary of the lower Fraser River (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. For example, protecting the delta plain from inundation due to rising sea level using “living dykes” (e.g., Readshaw et al., 2018) or expanding the tidal marsh through sediment enhancement (e.g., Maxwell, 2021) 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 Holocene geological evolution and sedimentary system of the FRD. We link hydrodynamic processes with their corresponding sedimentary deposits 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 and coastal management. 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.

2. SYSTEM AND SETTING

2.1 Drainage Basin and Physiography

The Fraser River has a catchment area of ~230,000 km^2 and 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. 1). 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 is situated at elevations between 4 and 6 m above mean sea level and extends 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 landward (east) to seaward (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 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 conspicuous feature of the FRD is the broad (5–8 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) which is the approximate depth at which the flat-lying tidal flats transition to the steeping dipping delta front (i.e., the hinge point). Roberts Bank and Sturgeon Bank are intertidal and partly subtidal flats located south and north of the 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 an influence 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 the contiguous 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 (Kellerhals and Murray, 1969; Engels and Roberts, 2005). The much smaller Serpentine and Nicomekl rivers deliver a small volume of sediment to Mud Bay.

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 bottom 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) and decreases gradually towards the floor of the Strait of Georgia (Hart et al., 1992b; Hart and Barrie, 1995; 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; Mathews and Shepard, 1962; Hart et al., 1992a,b; Evoy et al., 1993; Hill, 2012; Ayranci and Dashtgard, 2016). 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 (Hart et al., 1992a; Hart and Barrie, 1995; Carle and Hill, 2009; Hart et al., 2013).

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 typically driven by seasonal snowmelt in the river catchment and is referred to as the freshet. Peak freshet flows 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 lower 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 (Hughes and Ages, 1975; Ages, 1979; 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 between 70 river km and ~100.5 river km inland from the Strait of Georgia to Yaalstrick Island (Fig. 1A; Venditti and Church, 2014).

Storms with high sustained wind speeds (Fig. 3C) are concentrated mainly in the winter months. Storm waves approach mainly from the northwest and west, with a secondary approach vector from the southeast (Fig. 3C; Ayranci and Dashtgard, 2016). These waves, while moderate by oceanic standards, impact sediment distributions on the tidal flats and rarely overtop dykes.

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 (McLean and Tassone, 1990; Kostaschuk et al., 1998). 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 (McLaren and Tuominen, 1996; Houser and Hill, 2010a). A substantial proportion of that sand is subsequently transported offshore by sediment gravity flows and slope failures (Kostaschuk et al., 1992, 1995; Hill et al., 2008; Ayranci et al., 2012; Hill and Lintern, 2022). 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 et al., 1989; Kostaschuk, 2002) and abundant mud is deposited in the channels, on the tidal flats, and on the delta slope (Sisulak and Dashtgard, 2012; La Croix and Dashtgard, 2014).

3. QUATERNARY EVOLUTION AND STRATIGRAPHY

3.1 Pleistocene Context

The FRD is 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 extended 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; Clague and James, 2002).

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 (Friele and Clague, 2002).

The lithosphere was displaced downward during growth of the last Cordilleran ice sheet (Clague et al., 1983; James et al., 2000; Clague and James, 2002), and 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). Post-glacial isostatic rebound drove major changes in relative sea-level (RSL) along the coast (Fig. 6A), and this, in turn, impacted the evolution and architecture of the FRD.

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 (Roberts et al., 1985; Luternauer et al., 1986; Williams, 1988; Pullan et al., 1989; Williams and Roberts, 1989; Williams and Roberts, 1990; Williams and Luternauer, 1991; Monahan et al., 1993a; Hutchinson et al., 1995; Clague et al., 1998; Hunter et al., 1998;

Monahan, 1999). A prominent unconformity, 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 locally overlain by up to several hundred metres of Pleistocene diamict, sand, and gravel deposited mostly in glaciomarine and marine environments. The top of the late Pleistocene 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).

Holocene delta deposits are characterized by classic progradational and downlapping clinothems, with topset, foreset, and bottomset components (Fig. 8; Jol and Roberts, 1988; Pullan et al., 1989; Clague et al., 1991; Jol and Roberts, 1992; Pullan et al., 1998). 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, 1998; Monahan et al., 1993a,b). 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, 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; Williams and Luternauer, 1991; Monahan et al., 1993a,b, 1995; Hutchinson et al., 1995; Clague et al., 1998). 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). The topset contains the 7,700-year-old Mazama tephra and includes the domed peat bog at Burns Bog (Hebda, 1977; Clague et al., 1983).

Underlying the topset is up to ~165 m of dipping foreset strata deposited on the delta slope (Fig. 8; Pullan et al., 1989, 1998; Clague et al., 1991; Monahan et al., 1993a). The foresets comprise mainly bioturbated mud and sand (Christian et al., 1994; Dallimore et al., 1995;

Ayranci and Dashtgard, 2013, 2016; Ayranci et al., 2014). Erosionally based fining-upward beds are interpreted as sediment gravity flow deposits (Ayranci et al., 2012; Stacey, 2014; Lintern et al., 2016) and coarsening-upward packages are thought to record annual and interannual deposition seaward of the river mouth. The foresets are sandier at shallow-water depths and become muddier offshore (Barrie and Currie, 2000; Ayranci and Dashtgard, 2016).

Radiocarbon ages on 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 and began to onlap 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 by about 4,500 years ago (Fig. 11B; Clague et al., 1991; Hutchinson et al., 1995). Following closure of the tidal channel between Point Roberts and the FRD, the locus of deposition switched completely from southward to westward (Fig. 11C; 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

The most recent compilation of relative sea-level data for the FRD indicates an initial rapid postglacial RSL fall of ~200 m in response to isostatic uplift near the Last Glacial Termination. RSL reached 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.

Delta progradation rates have been estimated for different time periods during the Holocene and using different datasets. Williams and Roberts (1989) estimate that the FRD 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). They further estimated that the progradation rate slowed to approximately 3.8 m year^{-1} between 6,200 and 5,800 years ago and then to 2.4 m year^{-1} over the past 2,250 years. Johnston (1921) used marine chart contours to estimate that between 1859 and 1919 the average rate of advance across the entire western delta front was 3.1 m year^{-1} with the strongest progradation north of the Main Channel and negligible progradation to the south. In 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 (unpublished NRCan 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 (Hart et al., 1992b, 1998; Hart and Barrie, 1995; Kostaschuk et al., 1998; Carle and Hill, 2009).

Measurable present-day progradation is limited to the area extending about 1 km 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).

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 et al., 2012; Dashtgard and La Croix, 2015; 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 (Sisulak and Dashtgard, 2012; La Croix and Dashtgard, 2014).

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 are subdued in that channel relative to other distributaries (Dashtgard et al., 2012; La Croix and Dashtgard, 2014; Dashtgard and La Croix, 2015; La Croix and Dashtgard, 2015). Canoe Pass (5%), Middle Arm (5%) and North Arm (5%) are more strongly impacted by tides and brackish water (Sisulak and Dashtgard, 2012; Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2015).

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 (Hughes and Ages, 1975; Ages and Woolard, 1976; Ages, 1979; Kostaschuk et al., 1989; Kostaschuk and Atwood, 1990). 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 (Hughes and Ages, 1975; Ages and Woolard, 1976; Ages, 1979; Chapman, 1981; Chapman and Brinkhurst, 1981; Kostaschuk et al., 1989; Kostaschuk and Atwood, 1990; Johnson and Dashtgard, 2014).

Shifts in hydrodynamic forcing impart a predictable pattern in surface sediment distribution within channels. In the river and upstream of tidal influence (i.e., “River”; Fig. 1; Table 1), channel sediments comprise ~20–30% sand and ~70–80% gravel (Fig. 12; Venditti and Church, 2014). At the transition downstream into the tidally influenced reach of the Fraser River (i.e., seaward end of 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 (GS_{avg}) of mud through the FTT is 0.02 mm (medium silt), and the GS_{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. 13; La Croix and Dashtgard, 2015). There is a locus of mud deposition on channel bars near New Westminster where the Fraser River bifurcates (Fig. 14; La Croix and Dashtgard, 2014). In the FTT–Brackish subzone, most channel bars exhibit a mud-sand-mud profile from upstream to downstream (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., Smith, 1985; Dashtgard et al., 2012; Sisulak and Dashtgard, 2012; Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2014, 2015; La Croix et al., 2014; Dashtgard and La Croix, 2015). 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. 15E–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. 15C–D). Sand layers preserved in vertical successions in the FTT-Transitional subzone are current ripple cross-laminated and occur in either upper subtidal/lowermost intertidal positions or towards the base of the channel. Muddy deposits reflect the impedance of river flow by tidal incursion and potentially mud flocculation in brackish water (Sutherland et al., 2014; La Croix and Dashtgard, 2015). 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. 15A–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) comprises 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 dykes 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; Figs. 1B–C and 9) 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; Armstrong and Hicock, 1979, 1980; Luternauer et al., 1998). Peatland (e.g., Burn’s Bog) 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 cumulative plant growth atop generally poorly drained sediment and with hindered organic decomposition (Armstrong and Hicock, 1979, 1980; Armstrong, 1980a,b). Peat deposits range from sphagnum- to sedge-dominated depending on geographic location and the degree of soil drainage (Hebda, 1977; Styan and Bustin, 1983; Lowe and Bustin, 1985).

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; Figs. 1A and 16). 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 (Figs. 1B and 16). 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 dykes in the twentieth century, much of the delta coastline was characterized by tidal marsh located at the transition between the delta plain and the unvegetated tidal flats (Vancouver, 1798; Hayes, 1947; Church, 2017). Areas of tidal marsh remain in front of the dykes on Sturgeon Bank, Roberts Bank, Boundary Bay, and Mud Bay (Figs. 1B, 16 and 17; Kellerhals and Murray, 1969; Swinbanks and Murray, 1981; Hales, 2000; Church and Hales, 2007). 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.; Hutchinson, 1982; Adams and Williams, 2004; Bode, 2019). These species 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*; Yamanaka, 1975; Bode, 2019).

Sediment in the tidal marsh ranges from organic-rich clay and silt to fine sand, with mean grain size generally decreasing landward. This pattern of sediment distribution is a function of reduced wave and tidal energy as bed elevation increases, as well as increased trapping of fines by vegetation during submergence (Williams, 1988).

Williams and Hamilton (1995) used ^{137}Cs to measure sedimentation in the marshes that fringe Lulu Island, landward of Sturgeon Bank (Fig. 1A), and determined that between 1964 and 1991 the marsh there aggraded at rates of 2.6–8.5 mm year^{-1}. The highest rate of aggradation occurred in the middle marsh (8.5 mm year^{-1}), and the lowest aggradation rates (2.6–3.7 mm year^{-1}) were recorded in the low marsh. The upper tidal marsh aggraded at 6.1–6.3 mm year^{-1}. Williams and Hamilton (1995) also showed a 51% decrease in marsh aggradation rates from 1964–1991 relative to 1954–1964. They suggest that this reduction in sedimentation is the combined result of erosion and reduced fluvial sediment input. More recently, Marijnissen and Aarninkhof (2017) show net elevation loss of 0.25–0.5 m over much of the middle to high marsh between 1985 and 2015 and across Sturgeon Bank and Westham Island (-8.3 to -16.7 mm year^{-1}; Fig. 17B). However, they caution that elevation change was derived from observed inundation patterns on satellite imagery, and vegetation can obscure the detection of water beneath it; consequently, part of the estimated elevation loss is probably due to loss of vegetation rather than sediment erosion (Marijnissen pers. comm.).

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 the early 1990s (24 x 10^{6} m^{2}) (Fig. 17A; Hales, 2000; Church and Hales, 2007). Most of this expansion occurred near the Fraser River distributaries where they transect the tidal flats. Church and Hales (2007) also suggest marsh expansion between 1994 and 2004; however, more recent work has shown that the tidal marsh, and mainly the low marsh, has shrunk significantly over the past 30–40 years (Balke, 2017; Marijnissen, 2017; Marijnissen and Aarninkhof, 2017; McDonald, 2018). Balke (2017) estimates that 1.6 km^{2} of low marsh was lost on Sturgeon Bank between 1989 and 2011. Marijnissen and Aarninkhof (2017) concur and report 200 m of landward recession of the marsh edge between 1985 and 2015 and a loss of 1.5 km^{2} of marsh area. They also report the conversion of 0.4 km^{2} of marsh to tidal flat internal to the tidal marsh on Westham Island (Fig.

17C). Both deflation of the marsh surface and edge erosion is consistent with marine transgression driven by relative sea level rise.

Marsh is absent along the southern portion of Roberts Bank except for a small section of artificially maintained salt marsh located behind the dyke. Marsh is absent 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 to 4,350 ± 100 years ago (Fig. 18; Kellerhals and Murray, 1969), and old marsh deposits were encountered below 10 cm of sand approximately 430 m seaward from the dyke (Fig. 18A; Dashtgard, 2011a). As well, a peat situated at 1.5 m depth in a borehole directly landward of the dyke returned an age of 4,240 ± 60 years ago and contains mainly freshwater diatoms (Hutchinson et al., 1995). The radiocarbon ages, old marsh deposits below the tidal flat, and freshwater peat in a more proximal position indicate that the marsh in Boundary Bay was much more areally extensive 4,500 years ago, and is now being actively transgressed. The transition from progradation to transgression probably correlates to the onlapping of the Fraser River Delta with the Point Roberts Highland ~4,500 year ago and the effective termination of sediment delivery form the Fraser River to Boundary Bay.

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, especially the Main Channel (McLaren and Ren, 1995; McLaren and Tuominen, 1996; Hart et al., 1998; Houser and Hill, 2010a; Ayranci et al., 2012). 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 although total sediment volumes are low (Fig. 19). 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 the coarser sediment load bypassing the tidal marsh and tidal flats (McLaren and Tuominen, 1996). Sediment supplied to areas of the tidal flats near the jetties is limited to fine silt and clay advected in suspension back onto the flats during high tide and from the surface plumes at the mouths of the distributary channels.

Sediment supply to the active tidal flats is also influenced by asymmetric tidal currents (dominated by stronger flood flows) on the delta slope, which carry plume sediment in a net northward direction ("downdrift") of the Main Channel (Hart and Barrie, 1995; McLaren and Tuominen, 1996; Barrie et al., 2005). 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 (Hill et al., 2008; Ayranci et al., 2012). Sediment on the outer tidal flats is also mobilized and moved onshore by storm waves (Fig. 19; Houser and Hill, 2010a).

The jetty that confines the Main Channel, dredging, and net northward tidal flow have significantly altered delivery of sediment to the active tidal flats, which is reflected in their shore-normal profiles (Figs. 16 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, consequently the intertidal and subtidal flats are widest here, reaching nearly 8 km seaward of the dyke (Fig. 16). 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. 19E), 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. 19F). 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 300–500 m of the tidal marsh (GS_{avg} = 0.045 mm; coarse silt), and the mud transitions seaward into dominantly medium-grained sand (GS_{avg} = 0.3 mm) that extends to the outer limit of the subaqueous flats (5 m water depth) (Figs. 16, 20E–F, and 21B; Hart et al., 1998; Dashtgard, 2011b). Due to northward alongshore sediment transport, sediment on the north side of jetties and other man-made 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. 19A–B) and small-scale creek networks (known locally as “mumblies”; Fig. 19B, 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 wave reworking of the subaqueous delta slope (Kellerhals and Murray, 1969; Figs. 16 and 18). 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 (Kellerhals and Murray, 1969; Dashtgard, 2011a).

The Fraser River flowed into Boundary Bay before onlapping Point Roberts ~4,500 years ago (Hutchison et al., 1995; 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 (Fig. 16), but the subtidal profile shows evidence of sediment erosion in a zone ~4,500 m to 8,000 m from the dyke (Fig. 18B). The tidal flat profile at Boundary Bay is attributed to wave erosion caused by storm waves that approach from the southeast (Fig. 3C; Houser and Hill, 2010a; Ayranci et al., 2012). 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 sand (GS_{avg} = 0.12 mm) to fine-grained sand (GS_{avg} = 0.2 mm; Fig. 20A; Dashtgard, 2011a). Wave-sheltered Mud Bay is mud-dominated (GS_{avg} = 0.045 mm; coarse silt; Northcote, 1961; Kellerhals and Murray, 1969; Dashtgard, 2011a). 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 (Engels and Roberts, 2005; Dashtgard, 2011a). 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. 18A).

Interestingly, Boundary Bay shows a domed profile where the flats are colonized by eelgrass (middle flats; Fig. 18B; Swinbanks and Murray, 1981). The domed profile 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., Swinbanks and Murray, 1981; Houser and Hill, 2010b; Dashtgard, 2011a) 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

The break in slope between the delta slope and tidal flats at Boundary Bay occurs at ~8.5 m depth (Fig. 18B). Little work has been done on 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 hypopycnal plumes and tidal currents (Hill and Lintern, 2021), and in the upper ~20 m, by waves (Hill and Davidson, 2002; Ayranci and Dashtgard, 2016). Sand is transported offshore from the tidal flats during ebbing tides (Hill et al., 2008; Ayranci et al., 2012).

Near surface and intermediate water-depth currents are out of phase by several hours, indicating a distinct stratification of the water column (Pawlowicz et al., 2007; Hill and Lintern, 2021). 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 still greater depths, 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 (Masson, 2002; Ayranci and Dashtgard, 2020).

Net sediment redistribution is northward on the upper delta slope resulting from strong north-directed flood tides and weaker south-directed ebb tides (Thomson, 1981; Hart and Barrie, 1995; Kostaschuk et al., 1995; McLaren and Tuominen, 1996; Barrie et al., 2005; Hill et al., 2008; Ayranci et al., 2012). On the upper ~100 m of the delta slope, peak tidal current velocities exceed the critical threshold for erosion of previously deposited fine-grained sand (Kostaschuk et al., 1995; Hill et al., 2008), and sediment resuspension and winnowing processes impact depositional patterns. Specifically, subaqueous dunes and outcrops of older strata on the updrift delta slope indicate net erosion down to at least 100 m water depth (Hart et al., 1992b, 1998; Hart and Barrie, 1995; Kostaschuck et al., 1995; Carle and Hill, 2009), while the downdrift slope experiences 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 (Mckenna et al., 1992; Lintern et al., 2016). 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.

Sedimentation rates on the delta slope are low, averaging 0–2 cm year^{-1} on both the lower portion of the southern slope and on bottomsets across the entire slope, and up to 13 cm year^{-1} on the upper slope 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.

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

The sedimentary processes active on the delta slope produce a clearly asymmetric grain-size distribution of surficial sediments (Fig. 20C; Barrie and Currie, 2000; Ayranci et al., 2014).

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

North of the Main Channel (DS–Downdrift subzone), surface sediments on the upper slope are more homogenous, and consist of highly bioturbated silt and sandy silt (~20–30% sand; GS_{avg} = 0.014–0.023 mm; fine silt to medium silt; Ayranci et al., 2014). The lower downdrift subzone comprises mainly intensely bioturbated silt (GS_{avg} = 0.012 mm; fine silt) (Fig. 21C and E; Pharo and Barnes, 1976; Barrie and Currie, 2000; Ayranci and Dashtgard, 2013, 2016). 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. 21D and F; Ayranci and Dashtgard, 2016).

5. Natural Hazards

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 on recent delta 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. In contrast, parts of the delta plain are subsiding at rates up to 3 mm $year^{-1}$ (Fig. 22). Subsidence of 1–2 mm $year^{-1}$ translates to 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 eustatic sea level. Consequently, many parts of the lower delta plain will soon lie below the upper limit of tides and will be increasingly vulnerable to frequent flooding without improvement of the existing dyke network.

The Fraser Delta plain is protected from river floods and storm surges by ~250 km of dykes (Fig. 23) 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 dykes after the 1948 flood were funded under a joint Federal-Provincial flood risk reduction program. What remains uncertain is the extent to which existing dykes will prevent flooding if there is a re-occurrence of the largest recorded flood in 1894, which extensively inundated the delta plain.

The risk of flooding is being slowly amplified by sea-level rise. Eustatic sea level in 2100 is predicted to be 0.3–0.65 m higher than it was in 2005 (Horton et al., 2020). Mean relative sea level along Salish Sea shorelines has increased at an average rate of 1–2 mm year^{-1} over the past century and now exceeds 3 mm year^{-1} (Clague, 2022). There will be large regional and global differences in the rate and magnitude of relative 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 Fraser Delta. Only ~4% of dykes 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 Fraser Delta, 40% of which is situated on vulnerable parts of the delta plain (Northwest Hydraulic Consultants, 2017). Sensitive intertidal environments on the seaward side of the dykes (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 (Butler and Campbell, 1987; Adams and Williams, 2004), 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., dyked shoreline), rising sea level will result in “coastal squeeze” as accommodation 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 (Kirwan and Murray, 2008; Hill et al., 2013). Presently, the tidal marshes along the Fraser Delta are receding and decreasing in elevation (Fig. 17; Balke, 2017; Marijnissen and Aarninkhof, 2017).

5.2 Earthquakes and seismically induced liquefaction

The Fraser River Delta is situated inboard of an active subduction zone in a region with active crustal faults and hence is susceptible to major earthquakes. 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; Goff et al., 2020; Tanigawa et al., 2022). These events produce sudden changes in land levels, tsunamis, and shaking along the outer coasts of British Columbia, Washington, Oregon, and northern California (Darienzo and Peterson, 1990; Clague and Bobrowsky, 1994; Darienzo et al., 1994; Atwater, 1996; Atwater and Hemphill-Haley, 1997; Nelson et al., 1996). Over the past 175 years, there have also 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 (Clague and Bobrowsky, 1994; Rogers, 1994; Clague, 1997). Several of these earthquakes were locally damaging, although there is no direct evidence that any impacted the FRD (Rogers, 1994).

Geotechnical studies (e.g., Byrne, 1978; Fraser Delta Task Force, 1991; Finn, 1996) show that the shallow sand sheet that underlies much of the delta plain (Figs. 9 and 10) is susceptible to earthquake-induced liquefaction, and sand dykes and sand blows found in several shallow excavations on the delta indicate that this has happened in the past (Clague et al., 1997b). A shallow crustal earthquake (i.e. M_w 6–7 with an epicenter within about 50 km of Vancouver) would likely induce widespread and severe liquefaction of shallow sands within the delta (Clague et al., 1997b).

In the event of a shallow crustal earthquake, the spatial pattern of liquefaction would be highly variable. Liquefaction effects would differ based on the thickness of Holocene delta sediments, and the source, location and character of the earthquake. 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 local stratigraphy and deep basin effects (Bradley et al., 2018).

Earthquakes could also trigger submarine landslides along the delta slope, which would potentially threaten port infrastructure built at the edge of the Roberts Bank delta slope. Christian (1998) analyzed the stability of the delta slope under earthquake loading and concluded that there is potential for seismic liquefaction and therefore slope failure in the top few tens of metres of the slope. There is also evidence for past (<1,000 yrs BP) slope failures in the form of deformed sub-bottom sediments, notably the "Roberts Bank Slide Complex" (Hart et al. 1992b). More recently, active slope instability near the mouth of the Main Channel has been recorded (Hill 2012; Stacey, 2014), but these events are related to high sedimentation rates, canyon development and growth (Fig. 2), and tidal/storm wave cyclic loading rather than earthquake shaking (McKenna et al., 1992; Christian and Woeller, 1998; Rafiei et al., 2022). Nonetheless, seismic shaking could mobilize the low strength, gas-charged sediments in this environment. Slide-generated tsunamis, which we describe in more detail below, are another potential outcome of large earthquakes.

5.3 Tsunamis

The last great earthquake in the Cascadia subduction zone occurred in January 1700 (Satake et al., 1996; Atwater et al., 2005). 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. In the case of the Fraser Delta, the tidal flats at Boundary Bay would experience a wave resonance effect that might increase maximum wave heights to 2 m (Cherniawsky et al., 2007). 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 might overtop the protective sea dykes along the west side of Richmond (Fig. 23) and run some distance up the Main Channel of the Fraser River (distance dependent on Fraser River stage at the time of the 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, Orcas Island failure), 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).

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. Given 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. Whereas tsunami hazard is not explicitly included in the National Building Code of Canada, coastal infrastructure can still be designed to resist small tsunamis. Community-centred research is underway to evaluate tsunami hazards and risks in the FRD, focusing initially on Boundary Bay (Rabinovich et al., 2023; Fine et al. 2023).

6. Implications for Coastal / Delta 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 dykes along all Fraser River distributary channels (Fig. 23), navigation through the Main Channel is maintained by jetties and regular sand dredging to ensure ships can reach Annacis Island and New Westminster. An average of ~1.75 x 10^6 m^3 $year^{-1}$ of sand is removed through dredging (Fraser River Estuary Management Program, 2006; 2007), although a more recent estimate indicates the dredged volume is now ~4 x 10^6 m^3 $year^{-1}$ (iaac-aeic.gc.ca; accessed February 16, 2024). Dredging has contributed to coastal erosion by altering sedimentation patterns (Armstrong, 1990; Barrie and Currie, 2000) and adversely affecting ecosystems (Schaefer, 2004). Much of the dredged sediment is disposed of at a designated site on the delta slope at Sand Heads (Fig. 1) and eventually transits down the canyons to the lower delta slope. However, the dredged sediment is now being considered as a potential resource that can be used in coastal management.

In response to climate-related eustatic sea-level rise and associated recession of coastal marshes, new strategies are being tested to both protect communities against flooding and limit further coastal erosion. “Hard” engineering solutions, such as raising dyke heights or building seawalls, while commonly perceived as the appropriate solution (Sauvé et al., 2020), are expensive and generally harm marsh ecosystems. Efforts are underway on the FRD to change public perception and engage with communities to find alternate or sustainable solutions (Barron et al., 2012; Readshaw, 2018; Murphy et al., 2024). Two potential solutions being explored to restore and expand tidal marshes while providing flood and erosion protection are: 1) constructing a network of vegetated dykes (i.e., "living dykes"; Readshaw et al., 2018), which have been employed elsewhere as nature-based coastal management strategy (see Temmerman et al., 2023); and, 2) enhancing the tidal marsh through artificial sediment delivery (i.e., Maxwell, 2021).

In Boundary Bay (Mud Bay) the construction of “living dykes” has relied on the emplacement of infrastructure to promote sediment trapping and accumulation behind barriers (https://www.surrey.ca/services-payments/water-drainage-sewer/flood-control-and-prevention/coastal-flood-adaptation-projects/mud-bay; Accessed February 5, 2024). The promotion of marsh growth on Sturgeon Bank through sediment enhancement is being attempted to reverse marsh loss recorded over the past 35–40 years. The medium- to long-term success of these initiatives is premised on understanding sedimentation, erosion, and subsidence patterns on the FRD. Specifically, long-term transgression and coastal squeeze, subsidence (both natural and anthropogenic induced), changes in storm intensity with changing climate, increased geese herbivory, and natural and anthropogenic changes in sediment supply all impact ongoing tidal-marsh restoration initiatives. Increased utilization of dredged sediment may be needed to further enhance marsh restoration initiatives.

Jetties, causeways and a sewage disposal line that extend across the tidal flats have also greatly altered natural sediment distribution, enhanced seabed erosion, and increased the risk of slope failure (Luternauer et al., 1998; Barrie and Currie, 2000). Overbank sediment accumulation on the delta plain has effectively been shut off by dykes, and this is contributing to localized subsidence (Fig. 22; Lambert et al., 2008; Mazzotti et al., 2009; Samsonov et al., 2014). A perceived lack of sediment supply to the tidal flats has recently led to parts of the Steveston jetty (between the Main Channel and Sturgeon Bank) being removed in an attempt to increase sediment delivery to Sturgeon Bank (www.raincoast.org; accessed April 4, 2023). However, more research is required to understand the cause of marsh and tidal flat deflation and erosion, including the possibility that relative sea level rise and marine transgression may be an underlying cause.

Damage from earthquake shaking and liquefaction can be minimized by strong building codes, which, in the FRD region are based on frequently updated seismic hazard models (Halchuk et al, 2019). Neighbourhood-level seismic risk assessments have been used to develop recommendations related to infrastructure, building codes, community-based planning, response, and recovery strategies and thereby manage social and financial risks (Hastings and Hobbs, 2022). On the outer tidal flats/ upper delta slope, port infrastructure is susceptible to slope failure and port design must account for seismic hazard, local soil conditions, and the potential for seismic amplification (Cassidy et al., 1997; Cassidy et al 2010; Molnar et al, 2014; Jackson et al, 2017).

7. Knowledge Gaps with Implications for Delta Management

Like many populated deltas, initiatives to manage flooding and sustain navigable channels has impacted natural processes and sedimentation across the FRD and put significant stress on its various ecosystems. The present synthesis of the sedimentary history, sediment dynamics, and natural hazards of the FRD provides scientific context for informed decision-making as the urban communities of the delta develop adaptation and sustainability plans in the response to ongoing climate change. Future research needs will have to be defined within collaborative spaces that engage citizens and interest groups in solving complex problems related to future development pressures and sustainability principles (Dorsey, 2004; Lokman, 2019). Below are some key areas where knowledge gaps need to be filled.

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 will be a need to develop techniques that both protect the population and retain ecosystem sustainability. Nature-based coastal flood protection is defined as “consisting of natural or built assets that rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits” (Murphy et al., 2024). Nature-based solutions are being tested on the FRD, and these pilot projects are useful for deriving empirical information. However, uncertainty remains as to the efficacy of nature-based solutions, which require site-specific data to accurately assess their advantages and limitations (Möller, 2019; Seddon et al., 2020). Specific knowledge gaps include a contextual understanding of sediment transport pathways, sediment sources, and rates of sediment accumulation along the delta front and especially the tidal flats. Reliable wave, tide and morphodynamic modelling studies validated by field observations would provide a basis for predicting and evaluating change. Similarly, redistributing dredged material to help re-establish and expand intertidal marshes and wetlands (e.g., Maxwell, 2021) could be optimized with a more quantitative understanding of delta-front morphodynamics. This would enable optimizing sediment placement, forecasting sediment transport, and deciphering 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., Shepperd, 1981; Bradfield and Porter, 1982; Hutchinson et al., 1998), and in particular the tidal marshes, little is known about how floral and faunal communities within the marshes will respond to changing climate and rising relative 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, 2008a). Researchers are increasingly recognizing linkages between sea-level change, floral and faunal ecosystem composition, and geomorphological changes in tidal marshes (Feagin et al., 2005; Kirwan et al., 200b8; Crotty et al., 2020).

As a particular example of fundamental research that is required, algae and bioturbating (burrowing) animals can alter sedimentary properties, including their resistance to erosion by waves and currents (biostabilization; Amos et al., 1997; Sutherland et al. 2013). Despite the myriad of studies of bioturbating animals and their structures in the FRD (e.g., Chapman and Brinkhurst, 1981; Swinbanks and Murray, 1981; Swinbanks and Luternauer, 1987; Dashtgard, 2011a,b; Ayranci and Dashtgard, 2013; Ayranci et al., 2014; La Croix et al., 2015), the impact of bioturbation on the geomorphological evolution of delta zones and subzones and their effect on the geotechnical properties of the sediments are poorly understood.

A final, but major knowledge gap is the possible impact of changes in the seasonal and long-term regime of the Fraser River in a changing climate (Taylor, 2004; Shrestha et al., 2012; Brice et al. 2021; Mohanty and Simonovic, 2021). Significant changes in winter snowpack and glaciers within the watershed are probable as the climate warms, but the magnitude and effects of these changes on river temperature (ul Islam et al, 2017), discharge and sediment delivery to the FRD are not understood, much less their consequences for the delta ecosystems (Ferrari et al.,

2007) or complex morphodynamics at play in the distributary channels and at the delta front.

7. Summary and Conclusions

The Fraser River Delta is a large delta on Canada's west coast which has a complex geological history and is both ecologically and culturally significant. Following North American deglaciation, over the last 10,000 years, the FRD expanded westward building out into the Strait of Georgia (Salish Sea). The delta comprises four main zones (river, delta plain, tidal flats, delta slope), each of which exhibit distinctive sedimentary processes and depositional characteristics and evolve in response to changes in river flow, sediment supply, relative sea-level shifts, and climate change. Each delta zone and subzone is also susceptible to a variety of natural hazards including subsidence, earthquakes, and flooding. Together the distinctive character of delta zones and subzones present unique challenges to delta management, and the transport and redistribution of sediment between zones and across the delta dictates the evolution of the delta system.

The channelized portion of the FRD, includes the freshwater and tidal river, as well as the brackish and tidal distributary channels. In the freshwater portion, sediment transport processes are dominated by seasonal river flow patterns. The resulting deposits are sand-dominated at the landward end and become mixed sandy and muddy seaward. The distributary channels experience both tidal and fluvial processes, resulting in a mixture of sandy and muddy sediments in channels. Key challenges with the management of the channels lie in understanding the impact of climate change on seasonal and long-term flow patterns. This will influence sediment supply, which ultimately has downstream effects on the delta plain, tidal flats and marshes, and deltas slope. The distributary channels, on the other hand, lie at lower elevations relative to sea level and are threatened by flooding, and potential earthquake liquefaction. Management challenges for the distributaries include monitoring and understanding sediment transport pathways as well as the impact of sediment dredging, which affects sediment distribution to the wider delta system.

The delta plain, comprising floodplain and peatland, lies at or above sea level and has been shaped by delta progradation and historic flooding. Presently, the floodplain is protected by an extensive network of dykes. The floodplain consists of layered organic silt and clay, whereas raised peatland is composed of organic-rich sediments atop poorly drained substrate. The major delta management issue for the delta plain is flooding, which is exacerbated by subsidence, particularly in urban areas. Despite the presence of dykes, which effectively protect against flooding and storm surges, there is an increasing risk of large floods amplified by climate change and associated relative sea-level rise. It remains uncertain how effective the dyke network will be in the future. Additional challenges include the threat of subduction zone earthquakes, increased groundwater levels, soil salinity changes, and erosion associated with higher sea levels and flooding.

The tidal flats and marshes are situated between the delta plain and the delta slope and are dynamic sedimentary environments and ecosystems. The tidal flats constitute both active and abandoned regions, depending on the availability of sediment supplied by the Fraser River; the active flats are influenced by sediment and flow from the river, whereas tidal currents, waves and sea cliff erosion dominate the abandoned flats. The active flats are muddy in the nearshore area and coarsen seaward to the margins of the flats, although this is affected by the presence of jetties. The abandoned flats are almost entirely sandy, except for a few muddy regions (e.g., Mud Bay) that are protected from waves and significant tidal energy. Tidal marshes on the active tidal flats consist of brackish-tolerant species, and on the inactive zones the marshes are dominated by more typical saltmarsh species. Sediment accumulating in both marsh regions ranges from organic-rich silts to fine sand and grain size decreases landward and as bed elevation increases. Management of the tidal flats is challenged by understanding the impact of existing infrastructure such as jetties and dykes on tide and wave dynamics, as well as the implications of current and future sea level rise. As well net sediment transport across the tidal flats and marshes and between delta environments in not well understood. Better modelling supported by field observations is needed to fill these knowledge gaps. The tidal marshes, which are pivotal to the FRD’s sustainability are particularly threatened by relative sea level rise (subsidence plus eustatic). Nature-based solutions, such as "living dykes" and artificial sediment delivery, are promising mitigation strategies, but uncertainties exist regarding their efficacy. Bridging knowledge gaps related to sediment transport pathways, sediment sources, and rates of sediment accumulation is essential. The success of pilot initiatives in marsh restoration hinges on a comprehensive understanding of these processes.

Finally, the delta slope, which transitions from the tidal flats into deeper water experiences sediment transport influenced by buoyant flows from the Fraser River, tidal currents, and waves. Tidal asymmetry, which deflects sediment from south to north along the slope results in two distinctive regions, an updrift zone and a downdrift zone. The southern updrift delta slope is dominantly sand and silty sand in shallower water and fines to mud downslope. The northern downdrift delta slope is characterized by silt and sandy silt that passes downslope into homogenous mud. The delta slope region responds to changes in sediment supply and sedimentation patterns in the river (which are related to climate change), river flow conditions, and human infrastructure, and management of sedimentation on the delta slope can impact adjacent delta zones. Additionally, slope stability and submarine landslides that seismic events or other factors may trigger are an ongoing consideration that have implications for port infrastructure. Both the tidal flat and delta slope regions are also at risk to tsunami events associated with earthquakes.

The complexity and vulnerability of the FRD necessitates a deep understanding of its sedimentary processes and deposits as sedimentation is fundamental to the evolution of the delta and the ecosystems it supports. This paper provides foundational insights on these topics while identifying knowledge gaps. Future efforts should focus on establishing holistic and collaborative coastal/delta management strategies that involve community engagement. Continued research on the FRD will be pivotal for navigating the uncertainties associated with climate change and managing the delta's resiliency.

8. CRediT Author Statement

Andrew La Croix and Shahin Dashtgard: Conceptualisation, Methodology, Validation, Investigation, Data curation, Writing, Visualization. Phil Hill: Methodology, Validation, Investigation, Data curation, Writing, Visualization. Korhan Ayranci: Investigation, Data curation, Writing, Visualization. John Clague: Investigation, Writing, Visualization.

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The authors declare there are no competing interests.

Data Availability Statement

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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11. 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.

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 numbers 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 and Hicock, 1979, 1980; Armstrong, 1980a, b). 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. After 1992, data were only collected intermittently and discharge through the full flow season is not shown (data source: wateroffice.ec.gc.ca, accessed March 2, 2023). Flow data were only collected during the high discharge period after 1992. 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) 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 (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 from 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 from 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 shown in the close-up satellite image of the area outlined by the blue box (bottom right). The seismic line 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. Modified from Williams and Roberts (1989).

Figure 11 – Paleogeographic reconstructions of the Fraser River Delta as it prograded into the Strait of Georgia at A) approximately 8,000 years ago, B) approximately 6,000 years ago, and C) present. Maps A and C are modified after Clague et al. (1991). Map B is modified after both Clague et al. (1991) and Hutchinson et al. (1995).

Figure 12 – 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 13 – Maps showing sand and mud percentages on bars and the channel base at 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 Sisulak and Dashtgard (2012), Johnson and Dashtgard (2014), and La Croix and Dashtgard (2015).

Figure 14 – Fence diagram showing 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 15 – Lithological descriptions of vibracores taken from channel bars in 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 16 – Cross-shore profiles of the Fraser River Delta tidal flats and upper delta slope and their interpretations. Profiles are derived from LiDAR data.

Figure 17 – A) Historical extent of salt marshes on Sturgeon Bank, Roberts Bank, and Westham Island from 1932 to 1994 as mapped by Hales (2000) and Church and Hales (2007) using air photos. The colours for each time step depict the extent of the marsh in those years, and show that the tidal marsh increased in area from 1932 to 1994. The extent of the marsh in 2004, as depicted by Church and Hales (2007), is not shown due to discrepancies in the data used to map it. B) Elevation change in the tidal marsh between 1985 and 2015 as mapped by Marijnissen and Aarninkhof (2017). Note, elevation change was derived from observed inundation patterns on satellite imagery and did not account for changes in vegetation cover. Consequently, part of the estimated elevation loss is probably due to loss of vegetation rather than sediment erosion (Marijnissen pers. comm.). C) Distribution of tidal marsh (green polygons) in 2015 and marsh lost between 1985 and 2015 (red polygons; Marijnissen and Aarninkhof, 2017).

Figure 18 – 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 shown, 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 19 – 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 on 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 20 – 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).

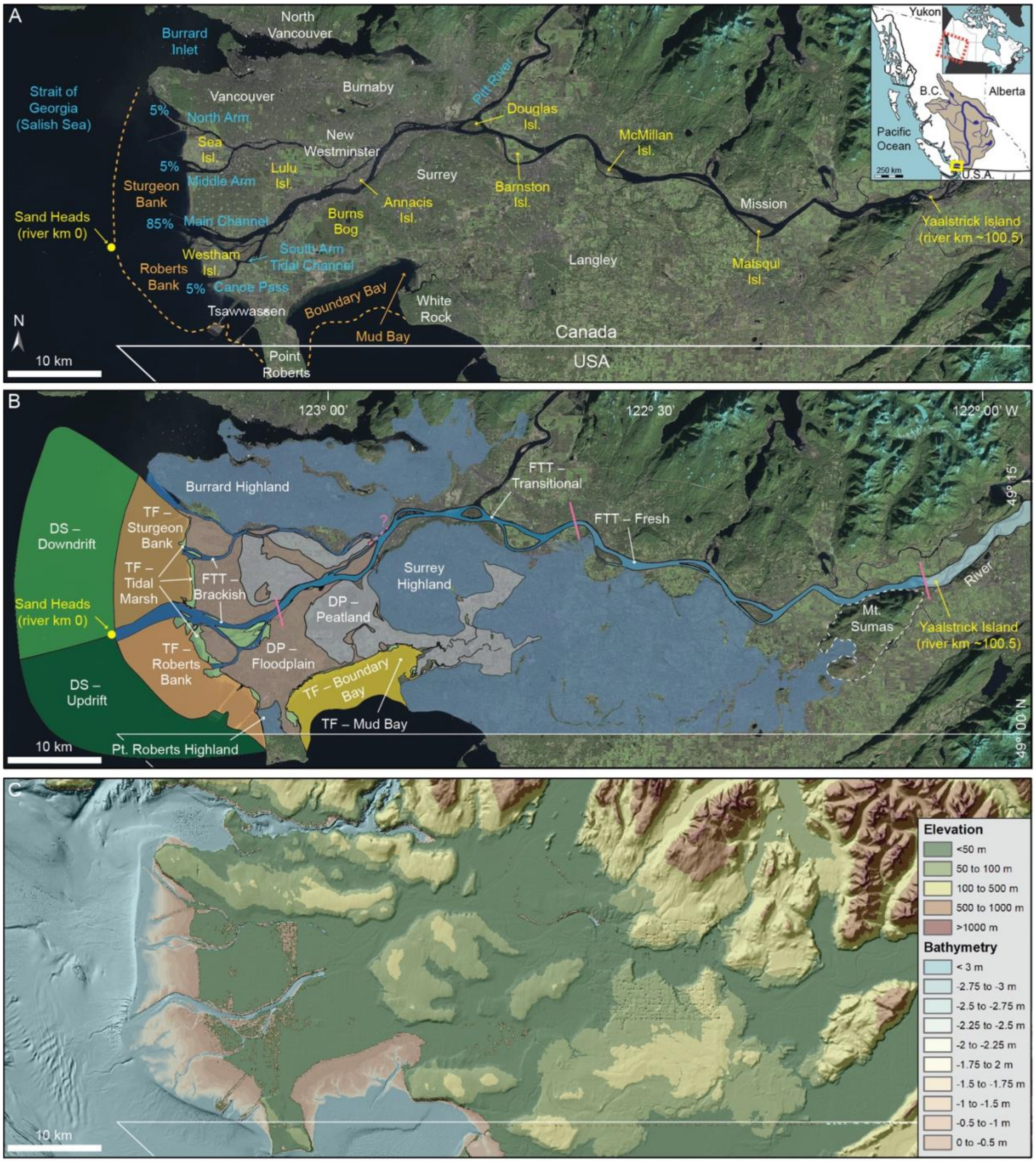
Figure 21 – Lithological descriptions of piston cores taken from the slope of the Fraser River Delta. A) Upper portion of the DS–Updrift subzone. B) Lower portion of the DS–Updrift subzone. C) Upper portion of the DS–Downdrift subzone. D) Lower portion of the DS–Downdrift subzone. E) Upper portion of the DS–Downdrift subzone. F) Lower portion of the DS–Downdrift subzone. Modified from Ayranci et al. (2016).

Figure 22 – 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), which means 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).

Figure 23 – 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).

Delta Category	Zone	Subzone	Name	Defining Characteristics	
				Geography and Hydrodynamic Processes	Sedimentary Products
Fraser River (including distributary channels)	Freshwater and non-tidal		**River**	Fluvial discharge that is not tidally modulated.	Cross-bedded and structureless gravel and sand on river bars and the river bed. Very small proportion of mud.
	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.	Primarily cross-bedded sand, but with small proportions of laminated mud on channel bars. Increase in the thickness and proportion of mud towards the river mouth.
		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.	Primarily structureless or rippled mud in side channels and on channel bars, with cross-bedded, rippled, and laminated sand on the channel bed and on the lower part of channel bars. The thickness and proportion of mud increases up channel bars and towards the river mouth.
		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.	Mixture of cross-bedded, rippled, and laminated sand with structureless, laminated, and rippled mud on channel bars and the channel bed. Decrease in the thickness and proportion of mud towards the river mouth.
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.	Laminated organic silt and clay.
	Bog / Peat Mire		**DP–Peatland**	Raised peat bog (e.g., Burns Bog) with high groundwater tables and heavily vegetated. Organic burial before decomposition / oxidation.	Domed peat deposits.
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.	Organic material derived from brackish vegetation contained within clayey silt to silty sand layers. Grain size generally decreases landward.
	Active Tidal Flats		**TF–Roberts Bank**	Roberts Bank. Updrift (south) of Main Channel. River influenced. Extends from tidal marsh limit to approximately 5 m water depth.	Mud dominated within ~300–500 m of the tidal marsh, otherwise sand-dominated to outer limit of the tidal flats. Small-scale tidal creek networks common.
			TF–Sturgeon Bank	Sturgeon Bank. Downdrift (north) of Main Channel. River influenced. Extends from tidal marsh limit to approximately 5 m water depth.	Mud dominated within ~500 m of the tidal marsh, otherwise sand-dominated to outer limit of the tidal flats. North side of jetties and other structures is finer grained than south side. Wave-formed bars and small-scale creek networks occur sporadically.
	Abandoned Tidal Flats		**TF–Boundary Bay**	Boundary Bay. Receives limited sediment from the Fraser River (non-river-influenced). Sand dominated. Extends from tidal	Dominantly sandy with sediment coarsening seaward. Minor gravel deposits present in SW corner forming north-prograding

				marsh limit to approximately 8.5 m water depth.	beach ridges. Tidal creeks, eel-grass beds, and wave-formed bars are common. Pioneer marsh colony mounds occur sporadically.
			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.	Mud dominated, with mud extending up the Nicomekl and Serpentine rivers. Tidal creeks and common and pioneer marsh colony mounds occur sporadically.
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.	Thin laminated sand and silty sand with uncommon soft-sediment deformation. 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. Grades into Strait of Georgia seafloor.	Bioturbated silt and sandy silt.
	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.	Thick-bedded, bioturbated silt and sandy silt.
		Downdrift prodelta		Downdrift (north) of Main Channel. Extends below 150 m bathymetric contour with an average slope of <1°. Strong alongshore tidal current influence. Grades into Strait of Georgia seafloor.	Intensely bioturbated silt.



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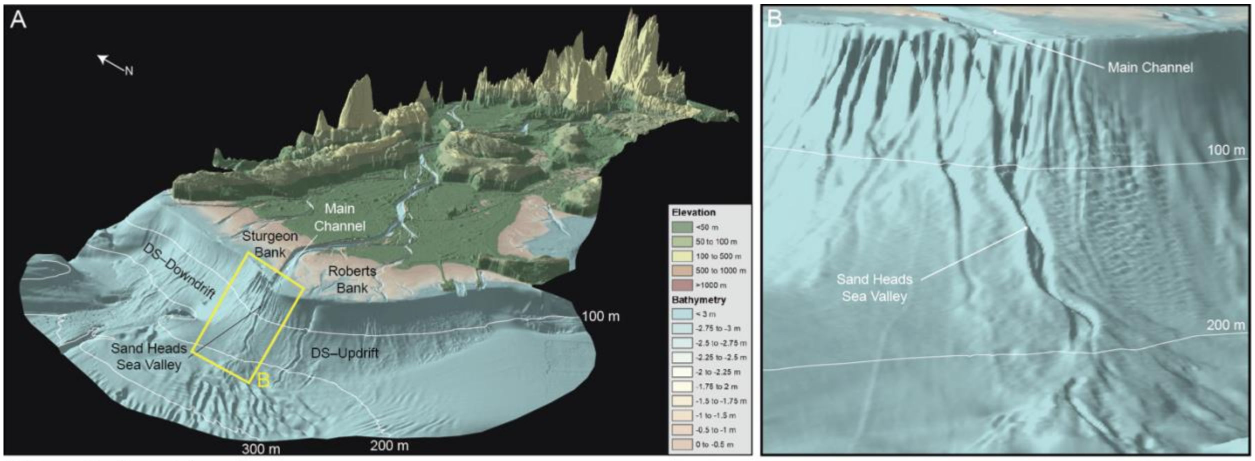

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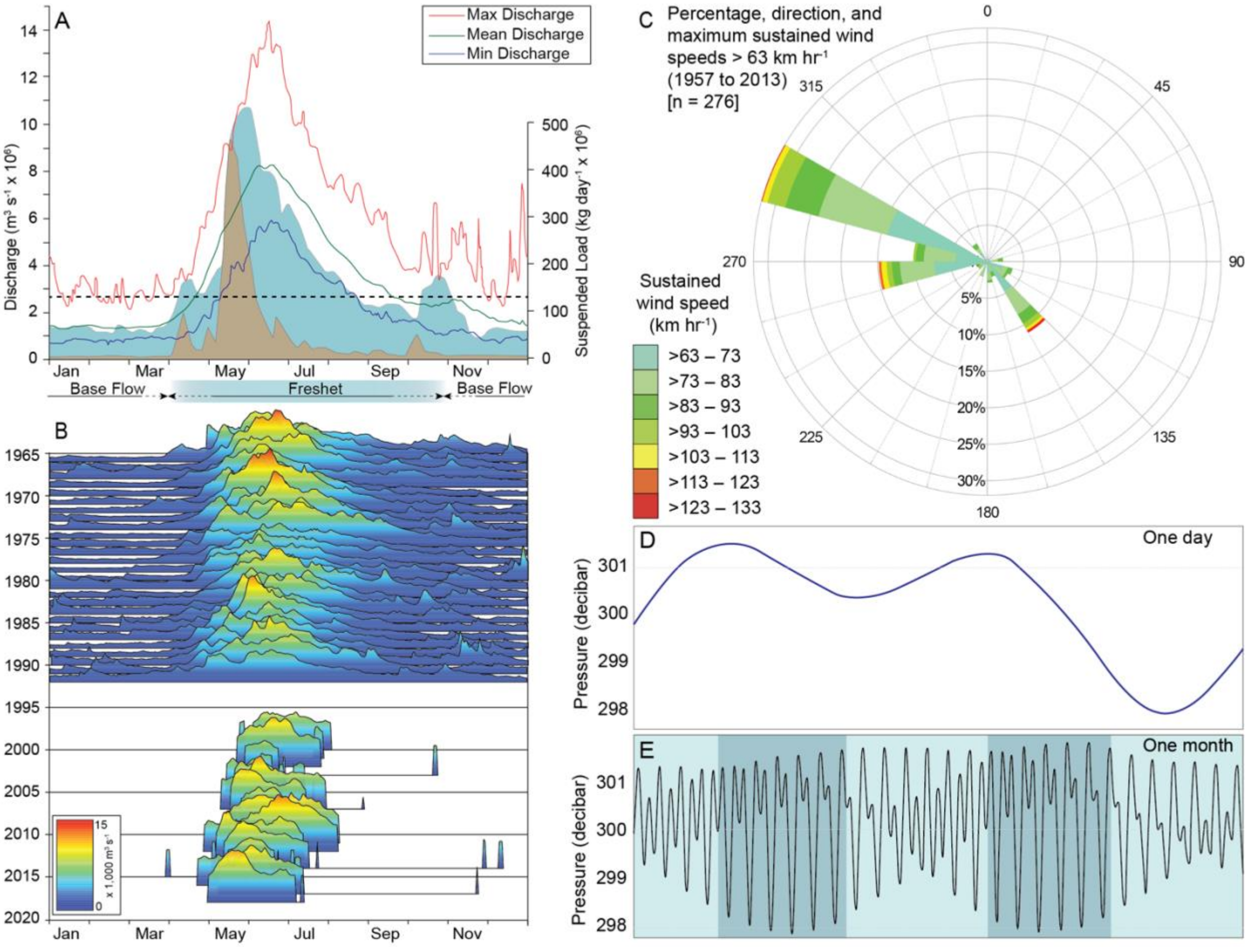

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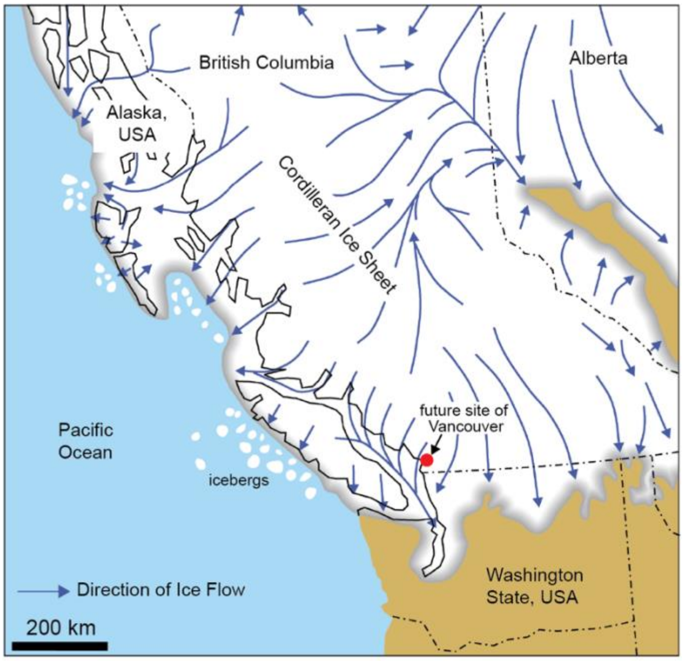

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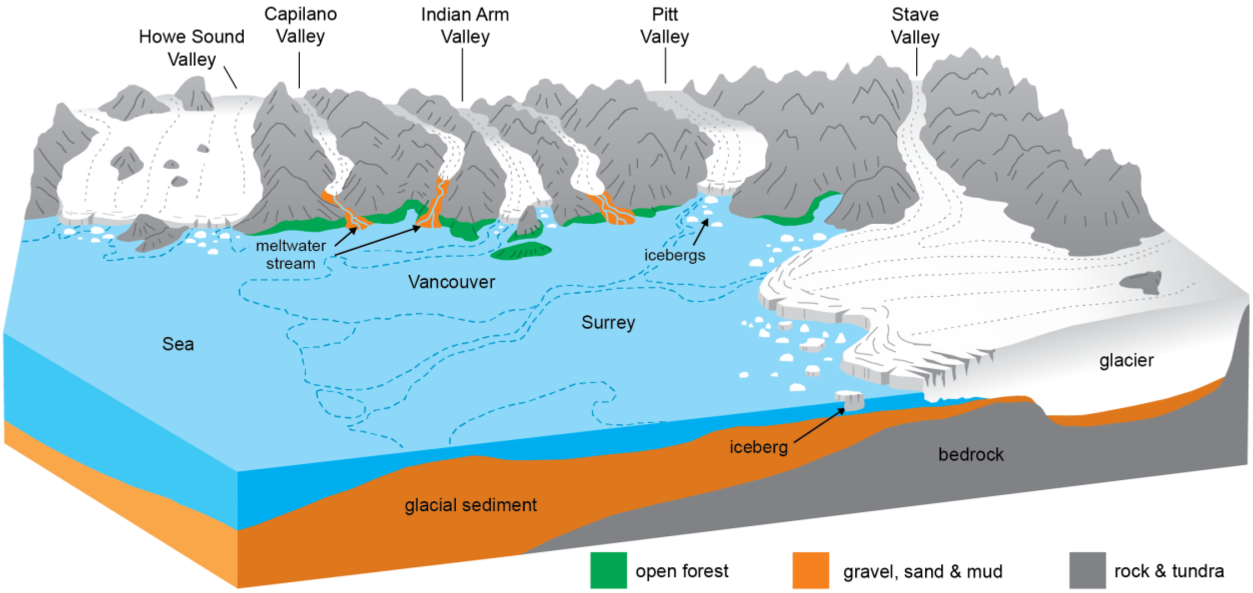

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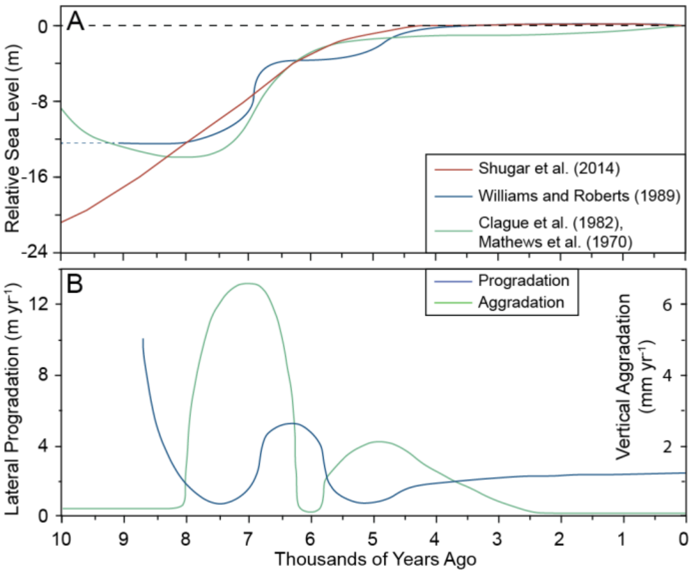

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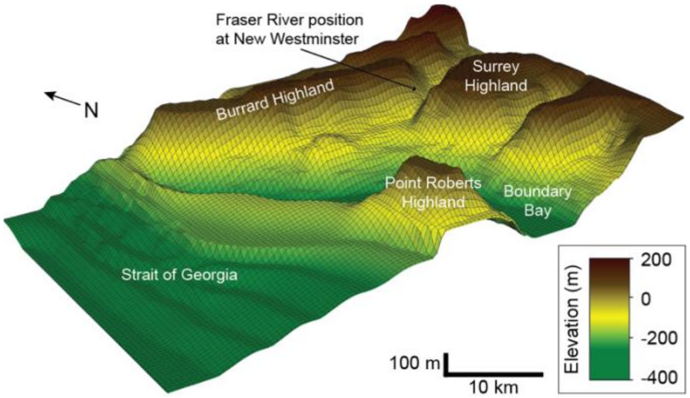

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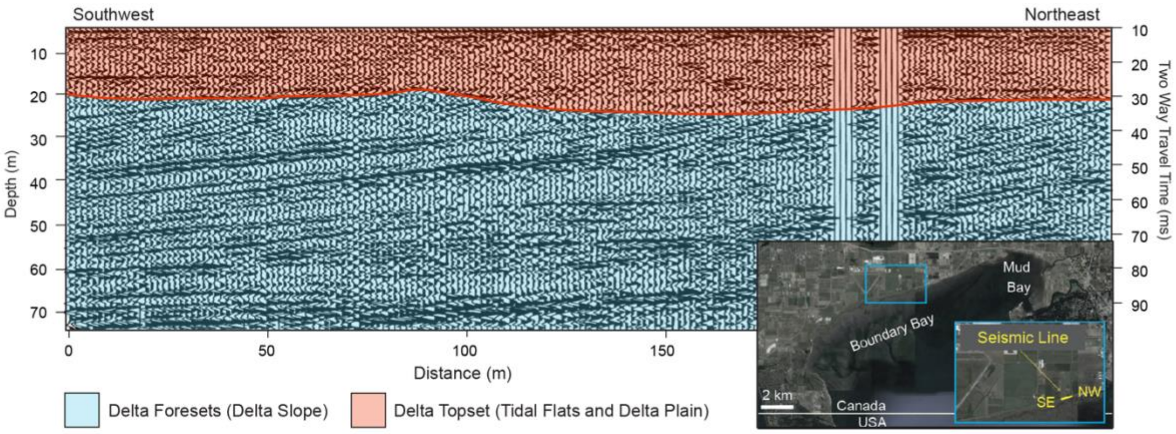

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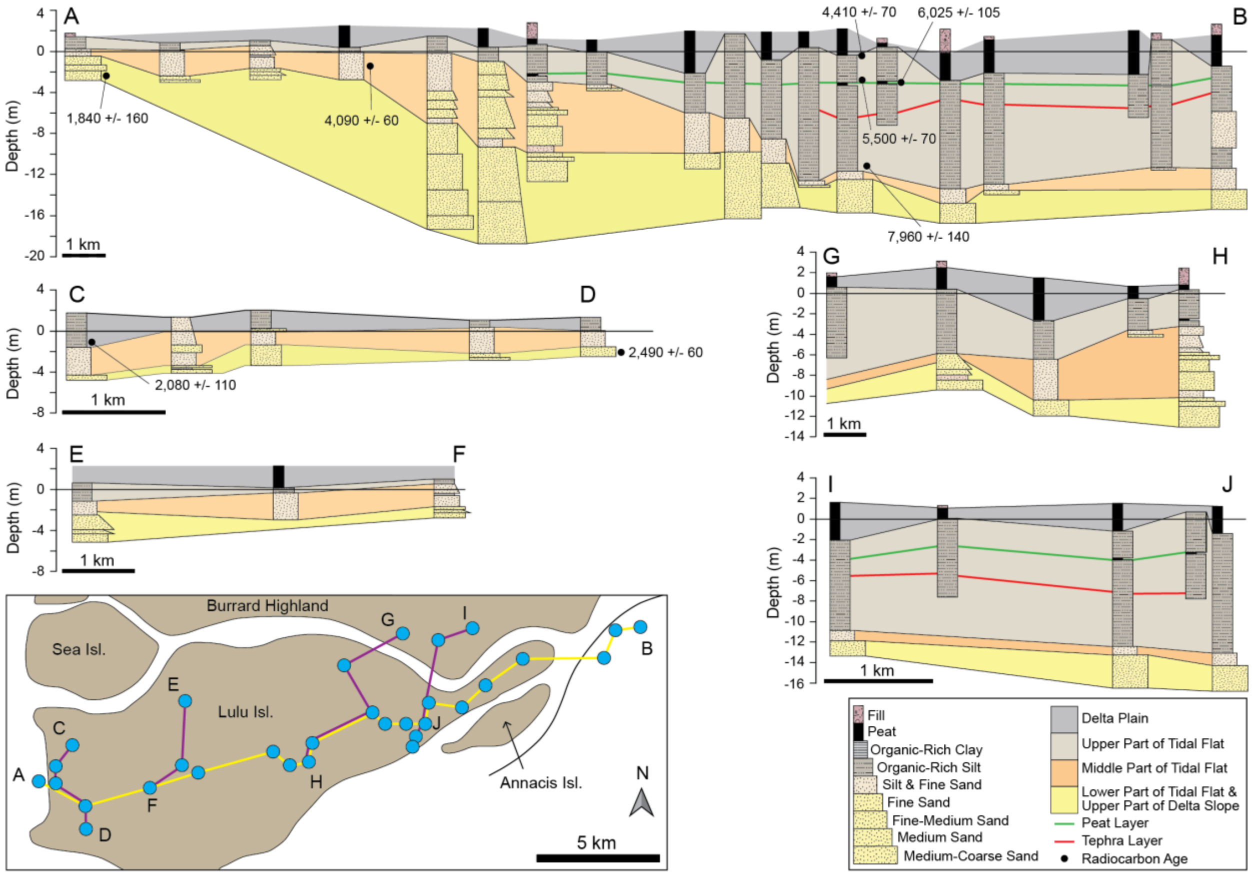

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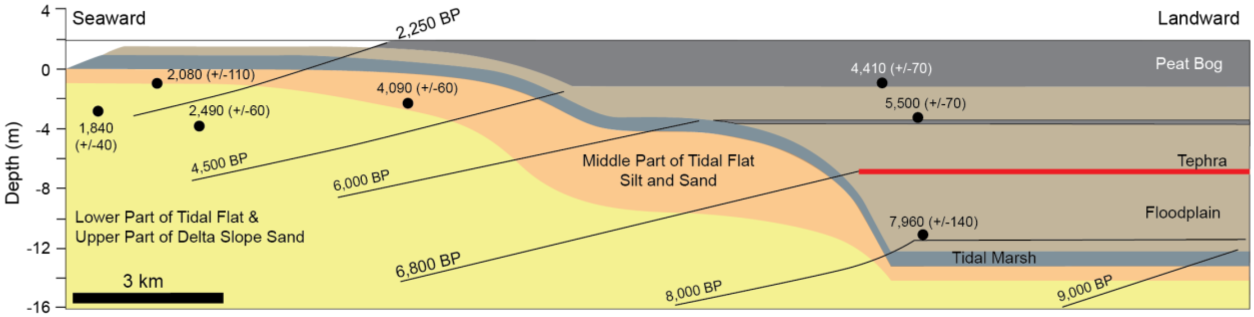

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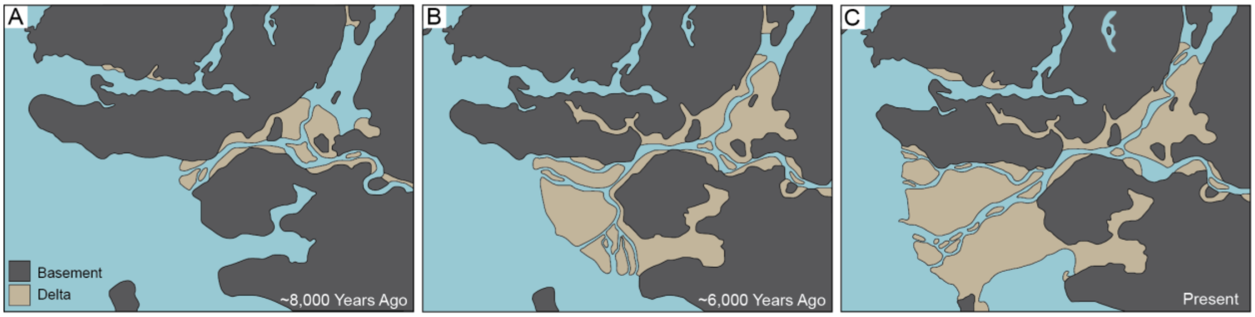

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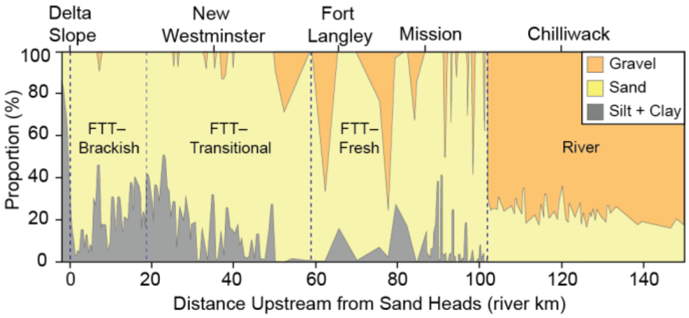

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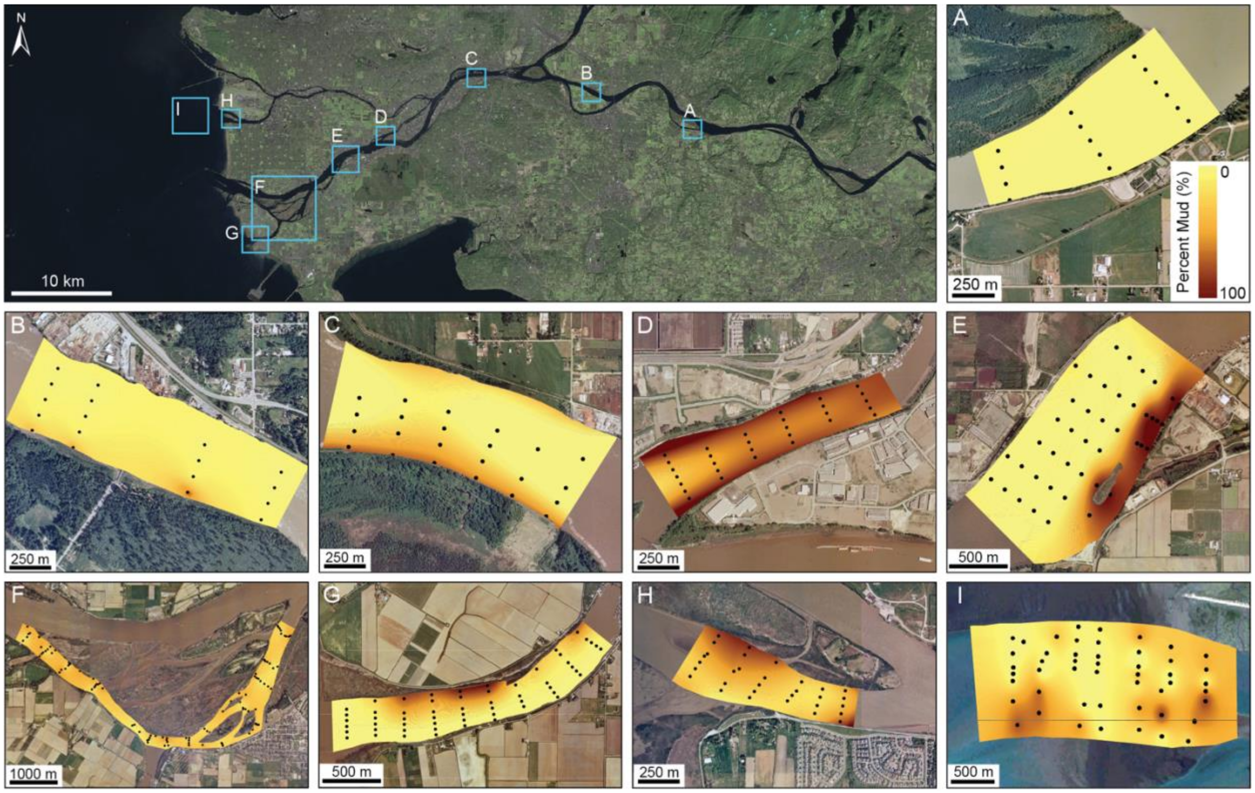

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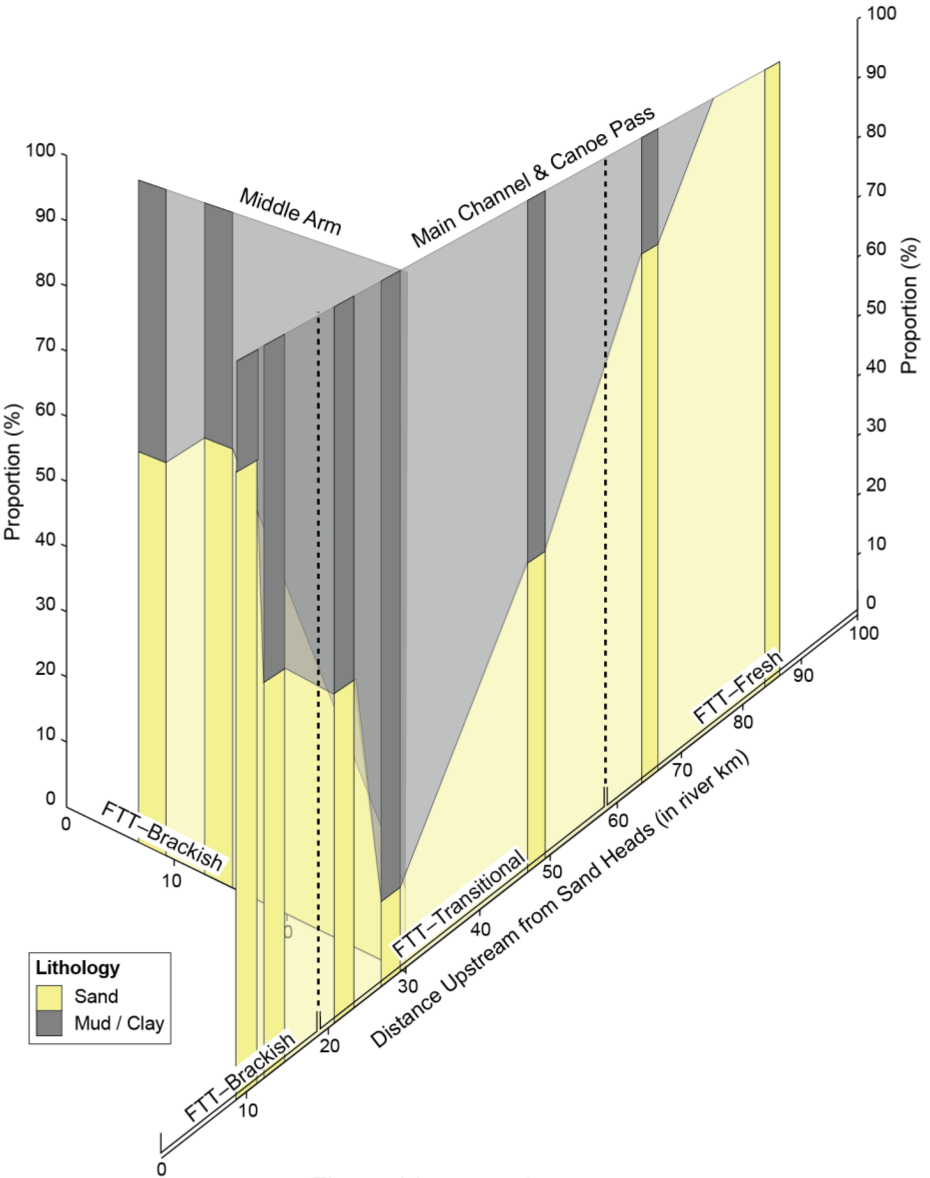

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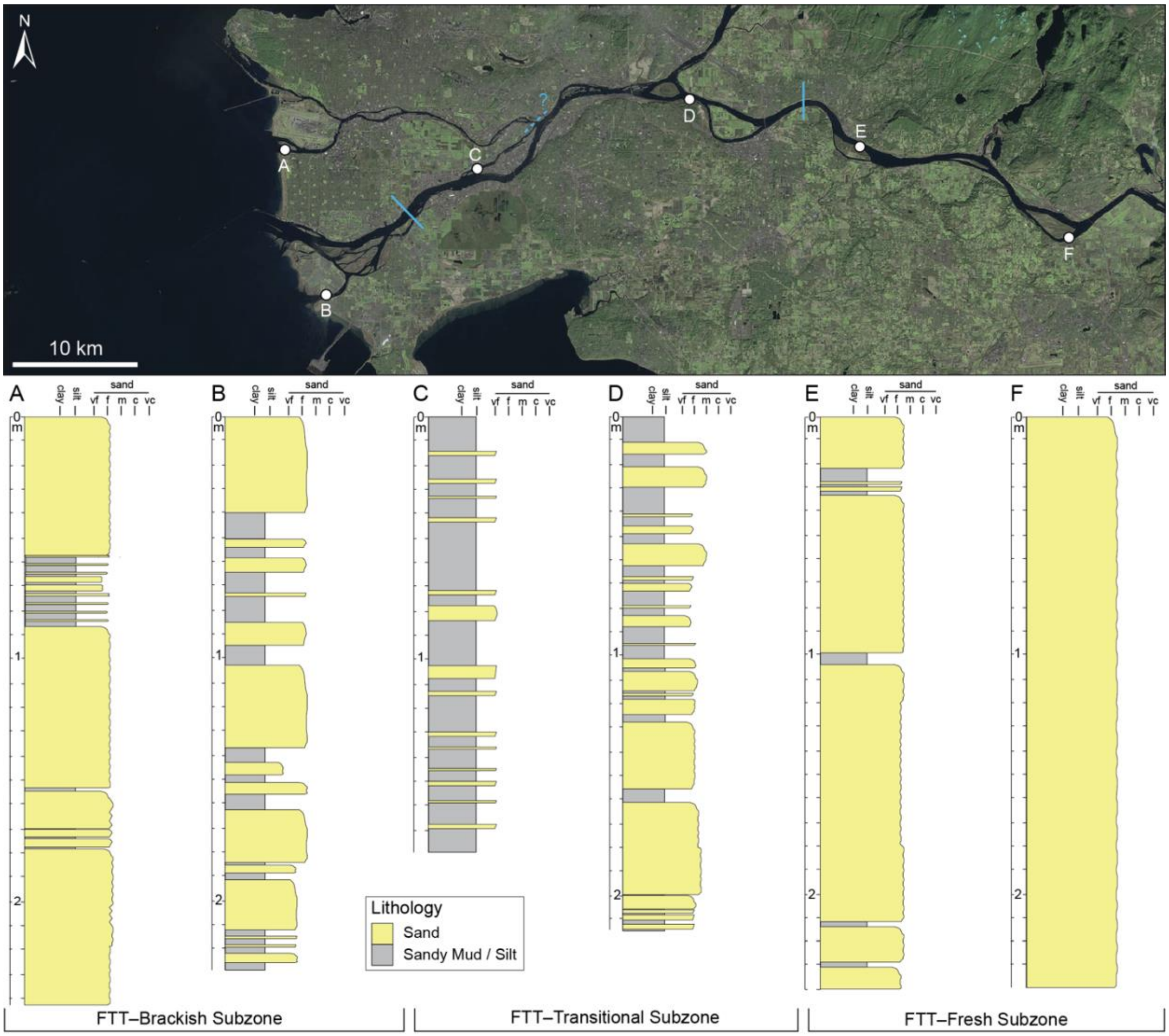

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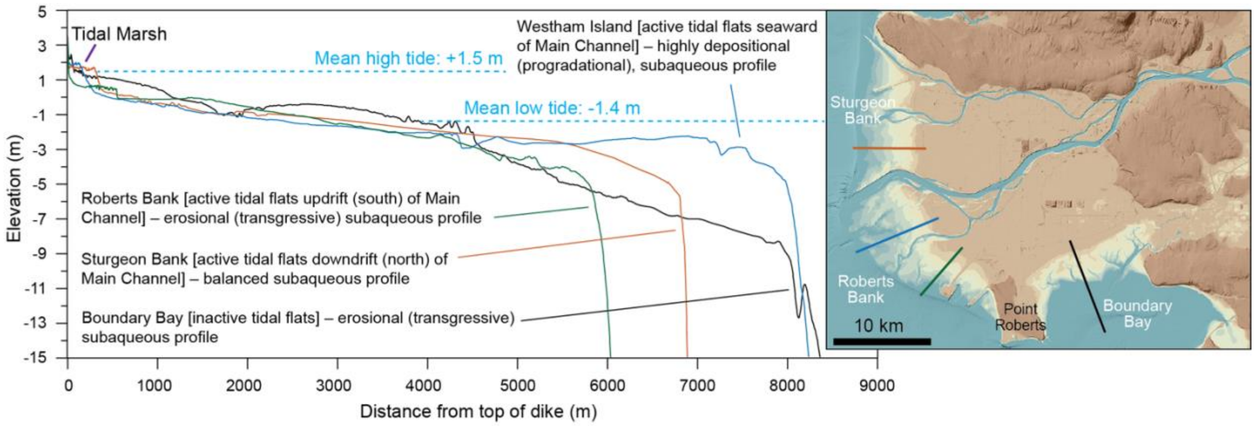

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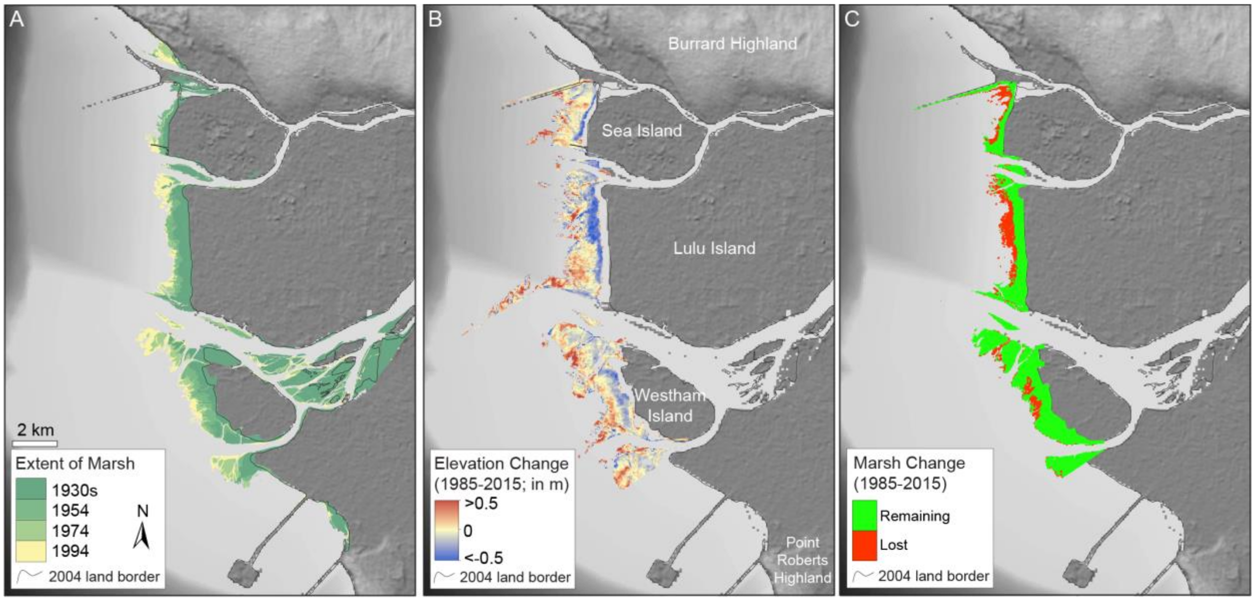

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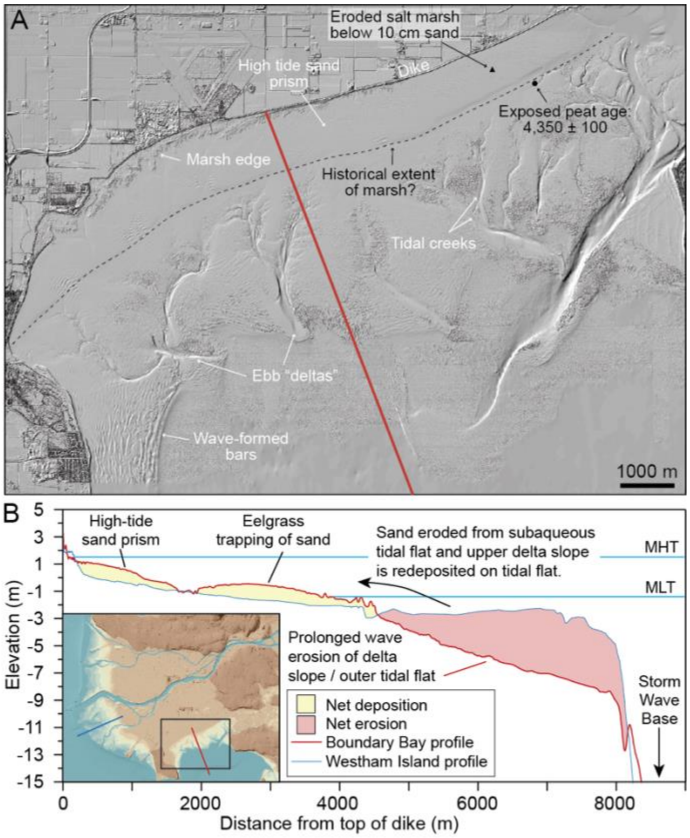

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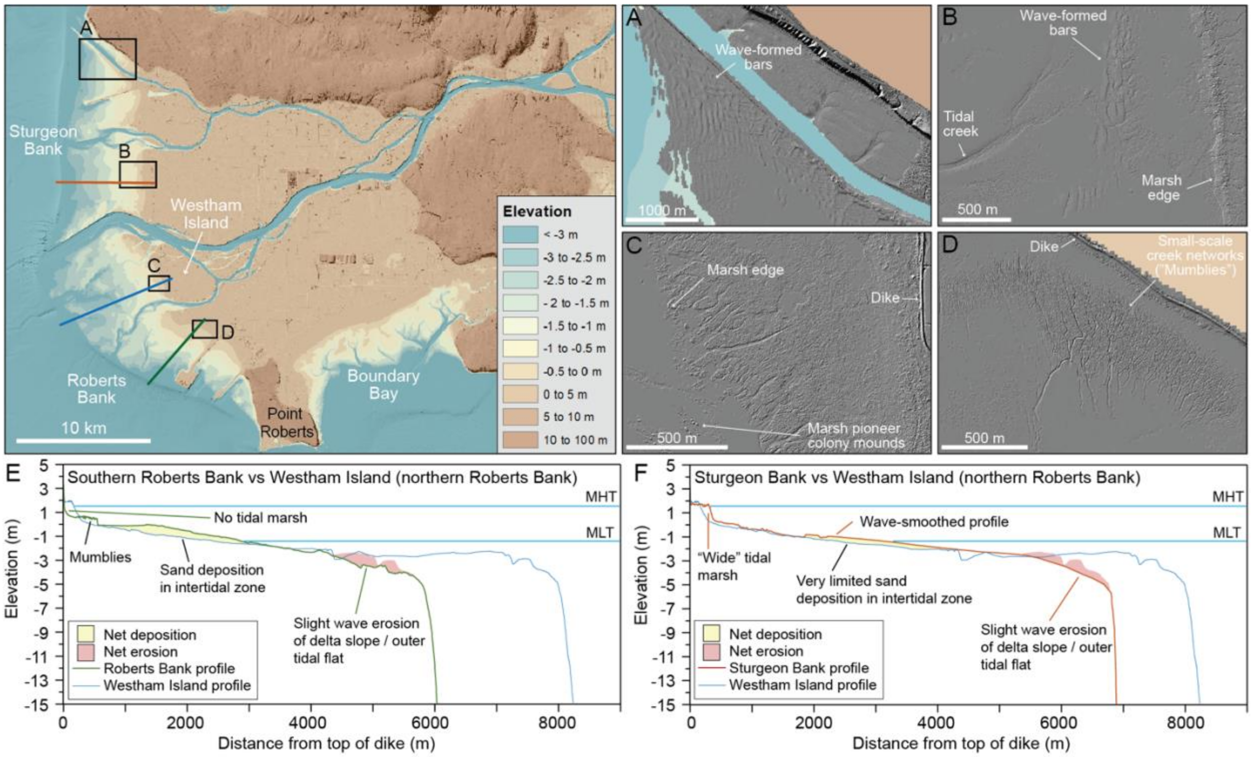

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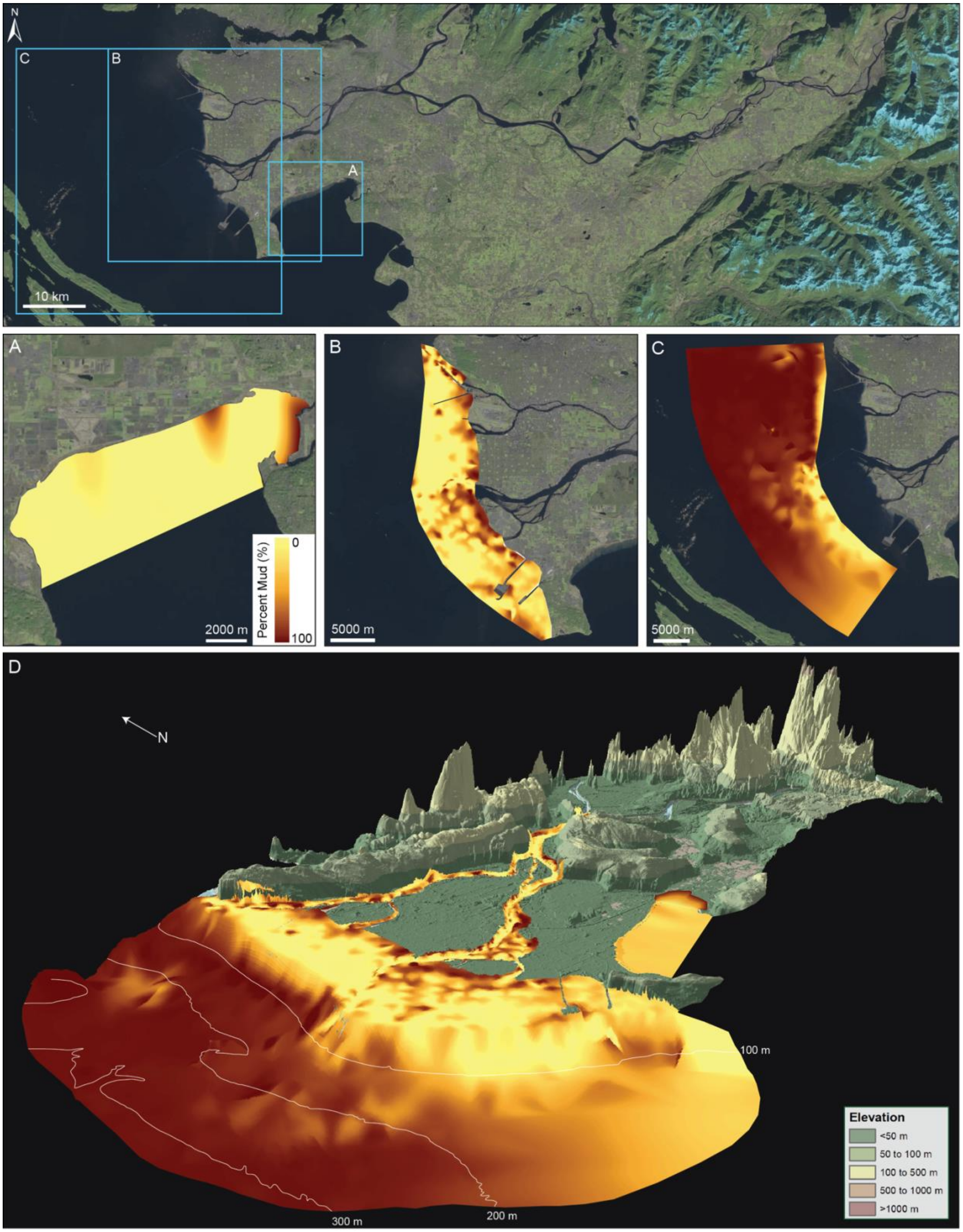

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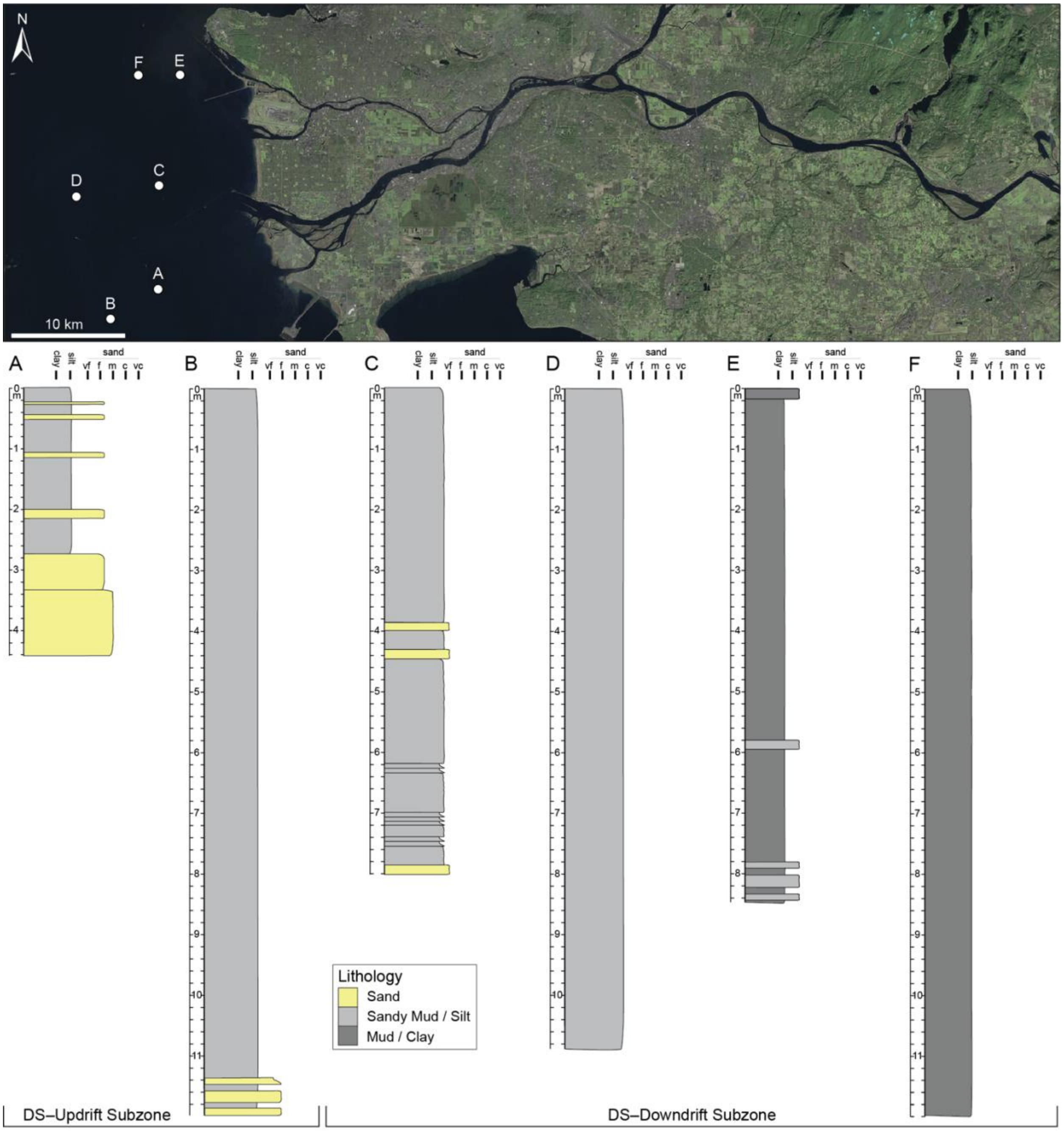

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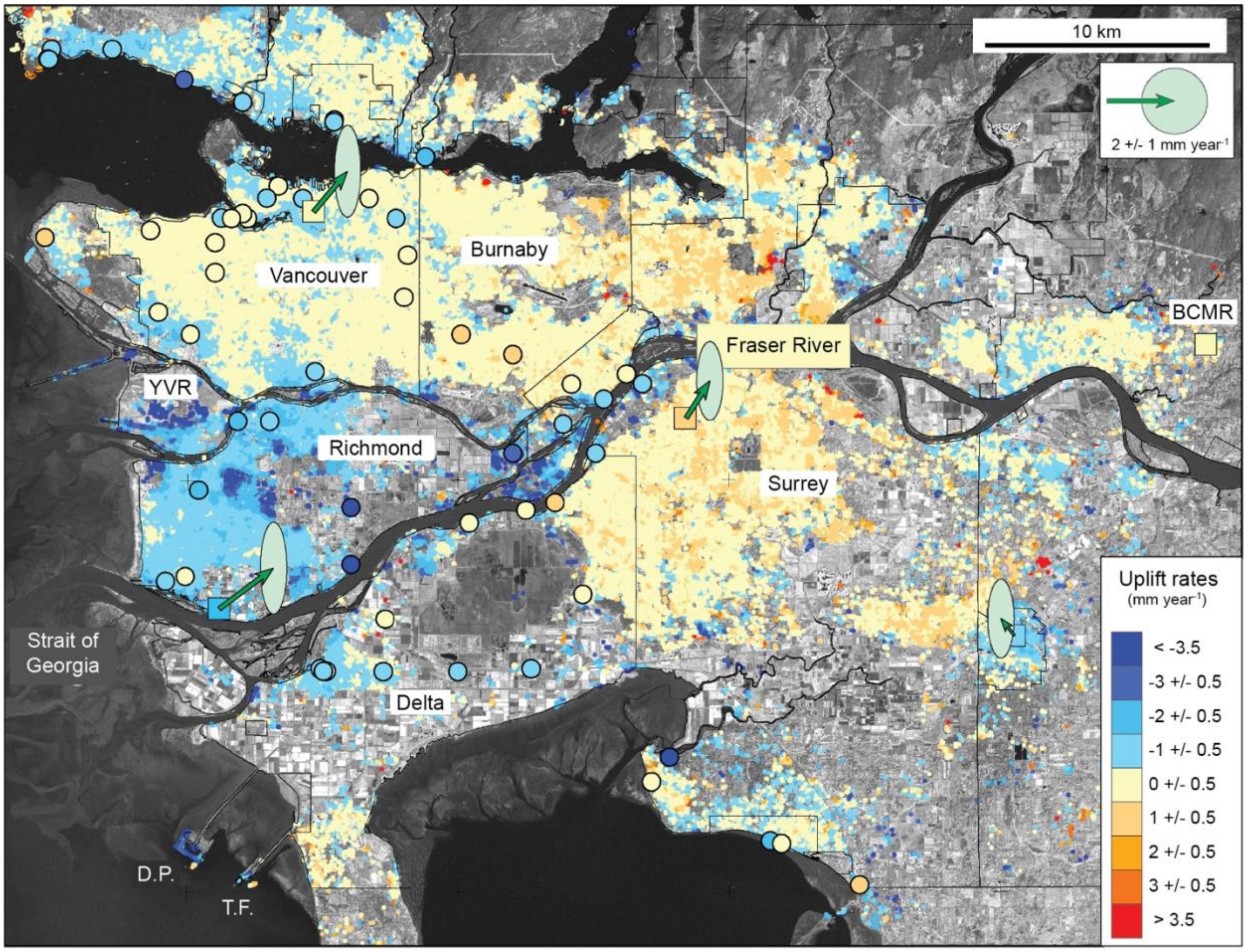

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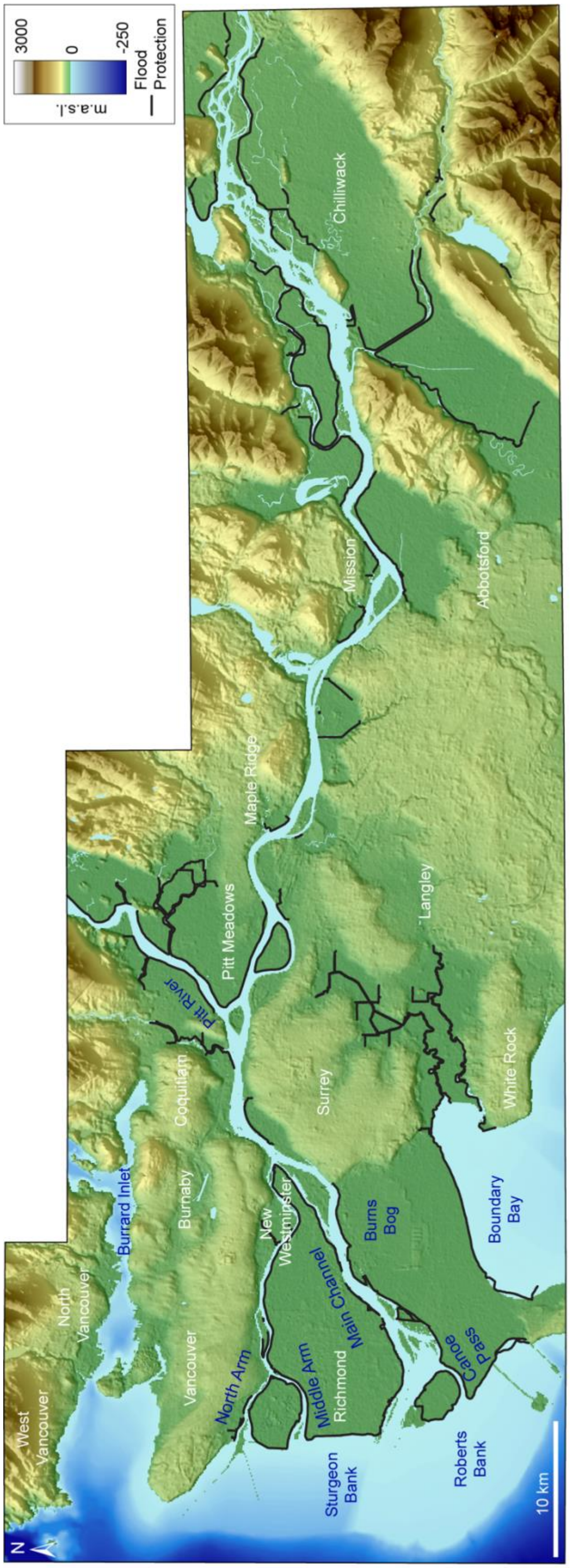

Figure 23 - one column or landscape