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Human Impact on the Sedimentary Regime of the Fraser River Delta, Canada

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ABSTRACT

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The Fraser River Delta is a Holocene, river dominated feature in a macrotidal environment, built into the deep (>300 m) waters of the Strait of Georgia on Canada's Pacific coast. The delta has been modified to provide port facilities and a navigable channel for the city of Vancouver. Prior to the confinement of the Fraser River to its present channels, during the early part of this century, the distributary river channels regularly switched and migrated across the entire delta front. The annual river load (approximately 17.3×10^6 tonnes) is 65% silt and clay, and 35% sand. Today, most of the sand is removed from the system by dredging and the mud is transported in a plume past the intertidal estuary and northwards into the basin by the dominant flood tidal flow. Three causeways that cross the intertidal zone to the delta foreslope act as barriers to the dominant northward sediment transport causing estuarine and localized seabed erosion. The presence of the causeways results in tidal flow separation with clockwise back eddies forming behind the structures focusing the tidal energy to the intertidal zone. On the delta foreslope, off the southern causeways, an eroded submarine distributary channel subaqueous fan complex has been exposed by enhanced tidal flows that scour the seabed and form northward migrating subaqueous dunes increasing the delta slope and, consequently, the risk of slope failure.

ADDITIONAL INDEX WORDS: *Channel switching, macrotidal environment, sediment distribution data, dredge spoil, sediment supply.*

INTRODUCTION

The Fraser River Delta on the Pacific coast of Canada (Figure 1) is a river dominated delta in a macrotidal environment. It has controlled its growth throughout the Holocene by continual channel migration laterally across the delta as each distributary channel aggraded with the deposition of the sediment load. The main river channel occupied six different channels between 1827 and 1912 (CLAGUE *et al.,* 1983). Channel switching is a common occurrence in deltaic settings and has been documented in the Nile Delta (SESTINI, 1989), Yellow River Delta (XUE, 1993), Ganges/Brahmaputra (COLEMAN, 1969) and the Fraser Delta (CLAGUE *et al.,* 1983). Indeed, MONAHAN *et al.* (1993) demonstrated that migration of the distributaries of the Fraser Delta has led to the generation of a nearly continuous sheet sand beneath the delta plain.

During the last 100 years the Fraser River Delta has been under development, a result of being adjacent to the fast growing city of Vancouver (1998 population of 1.9 million). The inevitable consequence is exploitation of the river, estuarine and nearshore areas for various purposes including navigation (jetties and breakwaters), port facilities, sewage disposal, building aggregates, dredge spoil dumping, fishing and the laying of submarine cables (electrical transmission, telecommunications). Prior to 1912, the charted water depth across the subaqueous intertidal delta plain was 2.5 m and no navigable access was available to the Fraser River. After 1912, dredging to create water depths of 12 m or greater has been continuous and has increased in recent years to supply aggregate to the domestic market resulting in at least 50 % (approximately 6×10^6 tonnes) of the sediment load coarser than 0.18 mm being taken from the river before reaching the delta (MCLEAN and TASSONE, 1990). The annual river load (approximately 17.3×10^6 tonnes) is 65% silt and clay, and 35% sand, transported primarily during the spring to summer freshet (MCLEAN and TASSONE, 1990).

Our objective is to demonstrate how humans have altered the natural sediment environment of the delta and provide an indication of geological hazards that will have to be mitigated in the near future. The interpretation is based on geophysical survey data, stratigraphic cores, swath bathymetry and, in particular, a dense surficial sediment database for the entire submarine portion of the delta and river.

REGIONAL SETTING OF THE FRASER DELTA

The Fraser River, which drains 234, 000 km^2 of British Columbia has produced a delta which is prograding into the Strait of Georgia, a semi-enclosed 300 m deep basin separating the British Columbia mainland from Vancouver Island (Figure 1). The 1000 km^2 delta is a Holocene feature evolving since the disappearance of the late-Wisconsinan glacial ice

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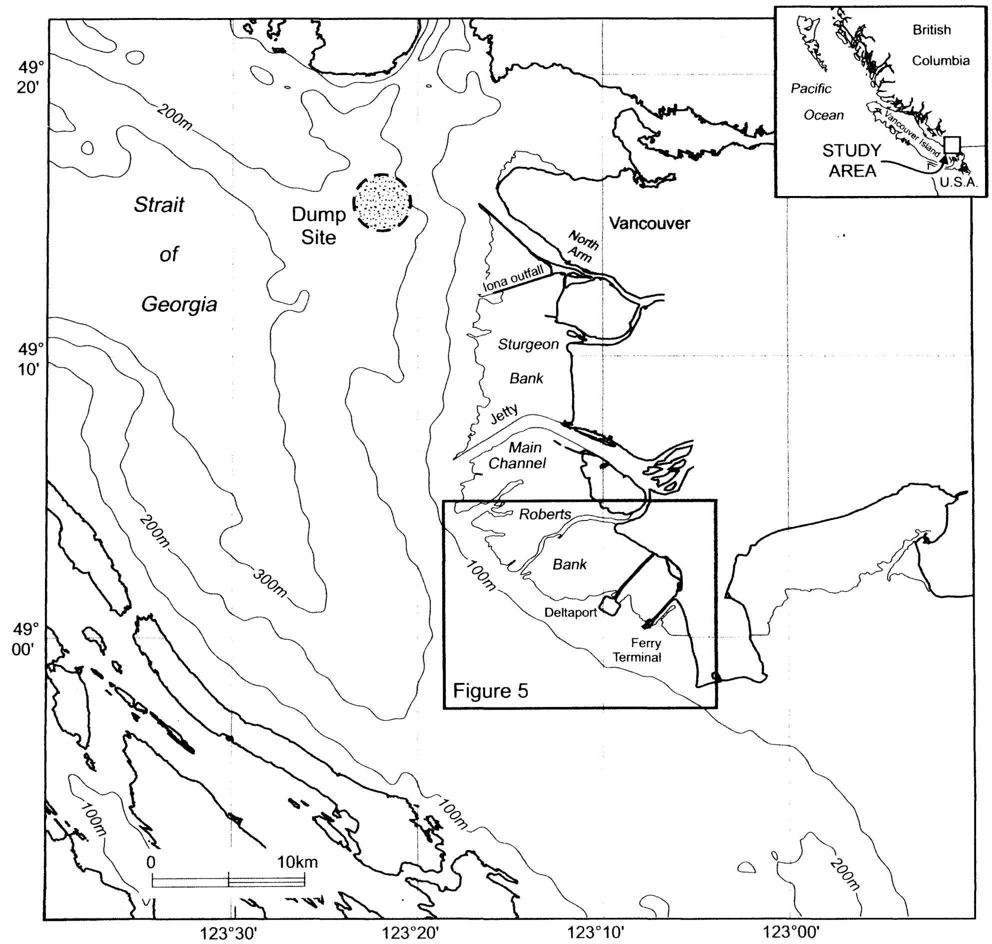

Figure 1. The Fraser River Delta, British Columbia, Canada.

(CLAGUE *et al.,* 1983). Mean annual flow of the river is $3.5 \times 10^3 m^3 s^{-1}$ measured 85 km upstream from the river mouth with approximately 88% of this volume discharged through the main channel (MCLEAN and TASSONE, 1990). About 80% of the sediment (and all of the sand) discharges through the main channel during freshet. HART *et al.* (1995; 1998) divide the subaqueous delta into three main morphologic zones, the delta front, delta slope and prodelta. The delta front is the wave-influenced portion of the delta at the seaward limit of the tidal flat and consists of fine to medium sands that have been shaped into low swells and crossed by both active and inactive distributary channels extending to the slope (LUTERNAUER *et al.,* 1998). The delta slope with typical dips of 2–3° and locally over 23°, occurs between 10 m and 100 m water depth on Roberts Bank and 180 m water depth on Sturgeon Bank (Figure 1). It is incised with both active and inactive submarine channels.

Sediment dynamics at the mouth of the river have been described by MILLIMAN (1980) and KOSTASCHUK *et al.* (1989; 1992). Fine sand is transported in suspension with the mud fraction. Coarser sand (transported as bedload) is deposited near the river mouth during freshet discharges and ebbing tides when the entire thickness of the water column in the channel is flowing seaward. At other times (including high tide during freshet) a salt wedge penetrates into the channel beneath the seaward flowing surface waters and bedload material is trapped in the estuary. The sand which reaches the river mouth is transported downslope in a submarine channel to the base of the slope reaching a zone of debris flow deposits and turbidites (HART *et al.,* 1992; EVOY *et al.,* 1993). EVOY et al. (1997) suggest that the subaqueous channels serve as conduits for sediment bypassing forming prodelta depositional lobes.

Offshore, the mixed, semi-diurnal tides with a mean range of 2.6 m and maximum range of 5.4 m control the dynamics of the suspended sediment in the plume (THOMSON, 1981). Tides are rectilinear along the delta slope with the flood towards the northwest and ebb to the southeast. Flood currents are both stronger and of greater duration than the ebb currents. The sediment laden plume that extends into the Strait of Georgia from the mouth of the main channel is pulled north towards the Sturgeon Bank slope by the effects of Coriolis on the dominant flood tide. Even during the ebb tide much, but not all, of the fine sediment is transported north-

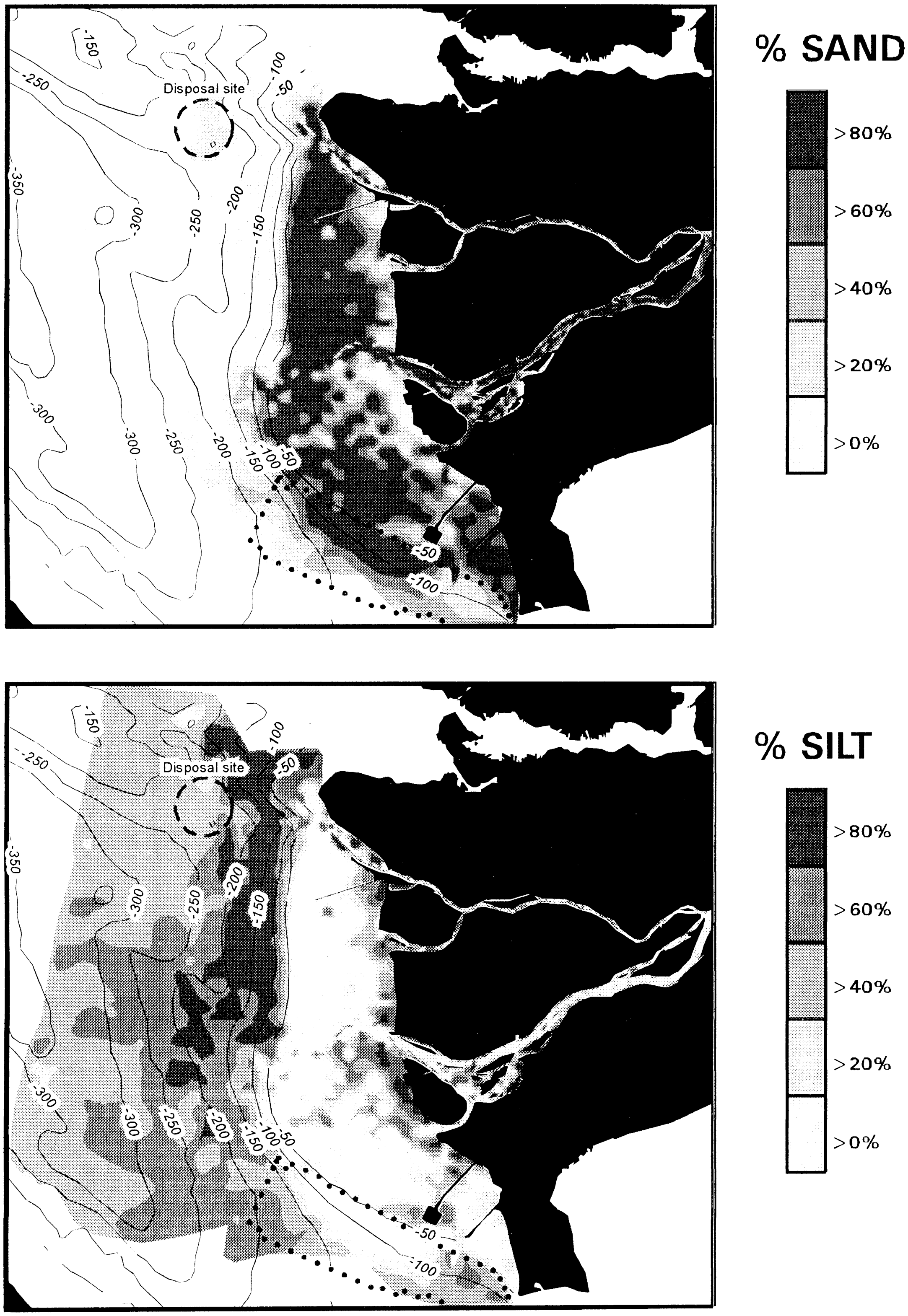

Figure 2. Percentage of a) sand and b) silt in surficial sediments of the Fraser River and delta.

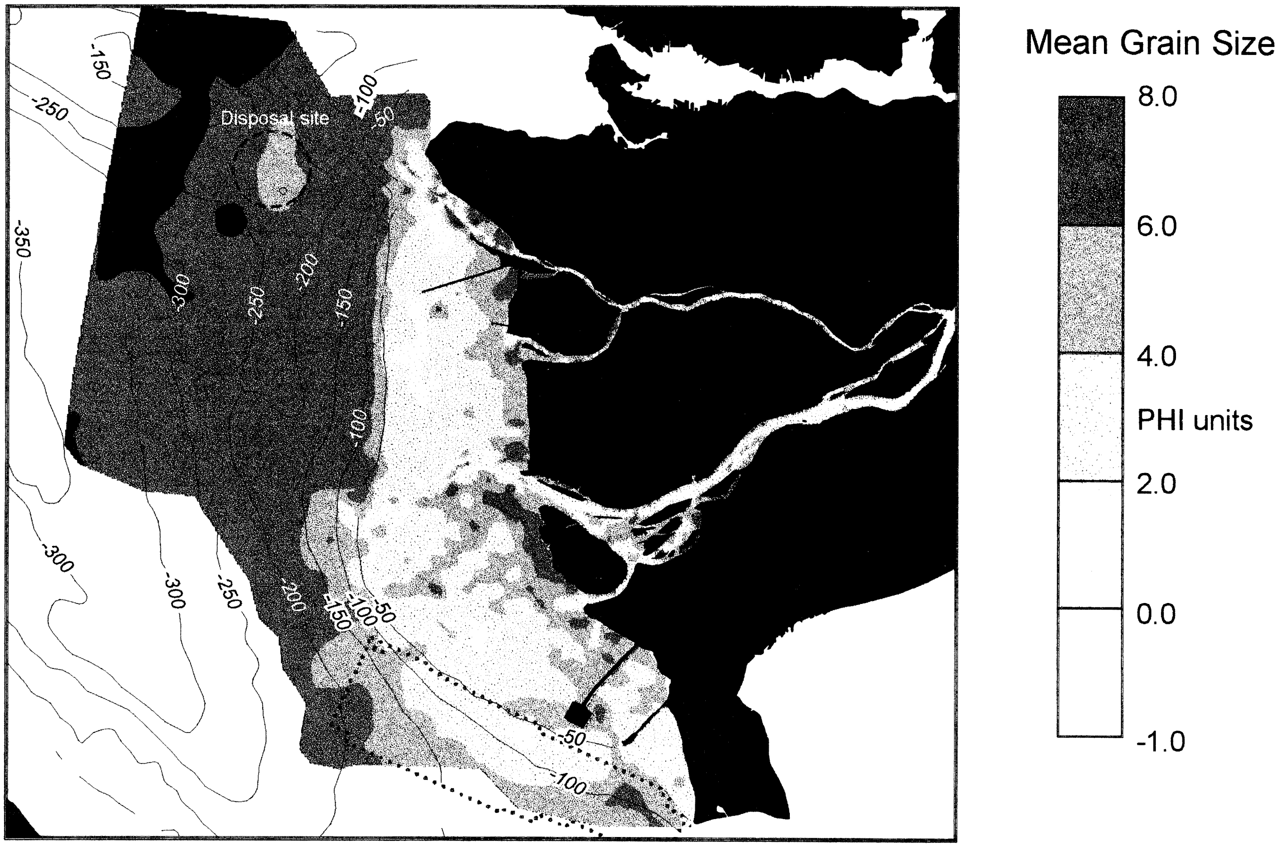

Figure 3. Mean grain size of surficial sediments of the Fraser River and delta.

ward as the southeasterly ebb tidal drag on the plume is balanced by the Coriolis effect (THOMSON, 1981). Waves in the Strait are primarily fetch limited with significant storm wave heights less than 2.1 m and maximum heights less than 3.3 m (THOMSON, 1981).

METHODS

The Geological Survey of Canada has conducted several marine geological and geophysical surveys over the Fraser delta slope using high resolution sub-bottom profilers and sidescan sonar since 1991. Interpretations of surficial sediment facies based on the geophysical and core data are summarised in HART *et al.* (1995) and HART and BARRIE (1995). During these marine programs more than 150 surficial grab samples were collected in the prodelta region and the basin of the southern Strait of Georgia. An additional collection of 1500 grab samples in the river, delta front and delta slope were collected by GeoSea Consulting under contract to the Government of Canada (MCLAREN and REN, 1995). The interpretations presented here are based on the textural analyses of these surficial sediment data sets in combination with the geophysical and core data. An ArcInfo GIS was employed to synthesis these relatively large data sets.

SEDIMENT DISTRIBUTION PATTERN OF THE SUBAQUEOUS FRASER RIVER DELTA

PHARO and BARNES (1976), from sampling undertaken in 1970, provided the first overview of the sediment distribution of the southern Strait of Georgia. Sturgeon Bank has a medium to fine grained sandy delta plain that changes into a muddy facies on the western edge before the break in slope (Figures 2 and 3), where a mixed sediment distribution occurs. The slope consists entirely of muds becoming increasingly finer downslope from primarily silts to a mixture of silt and clay. The muddy prodelta extends from the base of the slope to at least 60 km to the northwest, up the Strait of Georgia and becomes increasingly clay rich with increased distance from source (PHARO and BARNES, 1976). The outer delta plain and delta slope of Sturgeon Bank progrades with the deposition of mud from the plume that is deflected north, as indicated by ^{137}Cs fallout stratigraphy (Figure 4). Rates of 10 cm/yr occur near the mouth of the main channel, but these drop to less than 3 cm/yr farther than 4 km offshore (Figure 4). Roberts Bank, however, has a more variable sediment pattern on the delta plain with predominantly fine sand, changing progressively to silt towards the intertidal estuary (Figure 2). On the delta slope of Roberts Bank the surficial sed-

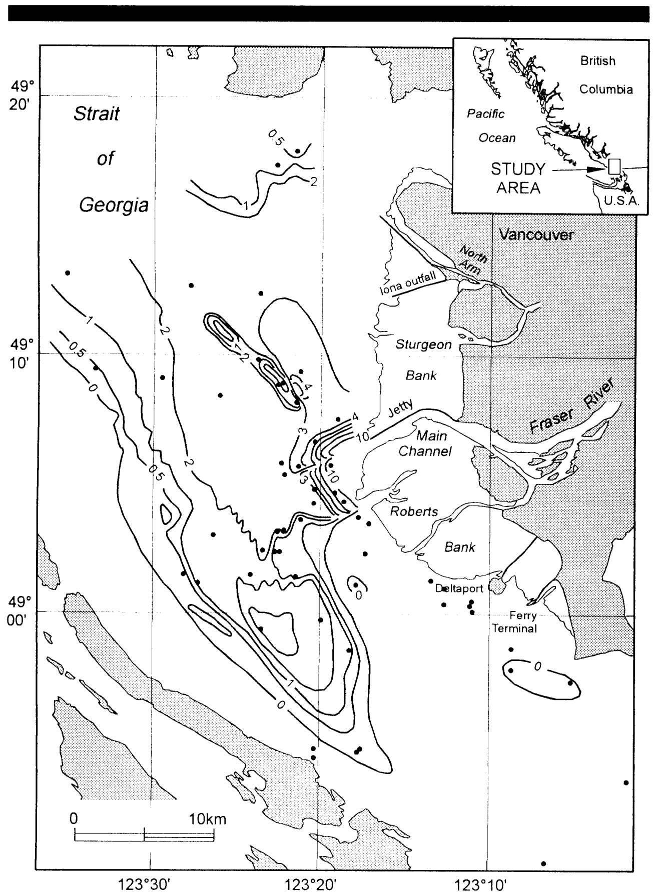

Figure 4. Distribution of sedimentation rates for the Fraser River Delta slope and prodelta based on the depth of the 1964 ^{137}Cs fallout record from HART *et al.* (1998) and EVOY *et al.*(1993). Contour interval is cm yr^{-1} and the dots indicate data points. Those data points that show no value represent areas of no present day sedimentation.

iments become progressively finer (silts) except for southern Roberts Bank where the dominant sandy delta plain continues and coarsens well onto the delta slope, becoming finer-grained at the base (Figure 3).

HUMAN IMPACT ON THE SEDIMENT DISTRIBUTION PATTERN

Several anomalies exist in this general sediment distribution pattern that do not correspond to normal delta sedimentation patterns. The first apparent anomaly is the sediment distribution pattern near the main distributary channel of the river (Figures 2 and 3), which is distinctly different on either side of the river channel. The channel jetty is on the north side of the river while the south side of the channel is not constrained. Just north of the channel wall the surficial sediments are well-sorted medium sands but south of the channel a mixture of sands and silts exists (Figure 2). HART *et al.* (1998), in establishing the sedimentation rates using ^{137}Cs fallout stratigraphy for the modern Fraser Delta, concluded that there is an asymmetry in accumulation rates near the river mouth, with higher rates extending onto the delta foreslope to the south rather than to the north (Figure 4). Jetty construction prevents sediment from being discharged to the north into the intertidal zone until the river reaches the break in slope. Net erosion of the marshes to the north on Sturgeon Bank have been directly attributed to the lack of sediment reaching the delta plain from the river (WILLIAMS and HAMILTON, 1994). Using ^{137}Cs, it was determined that sedimentation rates were lower by an average of 51% in the period 1964–1981. Bedload transport occurs to the south on the upper delta slope primarily during freshet conditions (HART *et al.,* 1998). Much of the material deposited near the mouth of the river and just south is transported to the prodelta as debris flows and turbidites.

Secondly, there is a linear region of fine grained sediment (silt) that extends in a E-W orientation for 6.0 km, centered on the Deltaport, totally surrounded by moderately-well sorted fine to medium sands (Figures 2 and 3). A borehole drilled in 1993, just to the west of the Deltaport, consisted of mud for the upper 1.7 m, overlying more typical interbedded sands and silts. This sediment facies does not conform to bathymetry and crosses from the shallow delta front to the delta slope. Sediment samples collected in 1970 (PHARO and BARNES, 1976), before the Deltaport was completed do not show this pattern, though their sampling only covered the seaward end of this anomaly. A similar but more limited situation exists just south of the Iona sewage outfall (Figure 1) causeway, which extends for 1.0 km.

This zone of finer-grained sediment on Roberts Bank would appear to be an area of deposition. Indeed, a study using the sediment trends method of MCLAREN and BOWLES (1985) for the Fraser River and Delta indicates that this distinctive area is one of flow separation of the main northwestward tidal current due to the existence of the Deltaport and ferry causeways (MCLAREN and REN, 1995). The anthropogenic features are barriers to normal flow resulting in the formation of back eddies. The causeways act in a similar fashion to a coastal headland in an area of unidirectional currents. For example, eddies are known to form behind headlands that protrude into macrotidal currents along coastline of the Bristol Channel, Great Britain (COLLINS *et al.,* 1979; PATTIARATCHI *et al.,* 1986). DAVIS *et al.* (1995) demonstrate how this eddy formation can take place past a headland using a two-dimensional steady flow model. If the currents are deflected away from causeways as they would by natural headlands, then the tidal current velocities will drop close to the features, which unlike typical headlands, do not have a fully developed shoreface zone. These areas, therefore, would have reduced seafloor current energy resulting in silt deposition. The sources of the silt are the Fraser River plume, when it does come south, and primarily local dredge spoils. In the basin formed between the causeways, the changed tidal flow patterns allow for the periodic erosion of dendritic drainage channels within the eelgrass and altered the coastal habitat as tidal flows are focused towards the head of the basin (DUGGAN and LUTERNAUER, 1985; TARBOTTON *et al.,* 1993).

Finally, the most striking feature of the sediment distribution pattern on the present Fraser River Delta is the apparent difference between the delta front and slopes of Sturgeon Bank to the north and Roberts Bank to the south of the

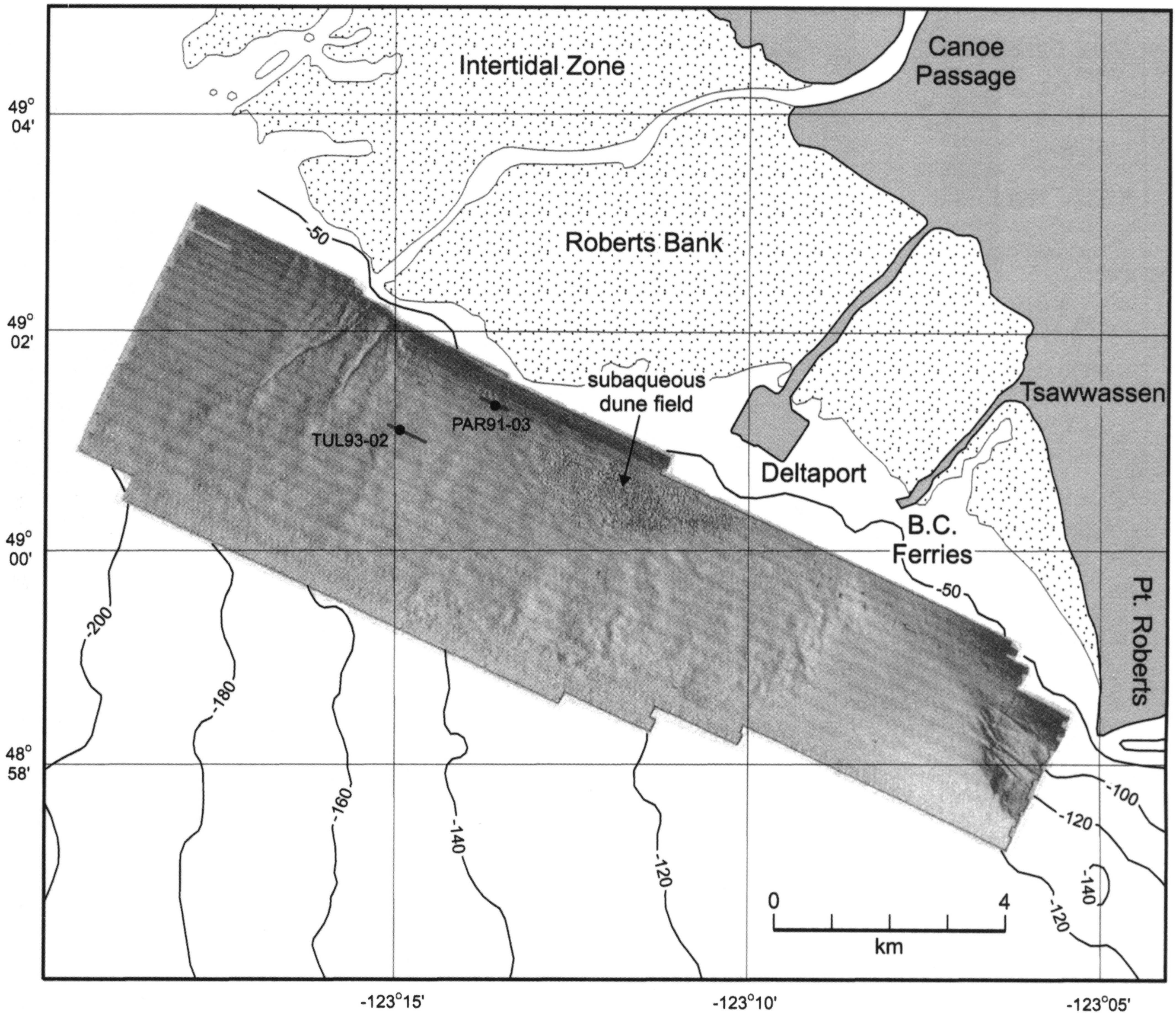

Figure 5. Swath bathymetry of southern Roberts Bank highlighting the subaqueous fan complex and relict submarine distributary channels.

main channel. Sedimentation occurs on the slope and prodelta of the Sturgeon Bank under natural conditions except in the area of the offshore dumpsite (Figure 1) where anthropogenic sediment of various grain sizes have been deposited (Figures 2 and 3). However, on southern Roberts Bank the mean grain size of the sediments of the delta front and slope (Figure 3) does not compare with the texture of the present sediment load carried by the Fraser River and there is no evidence for present day sedimentation (Figure 4). This area of southern Roberts Bank is defined acoustically by discontinuous wavy reflectors, buried channels and transparent mounds that consist primarily of fine sands and silts and form a volume of approximately $1 \times 10^9 m^3$. The nature of the gullies and failures highlighted by the swath image (Figure 5) are similar to those found on present submarine distributary channels elsewhere on the delta (HART *et al.,* 1992; CURRIE and MOSHER, 1996). High-resolution sub-bottom profiles collected within the subaqueous fan complex illustrate the existence of paleochannels and adjacent failed sediments (Figures 6 and 7).

As the river mouth changed location across the delta plain, the associated distributary channels migrated resulting in the fan complex being built up over a period of time on southern Roberts Bank. A similar situation would likely exist at the present river mouth if the channel had not been confined and no dredging was occurring. Radiocarbon dates taken on wood fragments from sediments collected in vibrocores on Roberts Bank that intersect different submarine distributary

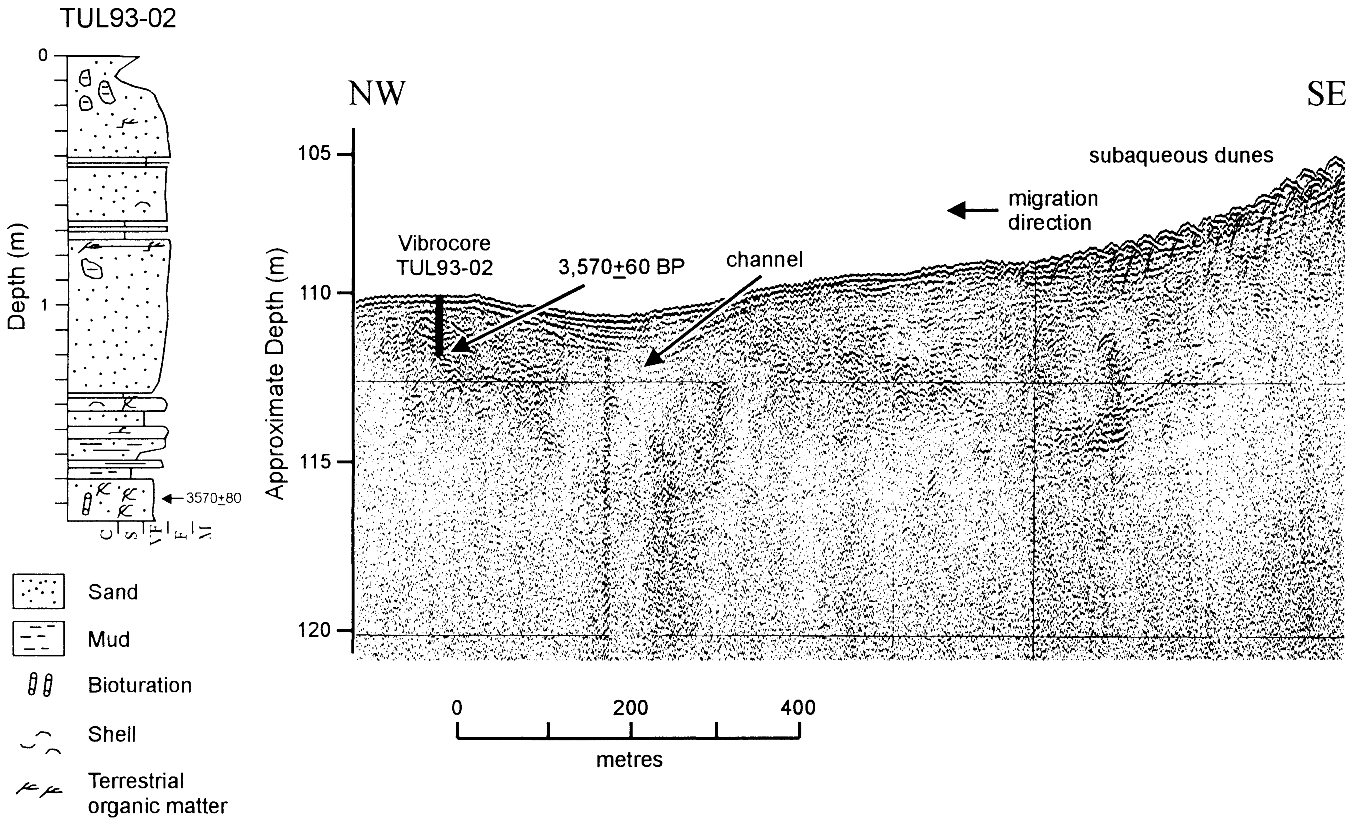

Figure 6. Seistec high resolution sub-bottom profile and vibrocore (TUL93-02) taken within the Roberts Bank subaqueous fan complex. Location of vibrocore shown in Figure 5.

channels suggest that these were active anywhere from 3,570 to 2,360 C^{14} yr BP (Figures 6 and 7). The dated wood fragments, however, may well have undergone significant transportation and subsequent re-deposition. Regardless, these dates do suggest that the river mouth was in this area of Roberts Bank from the later part of the Holocene up to historic times as suggested by CLAGUE *et al.* (1991). The last active channel which enters southern Roberts Bank from Canoe Pass can be seen in the northwestern portion of the swath bathymetric survey (Figure 5).

The Fraser River Delta appears not only to be non-progradational on most of southern Roberts Bank but also erosional. An erosional unconformity exists at the seafloor truncating the relict distributary channels with superimposed subaqueous dunes transporting the eroded sand (Figures 6 and 7). The radiocarbon dates suggest that the last 2000 to 3000 years of stratigraphy have been removed by erosion. Since the primary direction of sediment transport is northwestwards and the river has been north of Roberts Bank since 1827 (CLAGUE *et al.,* 1983) and is now constrained and dredged, little coarse-grained sediment has been available for deposition on Roberts Bank for the last 170 years. A large area of the Roberts Bank fan complex has a superimposed subaqueous dune field (Figure 5), with a predicted mean sediment transport rate of 127 kg/m/day in a northwesterly direction (KOSTASCHUK *et al.,* 1995). This suggests significant transfer of sand with the only source of sediment being the underlying seabed and local dredge dumping. ATKINS *et al.* (1998) argue that the subaqueous dune field exists due to reworked dredgate from the development and enlargement of the Deltaport beginning in 1968. However, there is no information with regards to the grain size of the material released as dredge spoils, particularly in the medium grain size range, the primary grain size of the subaqueous dunes. Seismic profiles collected in 1966 confirm that the subaqueous dunes preexist the development of the Deltaport, but these only detail the existence of the subaqueous dune field and not its extent. Regardless, dredge spoil dumping has had an impact on the development of the subaqueous dune field but does not in itself explain the existence of the feature. In addition, the delta slope appears to be greatest along the break in slope (exceeding 10°) at the shallow end of the subaqueous dune field adjacent to the causeways and flattens to less than 1° at the base of the foreslope based on the swath bathymetry (CHRISTIAN *et al.,* 1997). Whether this erosion is related to the causeways or enhanced since the placement of the causeways, by eddy formation, cannot be determined at present. However, it appears that the lack of sediment supply to this southern portion of the delta from the confined and dredged river has a direct impact on the rate of erosion.

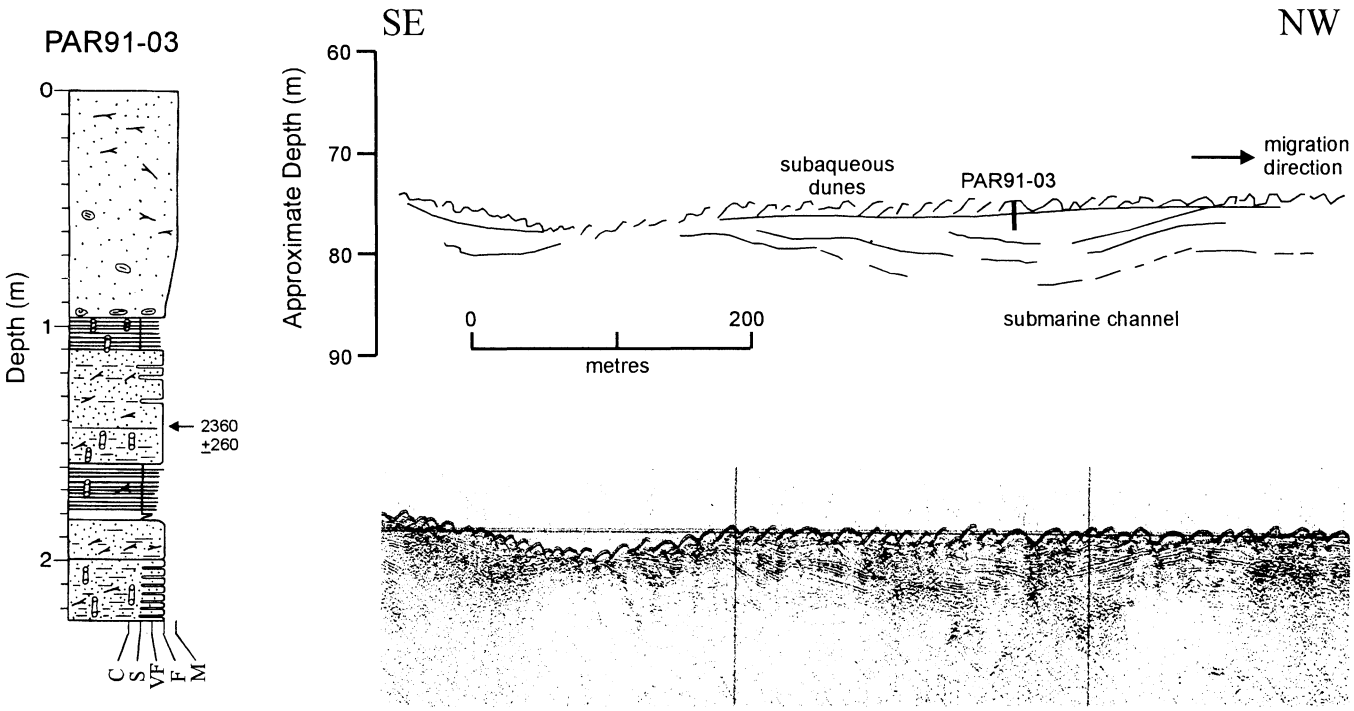

Figure 7. Huntec DTS sub-bottom profile and interpretation within the subaqueous dune field on Roberts Bank. Facies stratigraphy within a submarine buried paleochannel and the overlying subaqueous dune can be observed in Core PAR91-03. Index of stratigraphic symbols is shown in Figure 6 and the location of the vibrocore is shown in Figure 5.

DISCUSSION

There is indirect evidence from the sediment distribution data that the changes to the Fraser Delta environment have been caused by 1) the building of the causeways across the delta plain, 2) the confinement of the river channels to their present courses and 3) river dredging. McLean and Tasssone (1991) conclude that the volume of sand dredged for river maintenance and construction material exceeds that supplied to the estuary by the river. McLaren and Ren (1995) further suggest from their sediment trend analyses that the sand deposition over most of the delta plain is no longer the result of normal deltaic processes and the tidal flat environment will be subject to further erosion and sedimentological changes if the sand supply continues to be restricted.

Clearly, there is ample evidence that the amount of sand sized material now entering the delta is negligible, except at the mouth of the main channel where it enters the delta slope and primarily the prodelta. Fine-grained deposition does occur to the north of the main channel on the delta slope and prodelta of Sturgeon Bank but little sediment gets onto the delta plain or south of the river mouth except in the area immediately south of the river channel. Little is known of annual subsidence or compaction rate of the delta. Assuming even minimal subsidence, it is clearly evident that there is a risk of enhanced erosion and instability of the delta, particularly along the delta front and the intertidal estuaries. Moreover, the Fraser Delta is situated in an area of high seismic risk, where considerable damage is likely to result from liquefaction, ground motion amplification and landslides (Clague, 1997). If the delta foreslope is being eroded with no new sediment input, as is the case for southern Roberts Bank, then the impact of an earthquake on the stability of the delta and the structures built on it could well be great, particularly as the eroding delta foreslope sediments overlie a geotechnically sensitive marine silt and clay unit (Christian *et al.,* 1997).

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