



Environmental Geology of the Fraser Delta, Vancouver

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SUMMARY

Environmental geological and geophysical studies of the submarine portions of the Fraser delta at Vancouver reveal complex patterns of sedimentation, erosion and slope instability resulting from natural and industrial activity. Knowledge of the spatial and temporal variability of these processes is needed to help identify sea-floor hazards in areas of significant economic importance, and to monitor environmental contamination and changes to the physical environment due to industrial activity. Portions of the delta slope adjacent to the main fluvial distributary are prone to downslope mass movement in response to sediment loading, accentuated by the development of steep subaqueous slopes and interstitial (biogenic) gas. The presence of Canada's largest coal export facility, ferry terminals, and submarine high-voltage cables in close proximity to areas of mass movement are causes for concern. Triggering events for other large slope failure complexes (several tens of square kilometres in areal extent) include large earthquakes.

RÉSUMÉ

Des recherches géologiques et géophysiques sur l'écologie des portions sous-marines du delta du Fraser à Vancouver démontrent que les processus de sédi-

mentation et d'érosion y sont complexes, et que l'instabilité des pentes dépend à la fois de causes naturelles et de l'activité industrielle. La variabilité temporelle et spatiale de ces causes doit être connue pour aider à l'identification des risques naturels sur les fonds marins des zones d'importance économique et permettre une surveillance efficace de la contamination du milieu et la détection des changements physiques du milieu reliés aux activités industrielles. Certaines portions des bordures du principal canal d'évacuation fluviale sont sujet à des glissements de terrain dus à l'intensité de la sédimenta-

tion en ces endroits, et à la formation de pentes sous-marines abruptes et de gaz biogéniques interstitiels qui en accentuent l'instabilité. Les séismes forts sont parmi les déclencheurs de grands glissements de terrain (plusieurs dizaines de km²) sur la pente du delta.

INTRODUCTION

Like many other large cities, Vancouver and its outlying urban areas (1994 population 1.7 million) lie in close proximity to the sea (Fig. 1). The inevitable consequence of this proximity is the exploitation of the sea floor and overlying water column for a variety of uses, which in-

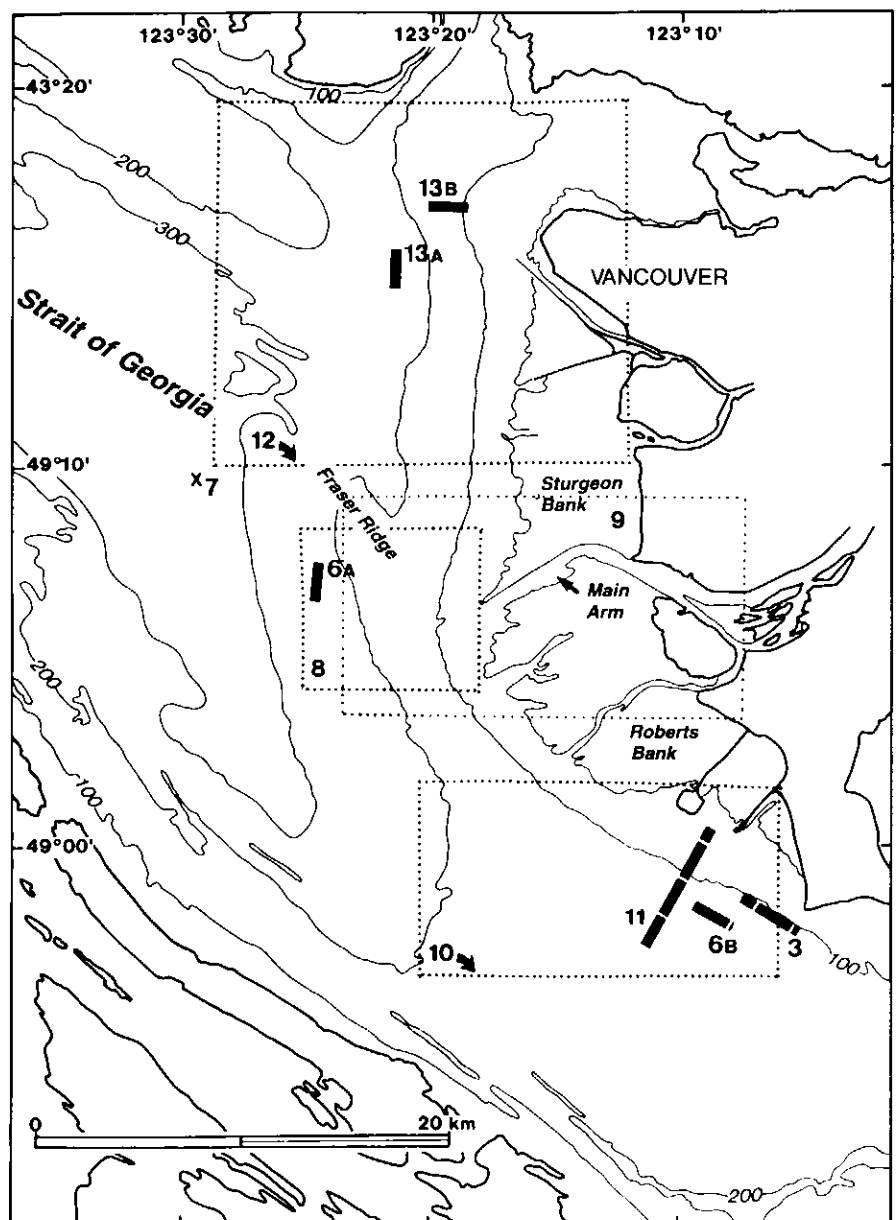


Figure 1 Location map of Fraser delta showing bathymetry and location of subsequent figures.

clude sewage disposal, fishing, dredge spoil dumping, construction of jetties, navigation/transportation, and the laying of submarine cables (electrical transmission, telecommunications). A partial summary of some of the developments on the sea floor and adjacent tidal flats is listed in Table 1.

Unlike most other coastal cities in Canada (e.g., Hamilton, Ontario, Versteeg *et al.*, see pages 145-151, this volume; Halifax, Nova Scotia, Fader and Buckley, see pages 152-171, this volume)

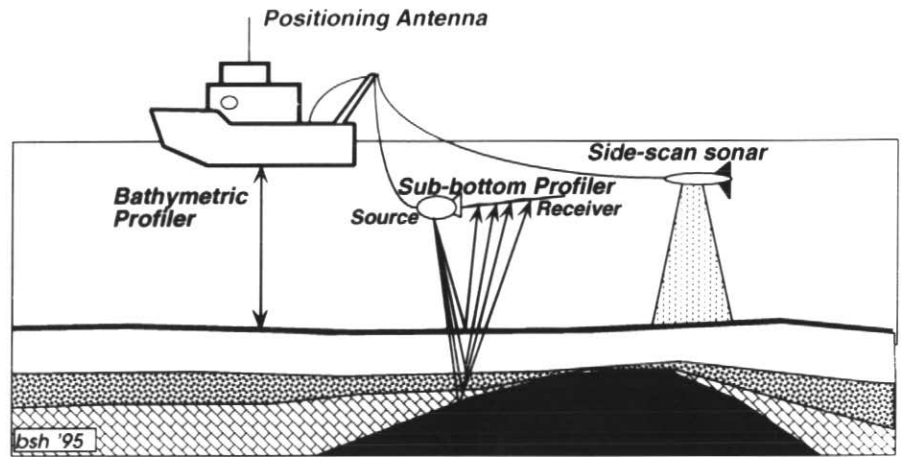
the Vancouver urban area is adjacent to a rapidly prograding delta. The Fraser delta is a post-glacial Holocene feature, no older than 10,000 years, that is rapidly building out into the Strait of Georgia (Fig. 1). Submarine sedimentation rates of a few centimetres to a few decimetres per year have been measured from some portions of the delta, while other parts are known to be eroding (Mathews and Shepard, 1962; Hart *et al.*, 1993; Evoy *et al.*, 1993). High sedimentation rates such as these are

commonly associated with various forms of submarine slope instability (e.g., Prior and Coleman, 1984). Furthermore, because this is a region of high seismic activity (Clague, in press), the potential exists for earthquake-induced submarine slope failure. Large failures have the potential to damage not only sea-floor installations, but also structures on the adjacent tidal flats (Luternauer *et al.*, 1994). It has been suggested that low-lying portions of the delta plain could also be affected if a

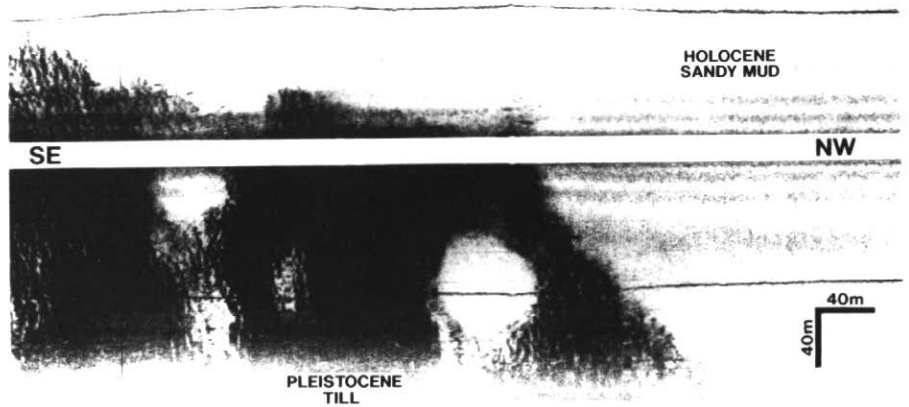
Table 1 Fraser Delta: selected sea-floor/tidal flat installations and activities.

WHAT	WHERE	HAZARDS/ISSUES
12 High Voltage Cables - BC Hydro Initially lain in mid-1950s Supply electricity to Vancouver Island	Crossing southern Strait of Georgia from Roberts Bank to Galiano Island	Trawling, burial by sediment (reduces conductivity), submarine failure
Fibre optics telecommunications cables Lain on seafloor in 1993	Galiano Island to Sturgeon Bank, Nanaimo Harbour to Point Grey (English Bay)	Trawling, illegal dumping, submarine failure
Jetty/dyke construction to fix courses of distributaries and to protect low-lying delta plain Began in late 1800s	Sturgeon and Roberts Banks	Habitat change, changes in sedimentary dynamics
Sand Heads lighthouse Constructed mid-1960s	Mouth of main Arm, Fraser River	River mouth failures
BC Ferries - Tsawwassen Terminal Constructed in 1959-60, expanded in 1991. 5.9 million passengers and 2.0 million vehicles in 1992	Edge of tidal flats, Roberts Bank	Delta slope failure, changes in sedimentary dynamics
Iona Sewage outfall Treated sewage from greater Vancouver region Initially discharged onto tidal flats, submarine extension (down to 100 m depth) in 1988	Sturgeon Bank, near Middle Arm	Discharge in proximity to trawling grounds, delta slope failure
Point Grey dumpsite Dredge spoils and other land-derived wastes Established in 1968 by Department of Transportation	Deep water (ca. 200 m) offshore from Point Grey	Illegal dumping outside limits interferes with fishing
Roberts Bank "Superport" Originally constructed in 1969, expanded in 1981-82 Canada's largest coal export facility	Edge of tidal flats, Roberts Bank	Delta slope failure, changes in sedimentary dynamics.

Figure 2 Illustration of simultaneous collection of bathymetry (hull-mounted system), sub-bottom profiler (high-resolution seismic) and side-scan sonar data during marine geophysical survey. Ship's position fixed using satellite-based system such as GPS. Location of profiler and side-scan towfish with respect to antenna (setback) determined by acoustic positioning systems mounted to towfish (for detailed work) or (for reconnaissance work) using cable length out, visual estimate (surface tow systems) or post-survey calibration to bathymetry data.



A



B

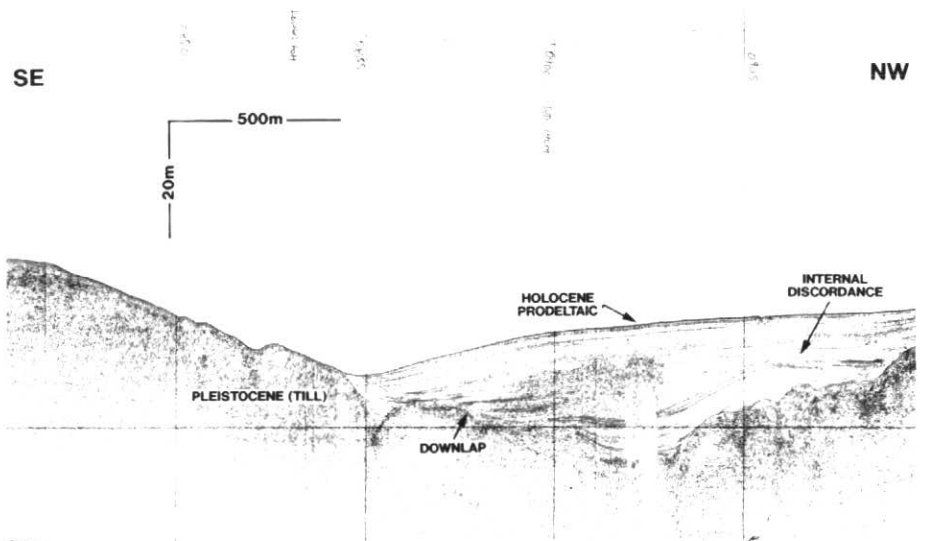


Figure 3 (A) Side-scan sonar image (Klein 100 kHz) and (B) corresponding high-resolution seismic profile (Huntec Deep Tow) showing Pleistocene deposits overlain by Holocene prodeltaic sediments. Using only the sonograph, it would be difficult to determine whether the dark patches represented a surficial deposit of dense material (e.g., Fig. 13) or an outcrop exposure of an underlying unit. Note fine-scale stratigraphic detail visible on seismic profile. For location, see Figure 1.

large submarine failure were to induce a tsunami in the Strait of Georgia (Hamilton and Wigen, 1987).

This paper will synthesize the results of previous environmental geological and geophysical studies of the submarine portions of the Fraser delta (Fig. 1). The principal objective is to use the Fraser delta work as an example to examine the role of the environmental geologist in conducting environmental or slope stability studies.

MARINE GEOLOGICAL AND GEOPHYSICAL SURVEYING

Generally, the seabed and underlying strata cannot be directly observed, but must be examined indirectly, using geophysical methods (Fig. 2). Seismic, or sub-bottom, profilers are commonly used. There is a trade-off between the vertical resolution and the vertical penetration of seismic profiling systems: high-resolution systems such as the Hunttec Deep-Tow Seismic system

employed on the Fraser delta (see below) have a theoretical bed resolution of a few decimetres (based on dominant frequencies of 3-5 kHz), but typically penetrate only a few tens of metres, whereas single-channel airgun profiling systems (dominant frequencies of a few hundred Hz) may penetrate hundreds of metres, but have significantly less vertical resolution (metre scale). Bathymetric profilers operate on a similar principal to seismic systems, but use higher frequencies (typically 12 kHz or more) and sub-bottom penetration is usually negligible. Side-scan sonar systems use even higher frequencies (typically 100 kHz or 200 kHz) to produce images of the sea floor in a fashion somewhat analogous to airborne side-looking radar.

Distances for all acoustic-based systems are originally recorded in time units (seconds, or milliseconds), but these can be converted to depths (seismic, bathymetry) or distances (side-

scan sonar) if the velocity of sound in the transporting medium (water, sediment) is known or can be assumed. Modern side-scan sonar systems can compensate for survey speed variations in real time, producing undistorted images of the sea floor. Ideally, seismic, side-scan sonar, and bathymetry data can be collected concurrently, so that the subsurface structure and surficial expression of sea-floor features can be determined to help facilitate interpretation (e.g., Fig. 3A, B).

Much useful information about substrate properties can be obtained through seismic facies analysis incorporating information such as reflection character, amplitude and frequency (e.g., Bouma *et al.*, 1983; Scaife, in press; Boyce and Koseoglu, in press). When combined with surface sediment sampling and coring, these marine geophysical methods allow mapping of surficial features and surficial geology and the determination of subsurface geolo-

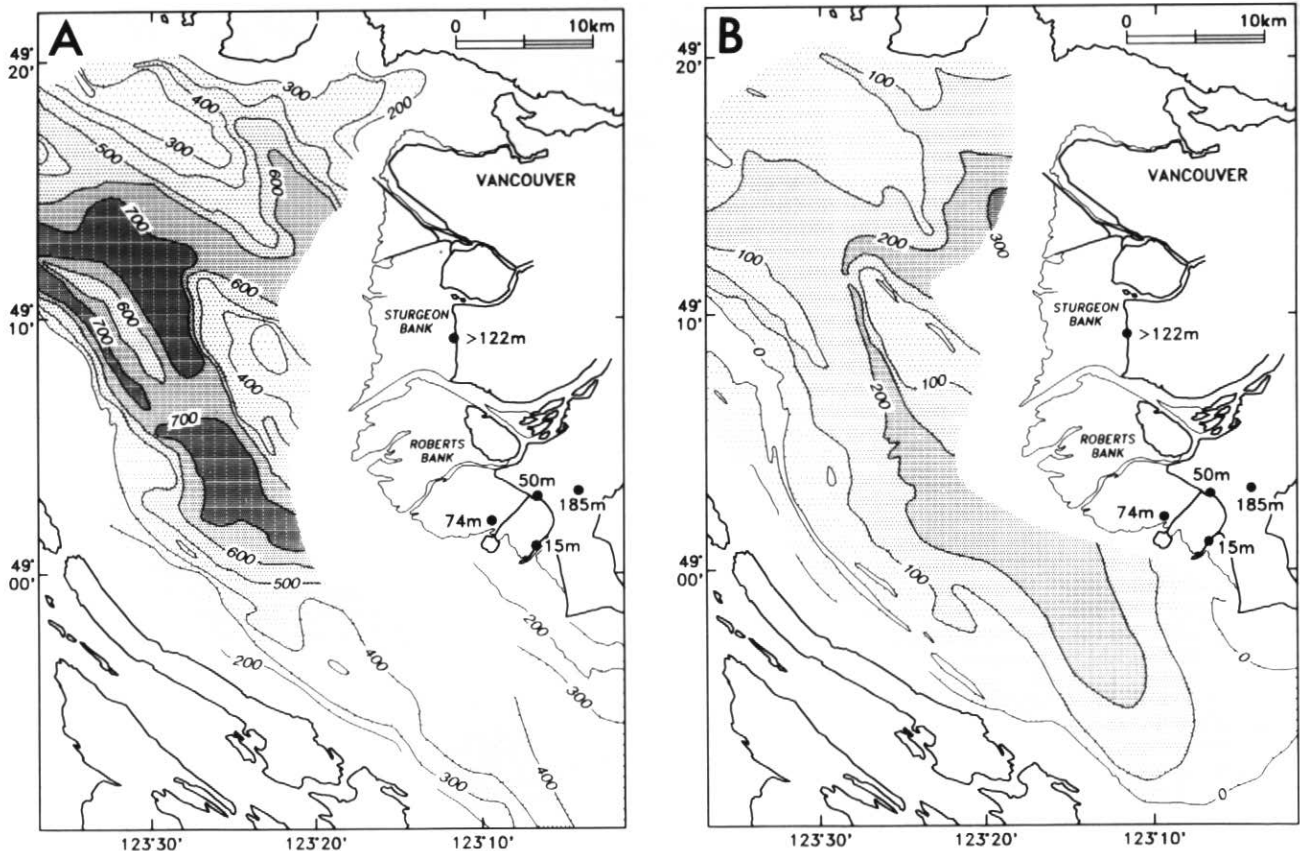


Figure 4 Example of (A) Time structure map (two-way time, milliseconds) from sea level to top of Pleistocene sediments or bedrock (where Pleistocene deposits are absent), and (B) isochron (two-way traveltime; thickness in milliseconds) map of Holocene deltaic and prodeltaic sediments, derived from seismic data. Isochron values can be converted to approximate thickness (metres) by dividing by 2 (to convert to one-way traveltime in ms) then multiplying by 1.5 m/ms ("average" velocity of sound in modern sediments). Note NW-SE trending ridges and troughs in structure map. Holocene sediments are absent in places, and are over 200 m thick offshore from Sturgeon Bank. Onshore points represent thicknesses of Holocene sediments (metres) measured from boreholes.

gy and stratigraphy. Experience has shown that the most beneficial approach to integrated marine geological and geophysical work involves conducting the geophysical work first, then using the coring or sampling to ground truth and sample acoustic facies, stratigraphic contacts, or other features of interest.

Several marine geological and geophysical surveys of the Fraser delta slope and adjacent Strait of Georgia have been conducted by the Geological Survey of Canada in the period 1982-1992. This work has resulted in the collection of 1) more than 1200 km of Huntex high-resolution seismic profiles along with fully corrected 100 kHz side-scan sonar imagery of the sea floor, 2) more than 5000 km of airgun seismic profiles (of which 2500 km is near or on the delta slope), and 3) more than 50 vibrocores, gravity and piston cores.

STRATIGRAPHY AND MORPHOLOGIC FRAMEWORK

The stratigraphy of the submarine portions of the Fraser delta was described most recently by Hart *et al.* (1995). At the base of the section are thrust Tertiary sedimentary rocks. Thrust sheets of these rocks form the Gulf Islands along the western margin of the Strait of Georgia and sea-floor ridges along the western part of the Strait. Stratified and unstratified deposits thought to be Pleistocene in age (based on coring, reflection character, stratigraphic position, and comparison with land-based studies) are present locally above bedrock. These deposits (tills, proglacial deposits, *etc.*) can be thick (many hundreds of metres in places). Glaciomarine sediments (clays with ice-rafted debris), deposited during glacial retreat, are found in the deep ice-scoured troughs and locally as a thin drape over ridges of bedrock or Pleistocene sediments. Holocene deltaic and prodeltaic sediments of the Fraser delta form the uppermost stratigraphic unit. These deposits are locally more than 200 m thick beneath the Strait of Georgia (Fig. 4), but are absent in places over ridges of Pleistocene or Tertiary deposits (*e.g.*, Figs. 3, 4). From coring and grab sampling (*e.g.*, Pharo and Barnes, 1976; Hart *et al.*, 1992a, b, c, 1995), delta slope and adjacent prodelta sediments are generally muddy, although sands are found locally (see below).

The Fraser delta is prograding into

water that is locally more than 300 m deep. Three principal morphologic zones of the submarine delta can be identified. The *delta front* is the wave-influenced portion of the delta at the seaward limit of the tidal flat, the lower limit of which is approximately 10 m depth. The *delta slope* is the relatively steeply dipping (typically 2° to 3°, locally over 7°) portion of the delta below the delta front that grades offshore into the less steeply dipping (typically < 1°) *prodelta zone*. The transition from the delta slope to prodelta occurs at depths that

increase northward, from approximately 100 m offshore of Roberts Bank to more than 180 m offshore from Sturgeon Bank. This morphologic picture is broken where the deltaic sediments drape and partially bury antecedent relief (*e.g.*, Fraser Ridge; Fig. 1).

By integrating geophysical surveying results, sampling and coring, maps can be constructed that depict the thickness (in milliseconds) of Holocene deposits (Fig. 4) and the surficial geology of the delta slope and proximal prodelta areas (Fig. 5). Seismic profiling suggests that

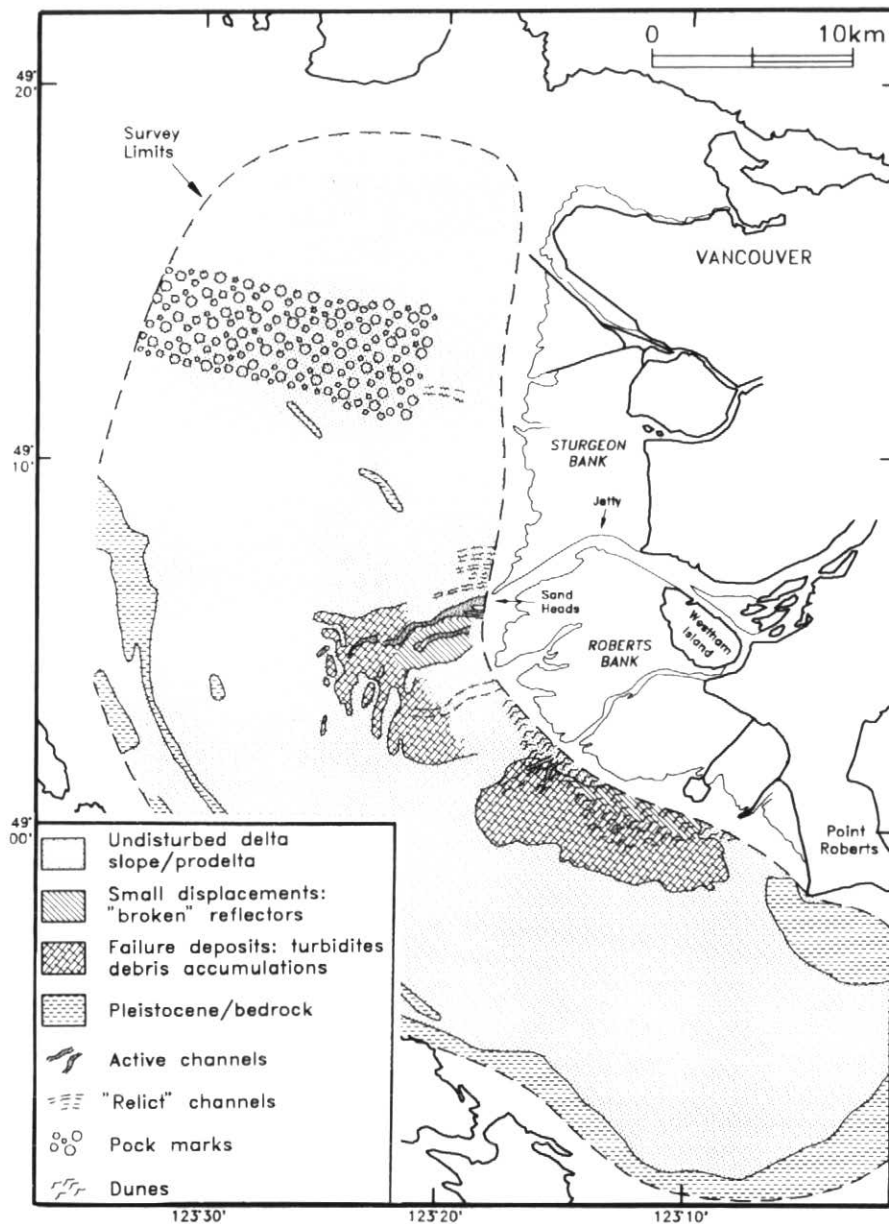


Figure 5 Surficial geology map of Fraser delta slope and prodelta areas derived from seismic and side-scan sonar surveys. Failure complexes form prominent components of the system in the southern and central regions. The northern part of the delta slope is relatively unaffected by slope failures, although a field of pockmarks (gas escape features) is found at the base of the delta slope.

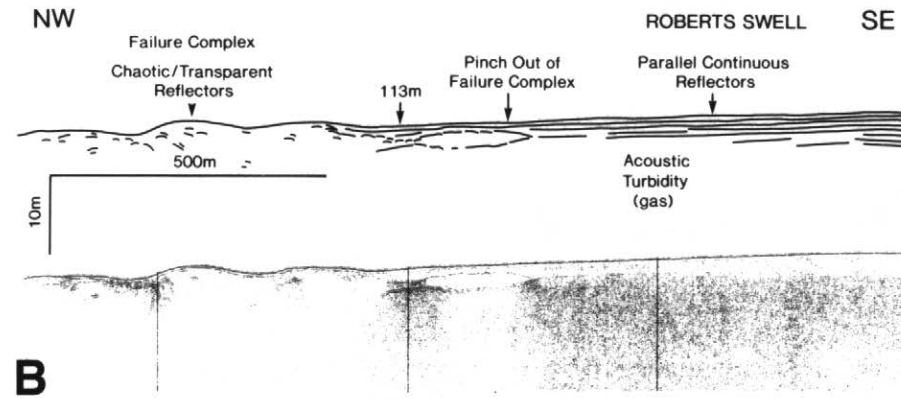
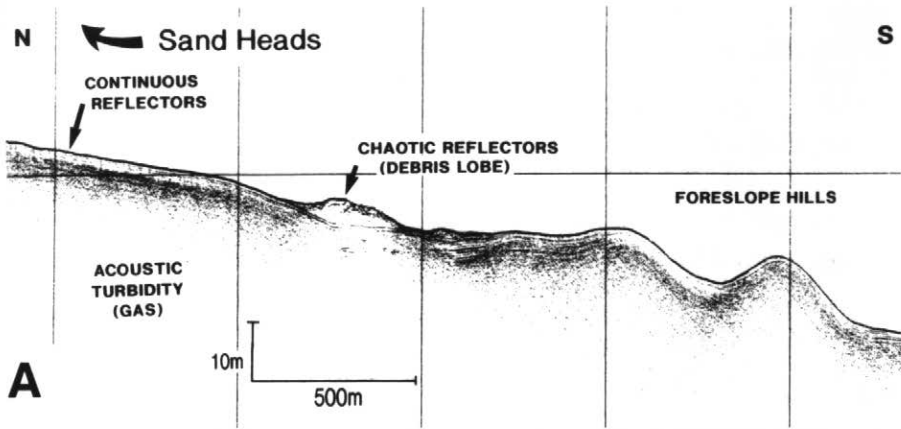


Figure 6 (A) Hunttec seismic profile from near base of delta slope seaward of Sand Heads. Parallel continuous reflectors with acoustic turbidity (fog-like seismic character which masks structure deeper than a few metres), characteristic of gassy, undisturbed muds and mounded chaotic reflectors of debris flow lobe. For location, see Figure 1. (B) Hunttec profile, with interpretation from base of delta slope near Roberts Bank. Chaotic and transparent reflectors which attenuate seismic signal represent sandy failure deposits, and interfinger with gassy, undisturbed muds.

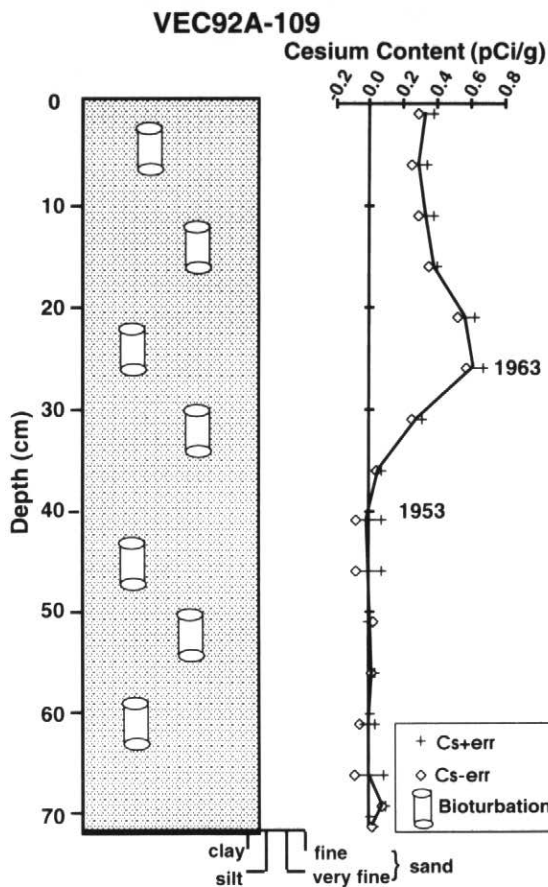


Figure 7 Sample core showing profile of ¹³⁷Cs with depth. Error bars also shown. The peak in ¹³⁷Cs activity at 26 cm depth corresponds to 1963, suggesting an average sediment accumulation rate of 0.93 cm a⁻¹. For location, see Figure 1.

most of these areas are unaffected by sediment instability phenomena, and that failures are restricted to specific areas (see below). Parallel continuous seismic reflectors are characteristic of undisturbed sediments, whereas failure deposits are characterized by transparent, chaotic or truncated reflectors (Figs. 6 A, B). Unfortunately, interstitial methane gas (manifest as acoustic turbidity on seismic profiles) adversely affects both resolution and penetration of seismic profiling systems on much of the delta slope and prodelta (e.g., Figs. 3, 6A, B; Hart and Hamilton, 1992), thereby limiting the ability to image much of the internal structure of these areas (see also Fader and Buckley, in press). The gas is derived from bacterial degradation of buried organic matter in the sediments, and *in situ* gas saturations have been measured which exceed 6% (Hart *et al.*, 1993). By raising sediment pore pressures, the gas contributes to submarine slope instability (Prior and Coleman, 1984).

Areas of deposition and erosion can at times be distinguished using seismic profiles (e.g., Hart *et al.*, 1992d) and can be identified by measuring activities of cesium 137 in cores. The presence of ^{137}Cs in a sediment qualitatively indicates recent deposition, since this man-made radioelement is known to be primarily a product of atmospheric nuclear weapons testing (there are no natural sources), which began in the mid-1950s. By measuring profiles of ^{137}Cs activity with depth in cores, it is sometimes possible to calculate sedimentation rates (Fig. 7). For cores of constant lithology, the relative variations in concentration of ^{137}Cs are determined by the fallout signal (which is well documented globally) and the rate of deposition. This technique has been applied to cores from the Fraser delta slope (Hart *et al.*, 1993; Evoy *et al.*, 1993), and it is known that sediment is currently being deposited on most of the delta slope at rates typically about 1-2 $\text{cm}\cdot\text{a}^{-1}$, but locally more than 30 $\text{cm}\cdot\text{a}^{-1}$ near the mouth of the Main Arm. Sedimentation chronologies help establish contaminant-loading histories; Macdonald *et al.* (1991) have used this approach to examine heavy metal fluxes in the Strait of Georgia. The southern part of the delta slope (next to Roberts Bank) is swept by strong near-bottom tidal currents, and is a zone of non-deposition and erosion.

In the remainder of this section, three

specific portions of the Fraser delta are examined in detail. These sites have been selected because they illustrate a range of specific environmental geological problems.

Sand Heads Failure Complex

A submarine channel and failure complex is found on the delta slope seaward of the main distributary at Sand Heads (Hart *et al.*, 1992c; Kostaschuk *et al.*, 1992; Figs. 5, 8). Several submarine channels are present on the sea floor here, and the largest (fed by tributary channels in its upper portions) has a depth of incision that decreases down-slope, from more than 35 m on the upper delta slope to less than 3 m at the 200 m isobath. The width of this main channel

is typically about 250 m. The channel has been cut by episodic density currents derived from submarine failures at the river mouth such as those described by McKenna *et al.* (1992). Deposition at the river mouth reflects the interaction of the sediment-laden river discharge and the saline, tidally influenced waters of the strait (e.g., Milliman, 1980).

The area north of the main submarine channel is characterized by undisturbed suspension deposits that blanket the slope and are infilling a series of relict (*i.e.*, inactive) channels on the upper slope. A smaller active submarine channel is found on the delta slope just south of the main channel. Shallow rotational slides composed of muddy sediments that are broken up into a series of

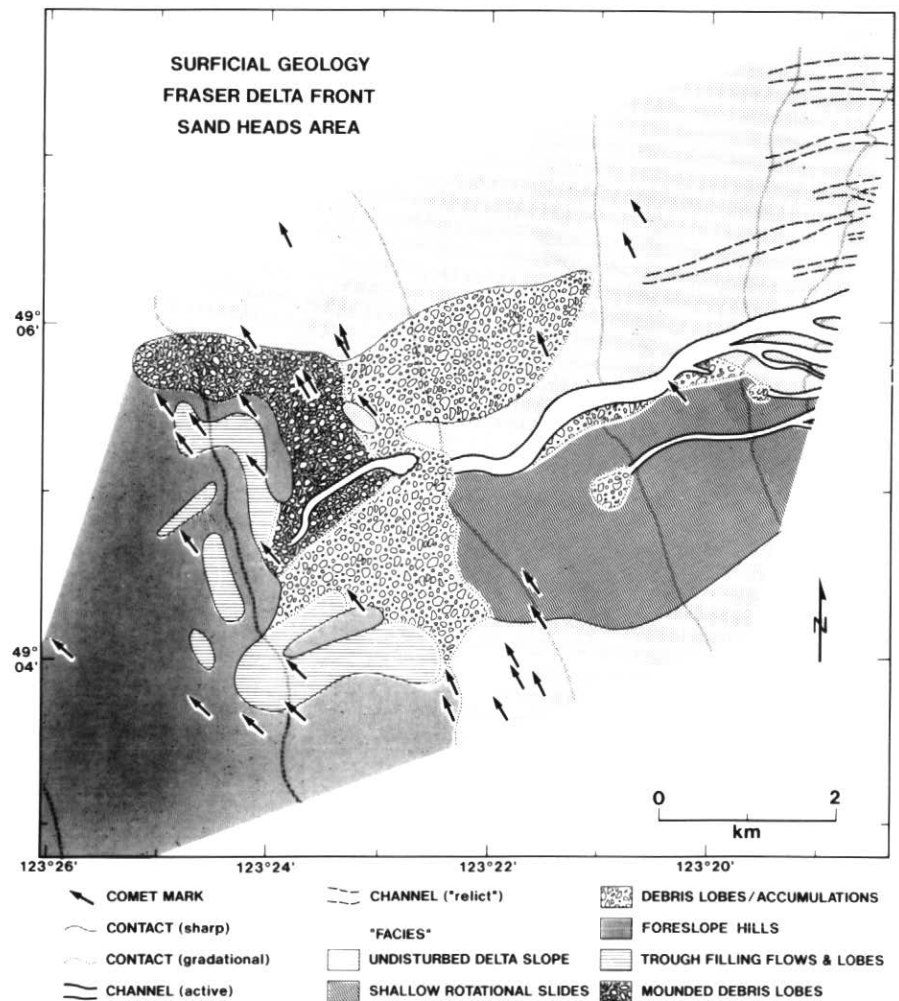


Figure 8 Surficial geologic map of the sea floor seaward of the mouth of the Main Arm of the Fraser River (see Fig. 1), prepared using side-scan sonographs, high-resolution seismic profiles, bathymetry and cores. Rapid sediment deposition on relatively steep slopes has led to the development of various failure-related morphological elements. Comet marks are current-formed scour marks around sea-floor debris, and can be used to identify dominant current direction. These are equivalent to the obstacle-induced sediment drifts of Fader and Buckley (in press).

rotated blocks, each many tens of square metres in areal extent, have developed south of the main channel in response to high sedimentation rates, steep sea-floor slopes (typically 6-7°) and elevated pore pressures.

Cores from the upper delta slope next to the Sand Heads submarine channel and its tributaries (Fig. 9) reveal the presence of centimetre- to decimetre-scale interbeds of sand (typically fine- to coarse-grained) and mud. Sand beds are generally absent from the delta slope more than about 250 m north of the main submarine channel, but are present on the delta slope south of the channel down to about 100 m water depth. The absence of sand beds to the north of the river mouth may be the result of jetty construction (Luternauer and Finn, 1983; Hart *et al.*, 1992c).

The Main Arm is not constrained to the south, and it seems possible that during spring flood conditions sand could be supplied to the upper slope, leading to slope failures that could have

generated the sand beds and laminae found in the mid-slope sediments. Morphological evidence presented by Hart *et al.* (1992c) from the upper delta slope south of the Main Arm (e.g., Fig. 8) indicates active failure on this portion of the delta, while north of the Main Arm the upper delta slope is undisturbed by recent failures and sand laminae or beds are generally absent. These results suggest that sedimentation patterns at the river mouth are measurably affected by jetty construction.

Beds of fine to medium sand can also be found in density current (turbidite) deposits near the base of the delta slope at the base of the Sand Heads submarine channel (Hart *et al.*, 1992c; Kostaschuk *et al.*, 1992; Evoy *et al.*, 1993; Fig. 5). Submarine channels are found incised in the sea floor offshore from other past and present distributary mouths, and lobes of sandy failure deposits are found at their bases (Fig. 5). In the past, these channels acted as conduits for the downslope transport of

sandy sediments. This association suggests that the failure complexes are part of the natural delta-building process. Since the Main Arm is no longer free to migrate, the sea floor seaward of the river mouth can be expected to continue to be a zone of ongoing slope instability.

Roberts Bank Failure Complex

The existence of a massive failure complex beneath much of the delta slope adjacent to Roberts Bank (Fig. 5) was first suggested by Hart *et al.* (1992b, d). Economically, this area is of major importance (Table 1; Fig. 10). Twelve of the high-voltage electrical cables that supply power from the mainland to Vancouver Island cross the tidal flats and the delta slope here. Canada's largest coal export facility (250 million tonnes loaded in the first 21 years of operations) was constructed at the seaward limit of the tidal flats (at the top of the delta slope), as was B.C. Ferry's Tsawwassen terminal, which handled nearly 6

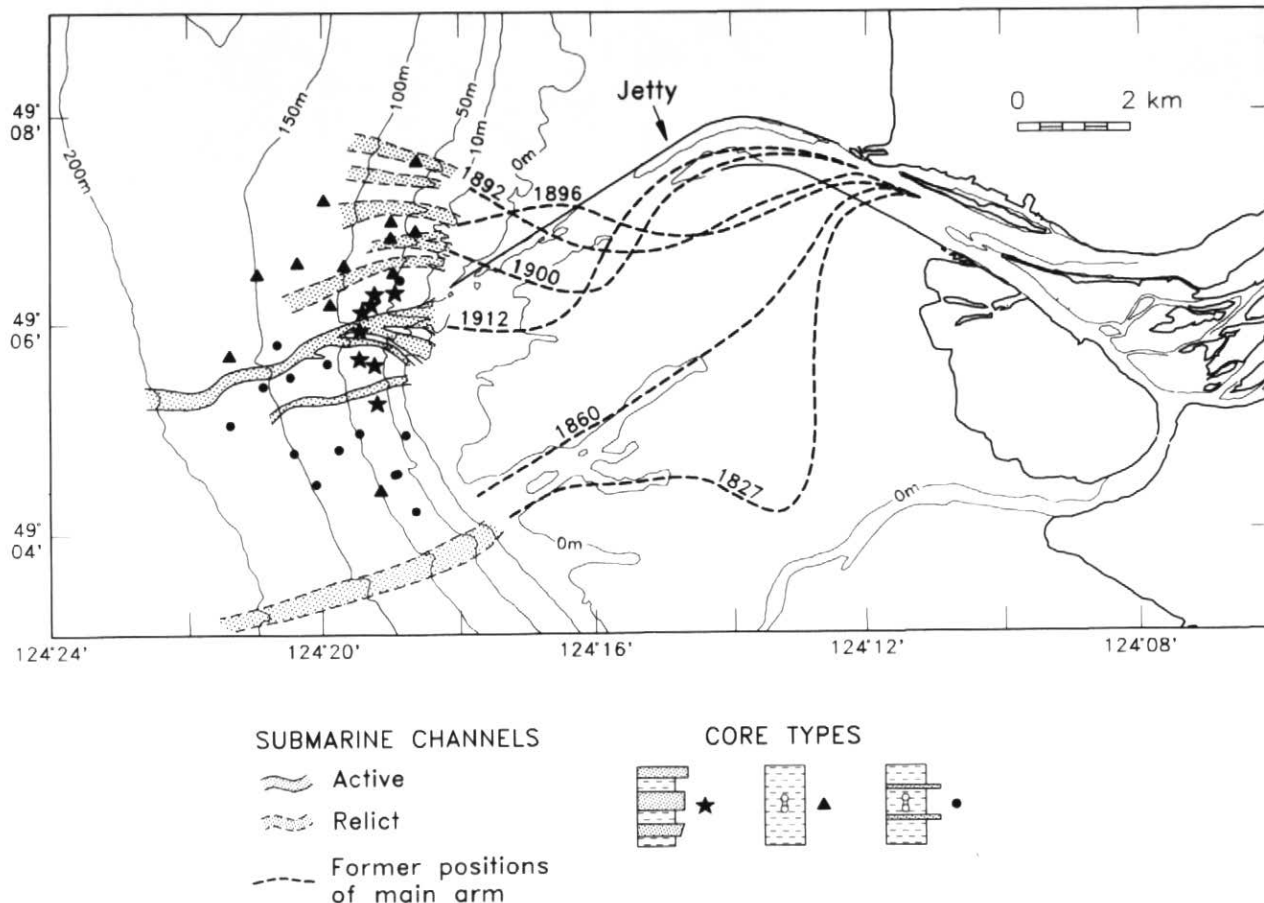


Figure 9 Distribution of lithofacies from upper delta slope seaward of mouth of Main Arm of Fraser River at Sand Heads as derived from core data. Former positions of river mouth shown (from Clague *et al.*, 1983). As discussed in text, stabilization of river course following jetty construction in early 1900s appears to have greatly influenced sedimentation patterns. See Figure 1 for location.

million passengers and 2 million vehicles during 1992.

Subaqueous sand dunes cover an area of the upper delta slope 28 km² in breadth centered offshore from the coal port (Figs. 5, 10). Bedform orientations measured on the sonographs and current meter measurements indicate that the bedforms are generated by strong flood tide currents (maximum currents reaching 1 m·s⁻¹ during spring flood tides). In places, the dunes have buried electrical transmission cables laid in the mid-1950s, attesting to the mobility of the bedforms. Trawler marks and dredge spoil patches are locally found in proximity to the cables.

Seismic profiles reveal the existence of a failure complex which underlies at least 40 km² of the delta slope (Fig. 10). Discontinuous wavy reflectors, chaotic reflectors and transparent mounds are all interpreted as failure deposits (Figs. 6B, 11) which together form a volume of approximately 1×10⁹m³ (Hart and Olynyk, 1994). The lack of subsurface penetration evident on high-resolution seismic profiles suggests that these are dominantly sandy deposits, an inference borne out by bottom sampling and coring (e.g., Pharo and Barnes, 1976; Hart and Hamilton, 1992). Airgun seismic profiles penetrate more deeply (but have less resolution of detail), and show that the failure deposits are more than 75 m thick beneath some portions of the upper delta slope.

As is often the case with large submarine failure complexes (e.g., Coleman and Prior, 1988), it is not possible to positively identify any single trigger

mechanism responsible for the initiation of failure. Hart and Olynyk (1994) suggested at least two episodes of large-scale retrogressive failure (involving liquefaction and subsequent flowage) of the delta slope. This conclusion suggests that the slope is affected by mass movements every few hundred years, and that the last such episode was a few hundred years ago. Such a magnitude and frequency of failure suggests that earthquake activity could have played a role in initiating failure (e.g., Clague *et al.*, 1992; Clague, in press). Given the current economic importance of the area, knowledge of the susceptibility of the delta slope to seismically induced failures is vital.

Point Grey Dump Site

The Point Grey offshore dump site was established by the Ministry of Transport in 1968 seaward of the North Arm of the Fraser River in about 210 m water depth (Figs. 12, 13). This is the most frequently used offshore dump site anywhere in the Pacific region, with up to 2.5 million m³ of material (mostly sand dredged from shipping channels, but also wood wastes and other types of miscellaneous debris; Packman, 1980) being dumped annually. Commercial fisheries in this area harvest at least 10 species of fish (including the bottom-dwelling sole and grey cod), and local fishermen catch 50-100 tonnes (t) of shrimp annually. Additionally, a submarine fibre

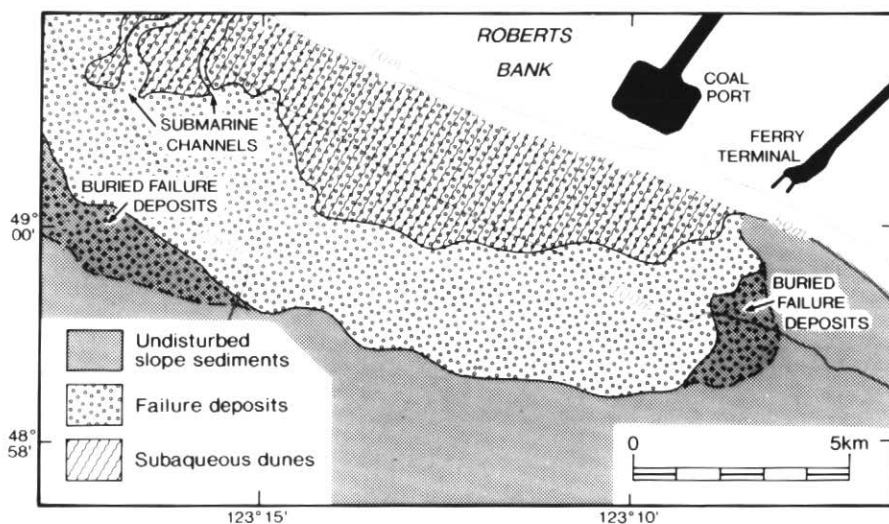


Figure 10 Surficial geology of delta slope adjacent to Roberts Bank showing extent of area underlain by failure deposits as mapped from seismic data and extent of subaqueous dune field mapped using sonographs. See Figure 1 for location.

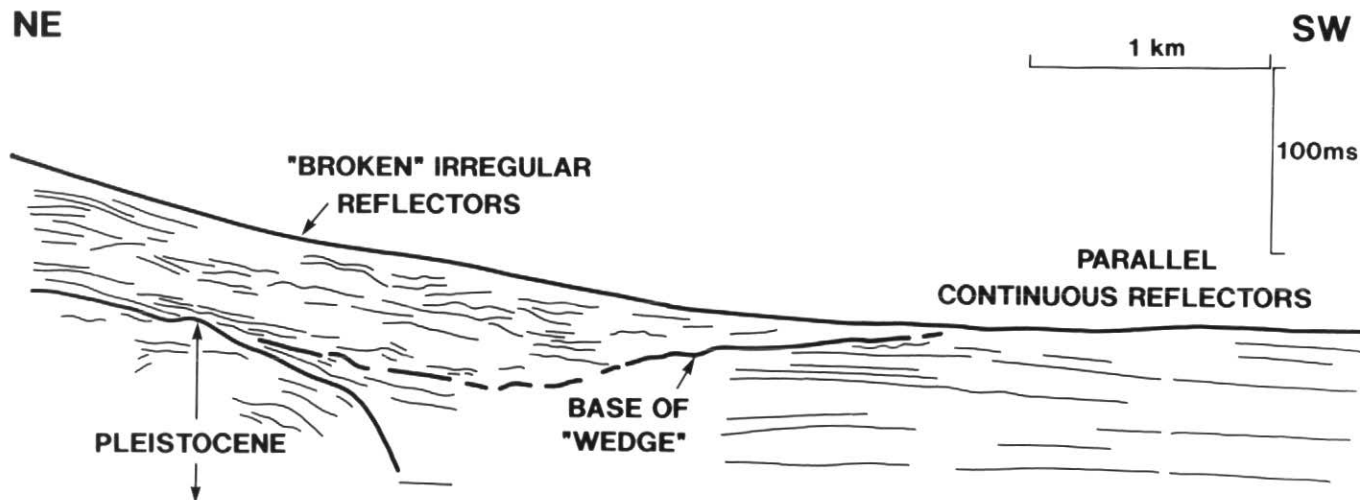


Figure 11 Line drawing interpretation of airgun seismic profile showing internal structure of delta slope adjacent to Roberts Bank, just seaward of Coal Port. Failure deposits in Holocene sediments exceed 75 m thick beneath upper portion of delta slope.

optics telephone cable (part of a \$16 million system to link Vancouver Island and the mainland) was laid on the sea floor close to the dump site in early 1993. Clearly, there is the potential for conflict between various activities in this area, and monitoring of the geographic range of each is essential. Dump site monitoring is an important component of the London Convention Waste Assessment Framework, and Canada has been using that accord to revise its ocean dumping regulations.

Unlike the featureless sea floor that characterizes most undisturbed portions of the Fraser delta slope, the sea floor in the vicinity of the Point Grey dump site shows abundant evidence of anthropogenic disturbance (Figs. 13A, B). Hart (1992) interpreted large (several tens of metres in diameter; Fig. 13A), circular to irregular dark patches as being produced by disposal from self-emptying (bottom-opening) barges. Linear to curvilinear successions of patches, each typically 15 m to 20 m in

diameter, were interpreted as the product of repetitive spoil dumping from a moving barge (Fig. 14B). Both types of dumping operations occur at the Point Grey dump site. The dredge spoils (sandy sediments and wood wastes) are visible on the side-scan sonar records because their acoustic characteristics differ from those of the adjacent sea floor (muds). High-resolution seismic profiles collected along with the sonographs indicate that the patches represent surface features, not exposures of till or other hard substrates (see Fig. 3). Other side-scan targets (miscellaneous refuse), typically several metres in length, are also visible in this area on sonographs. Some of the larger objects (probably concrete blocks) generated craters up to 10 m in diameter upon impact with the sea floor (Fig. 13A). The sea-floor heterogeneity observable on the sonographs (e.g., Figs. 13 A, B) could also explain some of the poor reproducibility of chemical analyses between successive sampling

surveys that has been noted for the Point Grey dump site (Sullivan, 1987). The dredge spoil patches are smaller than the positioning error of standard navigation systems, meaning that a contaminated patch sampled on one survey might be missed on a subsequent survey. Prior knowledge of such heterogeneity guides sampling design for biological or chemical sampling and analysis programs.

Dredge spoils were found on sonographs more than 4 km outside the dump site limit, and a well-defined trail of debris leading from Vancouver Harbour (e.g., Fig. 13B) has been mapped. Trawler marks (produced by bottom trawling) were also observed on the sonographs, and on Sturgeon Bank, dredge spoil tracks and trawler marks are found in close proximity. These results indicated that illegal dumping has occurred, and in places these activities directly conflict with fishing activities. Repeat side-scan sonar surveys of the area would detect whether enhanced policing is needed.

DISCUSSION

The Fraser delta is a moderate-sized (by world standards; see Bhattacharya and Walker, 1992) delta that has grown in Holocene times and is now affected by urban development and industrial activity. Comparison of this delta with modern and ancient analogs helps identify the principal factors controlling delta growth (Hart *et al.*, 1995). High sedimentation rates, relatively high subaqueous slopes, interstitial methane gas, and seismic activity combine to initiate submarine slope failures which have the potential to affect installations on the sea floor and adjacent tidal flats. The fine grain size of the sediments retards pore fluid expulsion, contributing (along with gas generation) to excess pore pressures and under-consolidation. Excess pore pressures have been associated with failures ranging in scale from the shallow rotational slides, 2-3 m thick, of the Sand Heads complex (Fig. 8; Hart *et al.*, 1993) to the Foreslope Hills, which represent failure of the upper tens of metres of the lower delta slope (Hart, 1993), possibly as a result of earthquake activity. The Roberts Bank study identified a large failure complex in an area of significant economic importance. Geological mapping and interpretation, using a range of geophysical techniques, provide the basis

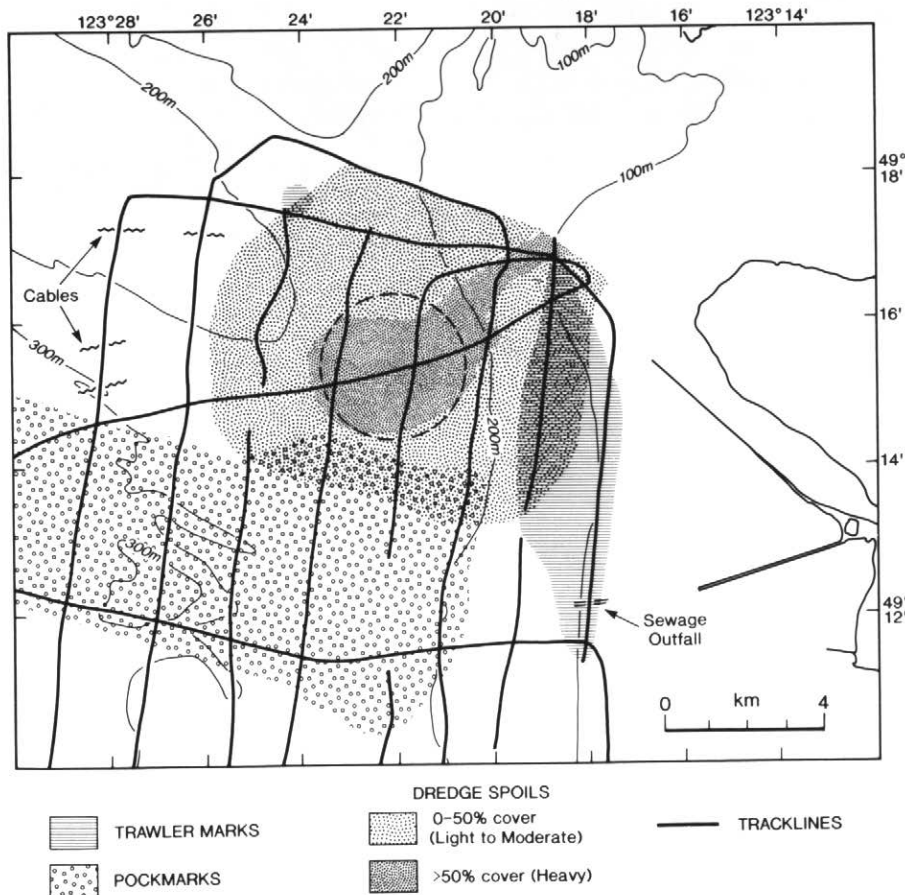


Figure 12 Map of Point Grey dump site prepared from side-scan sonographs and seismic data. Dredge spoils detected over 4 km outside of dump site limit (dashed circle), locally in close proximity to trawler marks produced by bottom fishing. Sewage outfall from Iona treatment facility can be traced over 100 m on sonographs. See Figure 1 for location.

for the initiation of site surveys which address the stability of the delta slope and nearby tidal flats in the event of large earthquakes. Finally, the surficial-features mapping of the Point Grey dump site has identified use conflicts and the need to enhance dump site

monitoring and policing.

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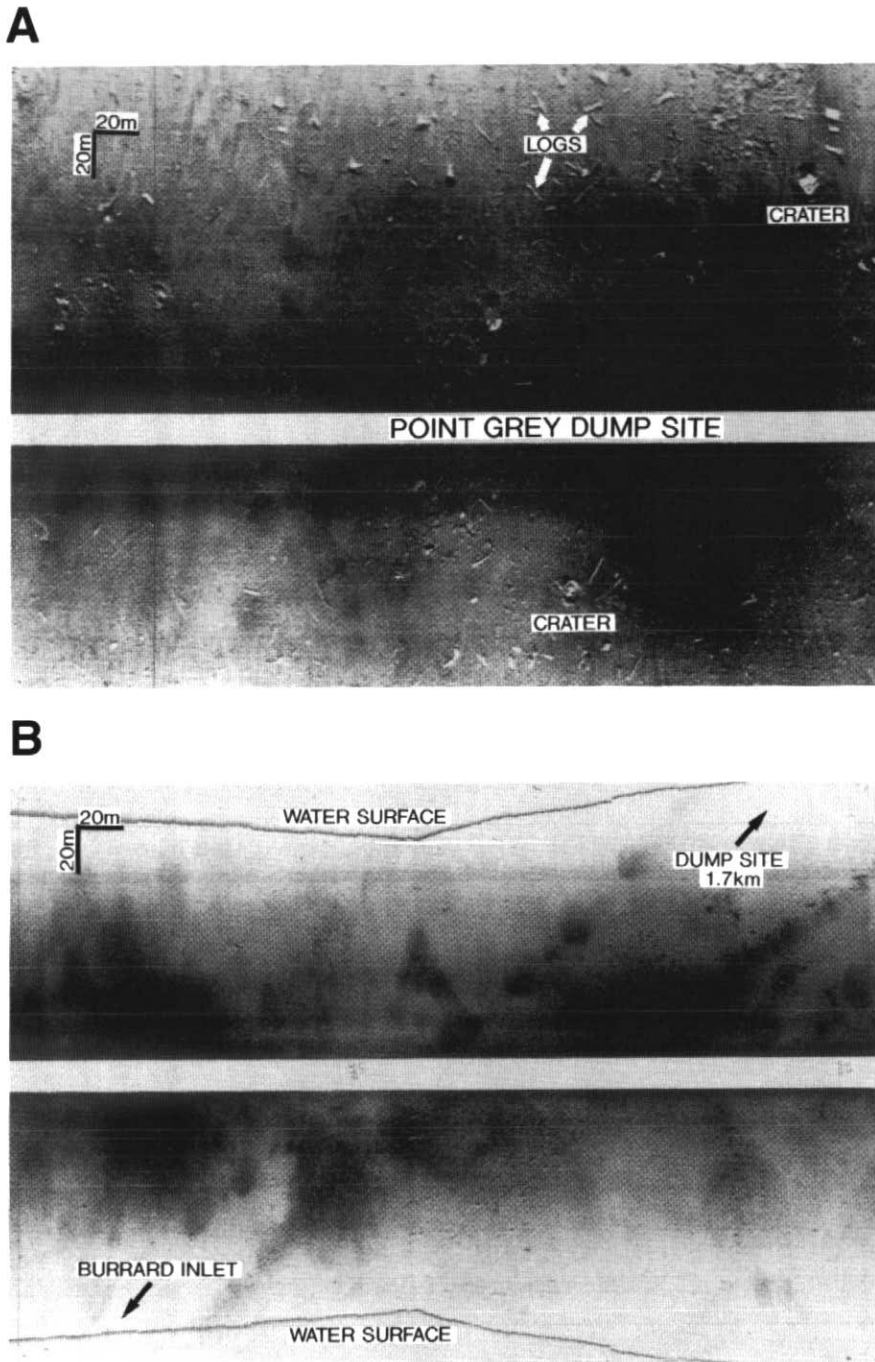


Figure 13 Sample sonographs showing characteristics of Point Grey dump site (Fig. 1). (A) Near continuous cover of the sea floor inside dump site limits by dark (sandy) dredge spoils, logs (from booming grounds of North Arm of Fraser River), and miscellaneous debris. Note large dark patch on right thought to be generated by disposal from self-emptying barge. (B) Linear trend of smaller patches thought to be generated by continued disposal from a moving barge en route from Vancouver Harbour (Burrard Inlet) to dump site. Lines marked "water surface" caused by reflection of acoustic pulse from sonar towfish (towed approximately 40 m above sea floor) on sea surface.

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