SENSITIVITY OF LEACHED MARINE SILTS AND CLAYS AT THE BASE OF THE FRASER RIVER DELTA

by

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ABSTRACT

The Fraser River delta has prograded westward into the Strait of Georgia over a period of about 12,000 years, over-riding a thick sequence of soft gas-charged marine silt and clayey silt. These offshore sediments appear to be laterally equivalent to a thick onshore normally consolidated sequence of early Holocene age. Downhole conductivity and resistivity cone penetration testing has indicated that fresh groundwater is advecting upward from underlying Pleistocene strata around the margin of the delta floodplain. The Geological Survey of Canada has conducted research to identify engineering geohazards. This has involved mapping of landslide deposits in the Strait of Georgia and development of a comprehensive geological model, partly as an aid in constraining numerical modelling of seismic ground amplification and prediction of fundamental site period. One aspect of this work, the evaluation of soil sensitivity in basal silts and clays, using the field vane is highlighted in this paper. Upward flow of groundwater and possible leaching at the base of the silt had been identified and the possibility of higher sensitivities at the junction with the till had been suggested. Sensitivities of 8 to 12 were measured with no apparent increase with depth. Cone sleeve friction measurements agree with remoulded vane shear results, suggesting that the large-strain strength used in previous assessments of submarine slope instability may be lower than assumed.

INTRODUCTION

The Geological Survey of Canada (GSC), in co-operation with industry and universities, has been mapping the Fraser River delta through onshore and offshore geophysical and geotechnical investigations. During the past 13 years, the GSC has carried out 86 onshore-offshore cone penetration tests (CPT's) as well as 52 boreholes, most of which have been logged using downhole geophysical tools (Hunter et al, 1998b). Surface refraction and reflection surveys have also been carried out over much of the Fraser delta in an effort to improve our regional understanding of the Quaternary geology. During this period, the Lower Mainland

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region has experienced rapid growth, leading to an increased requirement for engineering analysis of the response of the ground to changes in loading. Of particular interest is the amplification or attenuation of seismic waves as they pass through the soils of the Fraser delta. It is anticipated that the proposed future microzonation of seismic liquefaction potential will benefit from the efforts of the GSC to characterize the engineering properties of the delta.

In addition, recent questions regarding the stability of the delta front have required consideration of the strength and deformation properties of the soils observed there. Figure 1 shows two features interpreted to indicate regions of large-scale seafloor instability in the southern Strait of Georgia: the Foreslope Hills and the Roberts Bank Failure Complex. After detailed geological mapping, the origin of these features remains somewhat enigmatic, requiring a more in-depth evaluation of the soil properties than has been undertaken to date. In particular, the strain-softening potential of the fine-grained soils that appear to blanket parts of Roberts Bank slope and are known to form the base of the delta where it overlies the Pleistocene unit requires consideration. This paper presents results of recent onshore field investigations of these silts and discusses their behaviour with reference to our current understanding of the postglacial depositional history.

REGIONAL SETTING

The Fraser River delta began to form in the Richmond area as a submarine delta about 11,000 years B.P during the early Holocene era. Prior to this time, the region existed as a series of glaciated deltas and coastal plains. After the most recent glaciation, the submarine delta accreted rapidly, experienced isostatic (crustal) rebound and a 12 m sea level rise, occurring over the past 8,000 years. The early Fraser delta experienced large fluctuations in sea level and shallow water marine delta deposits were laid down over a hummocky Pleistocene unconformity.

Major distributaries of the Fraser River moved around as short-lived islands, salt marshes and peat bogs formed and were eroded, resulting in almost complete reworking of the delta topset (Monahan et al, 1993). Silt and clay levees were created adjacent to fluvial channels, but were periodically overtopped by spring tides and seasonally high runoff from the interior of B.C., allowing deposition of silts and clays across the delta floodplain. Freshwater peats and bogs increased in thickness to keep pace with rising sea levels. Dyking of the lowland floodplain has largely halted the natural process of overbank flooding which previously replenished and added sediment to the Fraser delta.

The resulting delta generally comprises fine-grained overbank, floodplain and intertidal clayey silts overlying river distributary sands, which in turn overlie marine foreslope deposits, consisting of loose to compact silty sands interbedded with soft to firm grey clayey silt (Armstrong, 1981). The silt is of prodelta, marine and glaciomarine origin and in places exceeds 200m in thickness. The height of the delta foreslope varies from about 100 m near Point Roberts to more than 350 m off the river mouth at Sand Heads. Underlying Pleistocene deposits consist of glacial till, interlayered with unsorted outwash sands and gravels.

RECENT FINDINGS ON THE FORMATION OF THE DELTA

An interpretation of the geological history over Holocene time indicates that the Fraser delta has prograded westward over a hummocky Pleistocene topography, with glacial troughs having been partially infilled by fine-grained glaciomarine and marine sediments. Recent correlation between deep GSC CPT and borehole logs suggests the existence of a NE-SW trending buried fluvial channel identified beneath and downstream of Annacis Island. This feature can be tentatively traced across the delta plain to the junction of the Vancouver DeltaPort causeway and the sea dyke in Delta, where its base lies 20 m lower in elevation (unpublished research). This channel may be an early fluvial distributary of the Fraser River, as it appears to be cut through a major N-S trending Pleistocene ridge beneath eastern Richmond, which in places rises to within 19 m of the ground surface.

There is growing evidence to support the existence of a much deeper channel trending roughly NW-SE beneath the Cities of Richmond and Delta. The Pleistocene surface is known to occur at depths of 236 m at No 4 Rd. and Westminster Highway and at 305 m at Richmond City Hall (Dallimore et al, 1994; Luternauer and Hunter, 1996; Hunter et al, 1997). It is believed that the these postglacial channels are partially infilled by fine-grained glaciomarine silty clays grading into overlying marine clayey silts and silts, which become interbedded with sandy silts, depending on the proximity to the locus of deposition in the early stages of Fraser delta evolution (10,000 to 5,000 years BP).

At present there are insufficient data to properly map these buried channels, but there is increasing acceptance of high vertical relief in eastern, northern and western Richmond and west and east of Ladner, as well as along the edge of the Surrey Uplands and Point Roberts. For example, the Pleistocene-Holocene boundary was encountered at a depth of only 50 m in a geological borehole drilled in King George Park less than 1.5 km NE of the No 4 Rd. site (Luternauer and Hunter, 1996). A major Pleistocene high has been detected beneath Roberts Bank (Clague et al, 1983).

Given widespread reports of artesian conditions within coarse-grained Pleistocene units, deep site investigations within the deep channel fills may be warranted to more thoroughly characterize their hydrogeologic regime and the resulting profile of effective stresses.

HYDROGEOLOGY

A number of GSC soundings have encountered artesian pressures at the top of the glacial sequence, most notably along the North Arm of the Fraser River (at No. 7 Rd and River Rd, on Mitchell Island, and at the BC Gas Frasergate station), immediately west of the Surrey Uplands at the north end of 112th Street in Delta and at the Tsawwassen Indian Reserve, north and west of Point Roberts. This confirms previous findings that elevated pore pressures exist near the base of the marine unit (R. Spence, pers. communication, 1997; Bazett and McCammon (1986).

In addition, downhole geophysical logs have produced deep conductivity profiles which, after conversion to pore water salinity, suggest that the buried marine silts and clays are being leached by upwelling groundwater. It is generally observed that pore waters within basal clays are slightly brackish to fresh, gradually becoming more saline toward the contact with the overlying fluvially-reworked sand unit, which displays higher conductivities and higher pore water salinities, attributed to the influence of a tidal salt wedge as described by Kostaschuk and Luternauer (1989). Several downhole conductivity logs are shown in Figure 2, illustrating the increasing influence of tidal effects in river distributary sands toward the delta front. GSC site investigations across the Fraser delta identified a general fining-downward trend corresponding to increased plasticity and slower dissipation of penetration pore pressures, in combination with a systematic reduction in pore water salinity, which may help explain why water content appears to remain largely constant with depth.

The existence of upward hydraulic gradients across the overlying fine-grained marine unit may indicate that leaching of the deposits has occurred, a condition which result in the formation of soils which exhibit structural collapse and strain softening behaviour when sheared. Interpretation of CPTU soundings carried out in the deep silts suggests moderate levels of sensitivity. Artesian conditions can also create problems during drilling and care must be taken to ensure that uncontrolled flows do not occur.

PREVIOUS WORK IN FRASER DELTA SILTS

Soil conditions at the current delta front may provide an indication of depositional environment of the older silts to the east, underlying the delta. At the delta front, silty sediments presently cover much of the slope along the western margin of the Fraser River delta, from Point Grey to Point Roberts. Sediments south of Sand Heads are notably less clay-rich at the seabed, due to alteration of depositional patterns though emplacement of river training structures and tidal currents which transport fine-grained sediment northward to Sturgeon Bank. Roberts Bank now appears to be a region of current-induced erosion (Figure 1), as demonstrated by the existence of zone of large-scale sand waves immediately west of the Vancouver Deltaport (Hart et al, 1992; Currie and Mosher, 1996). This material may have been derived from remobilisation of dredge spoils deposited at the head of the foreslope. Recent seismic profiling has shown a high degree of acoustic layering elsewhere across the upper slope, suggestive of a draped fine-grained facies (Christian et al, 1997). Cone penetration tests at the crest of the slope have identified a seafloor sequence of organic-rich gas-charged silt up to 35 m in thickness, west and northwest of the Deltaport. Site investigations at the western edge of the Deltaport pod have shown that this silt unit pinches out or becomes very thin inshore, evidently merging into intertidal silts and sands (Christian et al, 1995).

Deep drilling and sampling at the Deltaport site (FD95S1) has identified sequences of layered sand and silty sand overlying a low to moderately sensitive clayey silt of low plasticity, occurring at a depth of 106 m below grade (grade elevation is about 2 m above geodetic datum). This deep silt sequence may itself represent a thinned end-member of the thicker silt facies encountered beneath the deltaic sands across the subaerial delta plain in numerous onshore drillholes and CPT's. Soft gas-charged clayey silts presently being deposited offshore may be a distal analogue to onshore silts underlying the Fraser River delta. High resolution seismic reflection surveys have also encountered gas-masking over much of the southwestern portion of the Fraser delta, toward Boundary Bay and Roberts Bank (Hunter, personal communication, 1994).

Crawford and Morrison (1996) described the deep marine unit as a grey, micaceous low plasticity silt with thin layers of fine sand and occasional thin seams of organic matter. Konrad et al (1985) studied a site on Sea Island (Figure 3) and reported that fine-grained soils at depth could be described as cohesionless inorganic silt, based on low to medium sensitivities inferred from field vane tests (FVT) and low plasticity indices obtained from recovered soil samples. Crawford and Morrison (1996) cited water contents within the deeper portion of the marine silt unit, ranging between 30 and 40%. Plasticity indices reportedly lie between 5 and 20% based on a deep soil boring at the Iona Sewage Treatment Plant (Ripley, 1995), in agreement with index testing of soils from the GSC Deltaport site (Christian et al, 1995).

Campanella et al (1983) described the deep silt unit as normally consolidated and concluded that undisturbed samples were difficult to obtain. Postglacial sediments were concluded to be normally consolidated, except where erosion by the Fraser River had replaced them with channel fills of lower density. In most cases, normally to lightly overconsolidated conditions should prevail within these sequences. A detailed evaluation of stress history from laboratory testing of deep samples is inconclusive due to sampling disturbance (Agra Earth & Environmental Ltd., 1996). There may be a need for further research to better illuminate the mechanical behaviour of these problematic 'marine' soils.

STUDY SITES

The study sites reported in this paper are all near the margins of the delta, where glacial deposits rise and outcrop at the ground surface (Figure 4). The 97-4 site is reported in detail. Previous studies suggested the existence of a regional sensitive silt unit below a depth about 30 or 40 m (Bazett and McCammon, 1986; Crawford and Morrison, 1996; ConeTec Investigations Ltd., 1995). Additional geotechnical data from a remediated site across the Fraser River provided an opportunity to check the southward dip of the Pleistocene unconformity which outcrops at SE Marine Drive near the BC Gas Frasergate Station (data provided by BC Gas and Golder Associates Ltd.). A cross-section across the North Arm is shown at this location, illustrating the subsurface geology, based on CPT soundings carried out on both sides of the river (Figure 4).

SITE INVESTIGATION METHODS

Given the considerable difficulty in recovering undisturbed soil samples in cohesionless or low plasticity soils, in situ testing techniques (piezo-cone with a resistivity module - RCPTU , and vane shear testing) were employed to investigate the sensitivity of the silts. An attempt was made to extend the range of application of the Nilcon field vane apparatus to twice the normal operational limit of 20 m, through use of an improved support system for the vane rods. These techniques were employed at various locations across the Fraser delta, including sites 97-4, 97-5, 97-6 and 97-7 (Figure 3).

RCPTU soundings were carried out to refusal at all sites, to characterize the resistivity of the silt unit at depth, as well as to provide data for estimating undrained shear strength parameters. A 15-ton compression cone with a 15 sq cm tip area and a 225 sq cm equal end area friction sleeve was used in all testing. The tip end area ratio was 0.85. A 5 mm-thick porous plastic pore pressure filter was located immediately behind the cone tip. Glycerin was used to vacuum-saturate the porous filters. Data on tip resistance (Qt), sleeve friction (Fs), dynamic penetration pore pressure (U) and electrical resistivity (R) was collected at 5 cm depth intervals. Electrical resistivity was measured with a module located behind the friction sleeve (Campanella and Weemees, 1990). The offset between the centre of the 2-electrode array (5 cm separation) and the cone tip was 70 cm. A non-polarizing 1000 Hz constant-current source was used in this module. Pore pressure dissipation tests were performed during each rod break, allowing on-site evaluation of fines content and soil permeability. Pore water salinity was estimated from conductivity, which is the reciprocal of resistivity.

To evaluate the shear strength characteristics of early marine sediments beneath the Fraser delta, efforts were made to obtain high-quality CPT data at depth. Drilling mud was injected down the cone rods to reduce friction, permitting deeper penetration testing. At Annacis Island, a seismic cone was pushed to 98 m without a drillout using this modification (ConeTec Investigations Ltd., 1997b); at the Vancouver Deltaport one was pushed to 90 m in the same manner. In our studies, the RCPTU was always pushed to refusal, followed thereafter by a mud-rotary boring, field vane testing, Shelby tube sampling and downhole geophysical testing.

A Nilcon field vane system was used to obtain measurements of peak and remoulded undrained shear strength in the fine-grained part of the soil profile at all test sites. The vane was 6.5 cm wide by 13.5 cm in length. The torque-recording unit was mounted on top of the drillhole starter casing. To deploy the vane in the clayey silt unit, the overlying sand unit was drilled out. Thereafter, the vane rods were lowered to the bottom of the borehole and advanced in 1 m increments by pushing with the drill rig. The vane rods were supported by 2.5 cm ID rods to minimize torsional rod friction. Peak and remoulded tests were carried out at each elevation. After peak failure, the vane was rotated through 20 revolutions to remould the soil prior to re-testing. After recovery of the vane, disturbed Shelby tube samples were obtained from several key elevations, for soil description and evaluation of index properties.

The borehole was then lined with 65 mm ID schedule 80 PVC casing and grouted, to allow downhole geophysical logging using a standard suite of GSC tools, including electrical conductivity, natural and active gamma, magnetic susceptibility, compressional and 3-component shear-wave velocity. These geophysical logs, when interpreted in conjunction with CPT data, provided a detailed characterization of soil stratigraphy. Downhole conductivity data were converted to pore water salinity for direct comparison with estimates made on the basis of resistivity cone measurements.

RESULTS

Figures 5 and 6 show summary profiles of RCPT, downhole geophysical logs and field vane test results for a typical site (97-4) along the North Arm of the Fraser River, located on City of Richmond property at No 7 Rd and River Rd. The soil profile consisted of 10 m of soft clayey silt over loose to compact fine to medium micaceous sand to 23 m, over inorganic low plasticity clayey silt and silty clay to 56.5 m. A very dense cobbly clay till was encountered at the depth where the RCPT met refusal. Natural water contents in the silt varied between 30 and 45%. Fines contents (silt plus clay-sized fraction) typically exceeded 80% in the silts. Water contents were not measured in the sands.

DISCUSSION

The resistivity cone and downhole conductivity test results show clear trends as a function of location. RCPT soundings near the margins of the lowland delta floodplain encountered more resistive soils (lower conductivity), which coincided with the detection of artesian pressures at depth (ConeTec Investigations Ltd., 1997a). Other conductivity profiles, from the western and central part of the delta show higher conductivities, indicating more saline pore water conditions (Dallimore et al, 1994; Hunter et al, 1998a). Figure2 illustrated this point, as the sites reported lay along a transect up the North Arm of the Fraser River and are therefore subjected to diminishing influence from the saline wedge in the Fraser River.

A secondary trend commonly encountered in the Fraser delta is a reduction in conductivity with depth, to near-freshwater conditions at the contact with the underlying Pleistocene sequence. This corresponds with lower salinities measured in pore water subsamples taken from disturbed piston tube samples (Christian et al, 1995). There may be a direct link between artesian pressure and pore water salinity within the basal silts and clays comprising the early postglacial sequence, which raises the question of its potential impact on effective stresses and available undrained shear strength, as well as long-term compressibility. Alternatively, this downhole trend could reflect depositional changes that have resulted in soils of different electrochemical properties. To date a thorough evaluation of clay mineralogy, fabric and index properties has not been carried out.

Peak vane shear strengths at site 97-4 increased with depth in a normally consolidated manner, giving a ratio of $S_u/P_o' = 0.22$, wherein P_o' was calculated based on the hydrostatic pressure profile, with unit weights obtained from CPT classification charts (ConeTec Investigations Ltd., 1997b). Artesian pressures were neglected in this calculation, hence the 'true' peak S_u/P'_o ratio may be slightly higher. The remoulded strength also followed a linearly-increasing trend, equivalent to $S_u/P_o' = 0.025$. This ratio was somewhat lower than expected, yet supported preliminary findings of low to moderate sensitivity obtained beneath the Vancouver Deltaport, investigated with the assistance of Westshore Terminals and BC Hydro (Christian et al, 1995). A preliminary infinite slope back-analysis of the Roberts Bank Failure Complex employed an assumed strength ratio of 0.06 (Christian et al, 1997). Further analyses may assist in estimating the 'true' shearing resistance mobilized at large strain.

Lunne et al (1997) reported that CPT sleeve friction is a reasonable measure of remoulded shear strength. Efforts to minimize vane rod friction through the use of small-diameter support rods above a depth of 42 m in our study appear to have been largely successful, giving good agreement between CPT sleeve friction and FVT data. Below 42 m, the remoulded field vane strength increased more rapidly as a function of overburden stress than did sleeve friction. This was attributed to the onset of vane rod friction or binding inside the casing, although there is a slight increase in sleeve friction below 53 m, corresponding to a zone of 1 to 2 mm-diameter dropstones observed in soil samples. This part of the soil profile was interpreted to represent early postglacial (glaciomarine) sediments.

From the data obtained, it is possible to estimate soil sensitivity. For elevations above 42 m in the soil profile, we calculated a range in sensitivity of 8 to 12 based on field vane data. Below 42 m, remoulded vane data were unreliable, so sensitivity calculations adopted sleeve friction as an estimate of the remoulded strength, giving a range of 8 to 10. It would therefore appear that acceptable results can be obtained from a combination of cone penetration and field vane testing. The increase in sensitivity expected at the base of silt, based on interpreted pore water salinity profiles, was not observed.

CONCLUSIONS

Major advancements have been made over the past decade in the study of engineering geohazards in the Greater Vancouver region, in the areas of seismic liquefaction assessment, slope stability evaluation, geophysical and geological mapping, as well as structural and process geology. While much remains to be done, key findings arising from collaborative GSC research are briefly stated below.

1. The geological evolution of the delta appears to be linked to changes in sedimentation patterns at the delta front, which are in turn associated with episodes of mass wasting and slope retrogression. The Fraser delta has overidden and infilled a hummocky glacial topography at a very rapid pace. This topography is now buried at depth or exists as isolated shallow ridges and outcrops of till and poorly sorted outwash. The great thickness of soft compressible soils in some areas presents an unusual challenge in the design of deep foundations for large structures, as well as the evaluation of their seismic performance. There are at present insufficient data to map this important geological boundary in sufficient detail, but there are strong indications of an infilled glacial trough several hundred metres in depth trending NW-SE parallel to the eastern shoreline of Point Roberts, with outcropping Pleistocene uplands bounding the eastern, southwestern and northern margins of the delta floodplain. Buried Pleistocene ridges have also been noted east of Richmond and and both east and west of Ladner. Recent mapping has identified a more recent channel, possibly cut across these buried Pleistocene highs beneath eastern Richmond and Roberts Bank.

2. An improved understanding is emerging regarding the structural architecture of the Fraser River delta and its soil characteristics, including the response to earthquake shaking. Geological, geophysical and geotechnical investigations have provided constraint for dynamic modelling, which will in future expand to include an examination of 2D and 3D effects to assist regional planners in identifying key regions requiring ground improvement. These studies underpin other applied research including environmental water quality monitoring through consideration of the hydrogeologic regime.

3. In situ testing at GSC research sites around the margin of the lowland floodplain has identified fine-grained sediments of low to moderate sensitivity, existing at overburden stress levels in excess of 200 kPa, which underlie the regional sand sheet deposited by the Fraser River. These fine-grained sediments are known to be compressible and may be capable of strain-softening under certain loading conditions. Further testing is required to characterize their regional distribution and their engineering behaviour. These silts and clays have been described by others as having a significant creep potential, manifested as secondary consolidation beneath large structures.

4. The Fraser River delta is an unique natural laboratory providing in a highly localized setting, a number of opportunities for studying geological and climactic change, assessing human impact, evaluating slope stability triggering mechanisms and seismic geohazards, which has greatly benefited from the local development of state-of-the-art technology.

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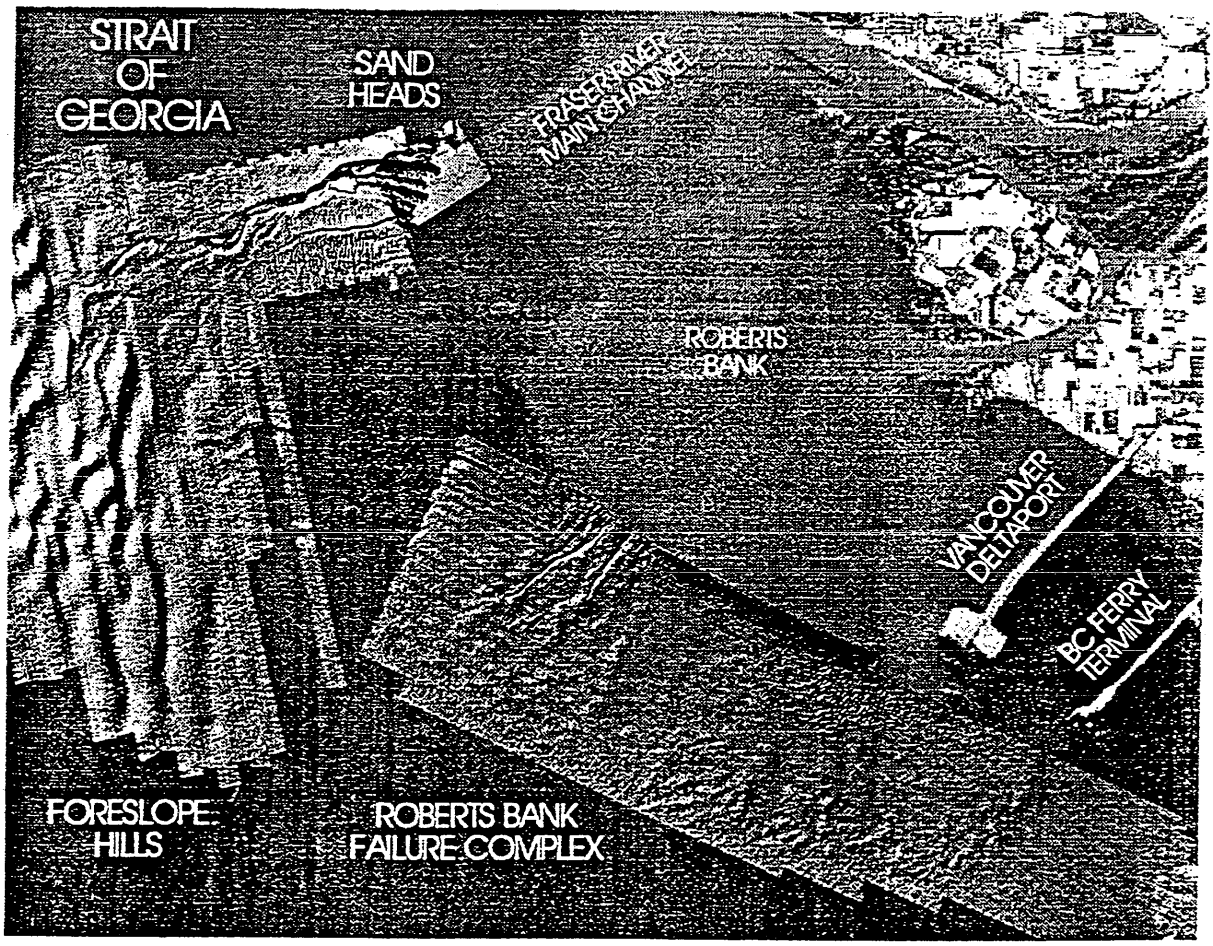

Fig.1. Shaded relief multibeam bathymetry image overlain on Landsat photograph, of the southern Strait of Georgia. Areas of seafloor instability are identified as Sand Heads, the Foreslope Hills and the Roberts Bank Failure Complex (after Currie and Mosher, 1996).

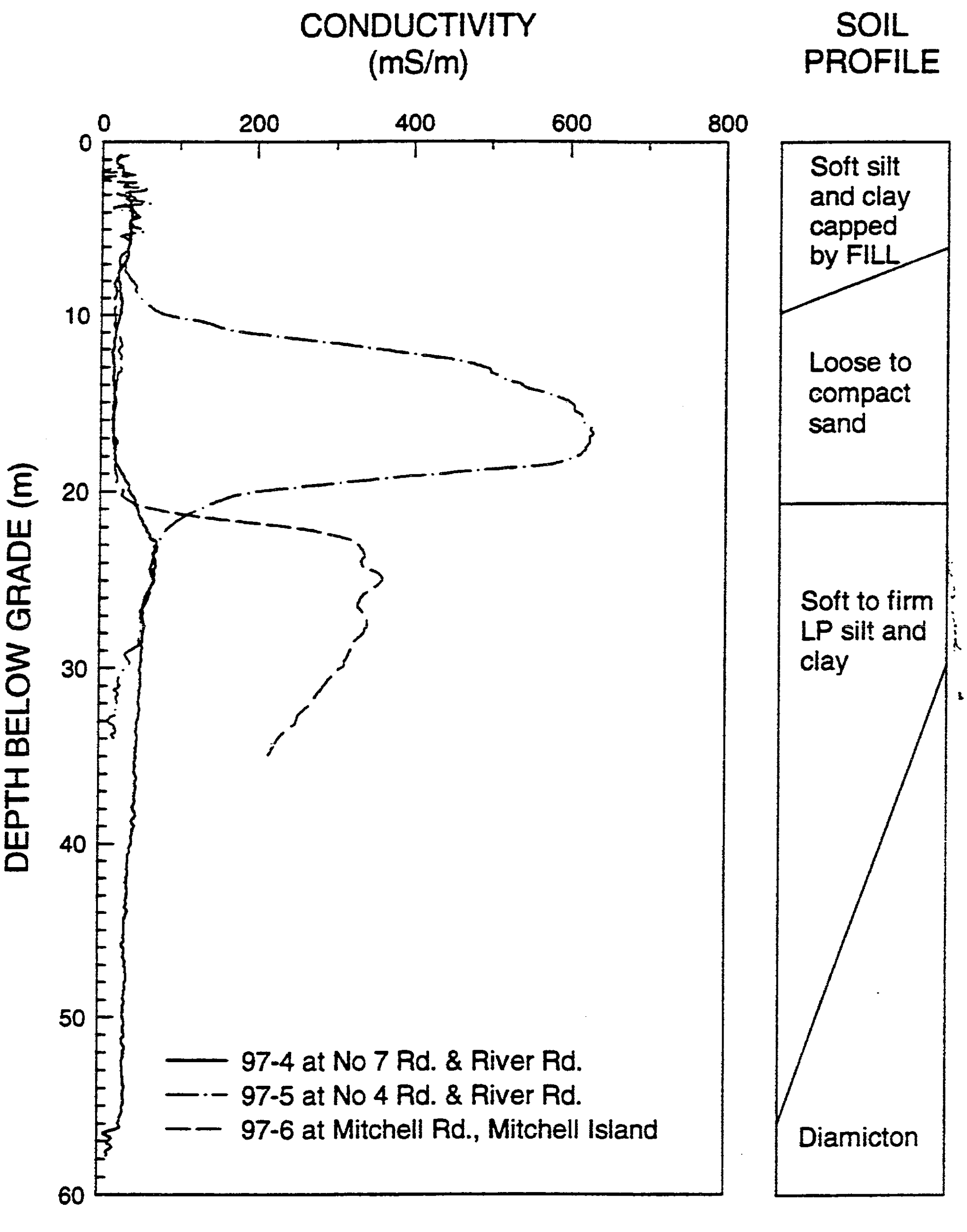

Fig.2. Downhole conductivity logs for three sites along the North Arm of the Fraser River, in the City of Richmond. The low conductivities toward the base of the silt facies may be indicative of groundwater leaching from underlying glacial strata, known to be under artesian pressure. Pore water salinity is high within river distributary sands toward the western regions, due to infiltration from a seawater tidal wedge.

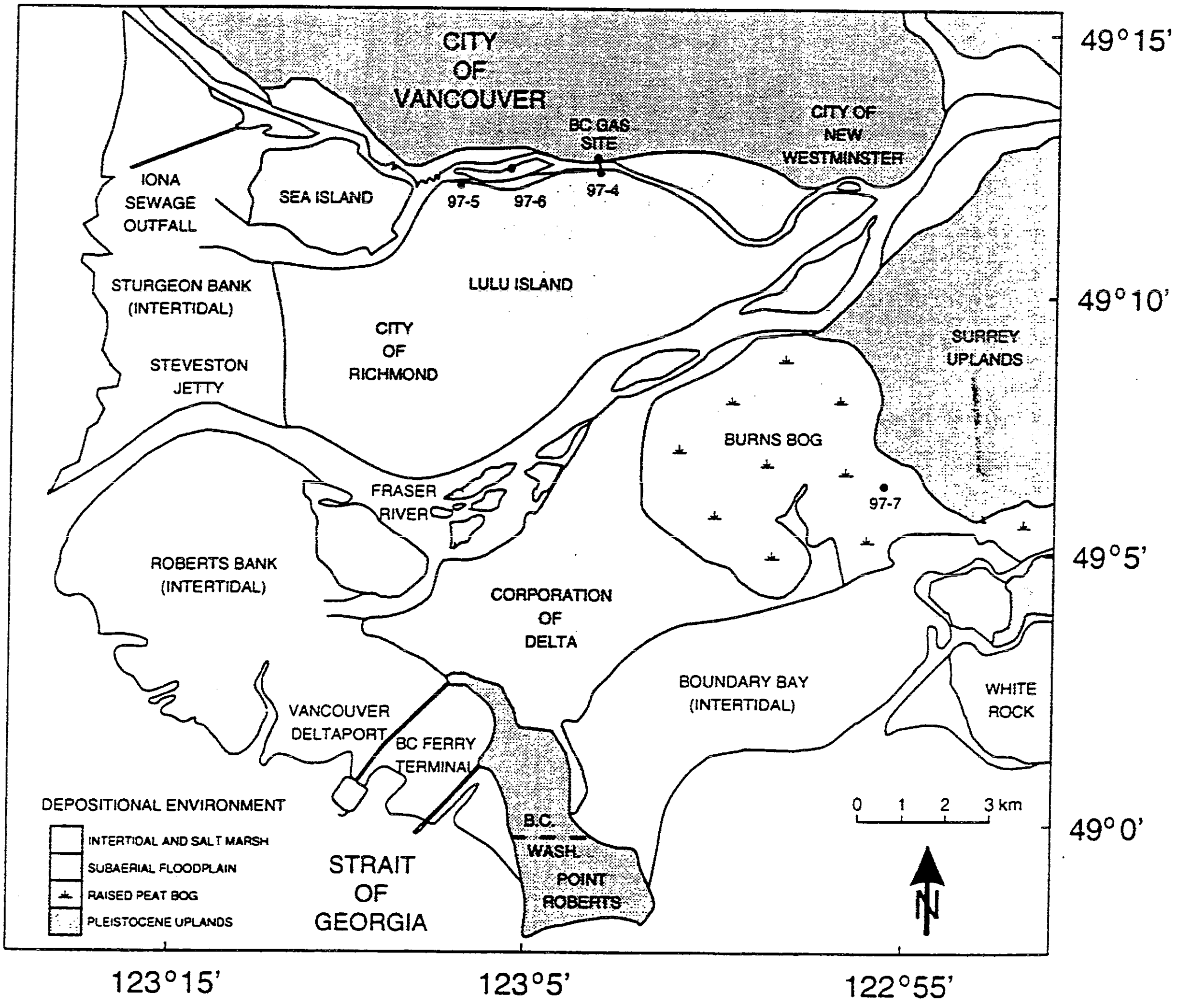

Fig.3. Map of the Fraser River delta, showing a classification of depositional environments and some recent locations of geotechnical site investigation (modified after Clague et al, 1991).

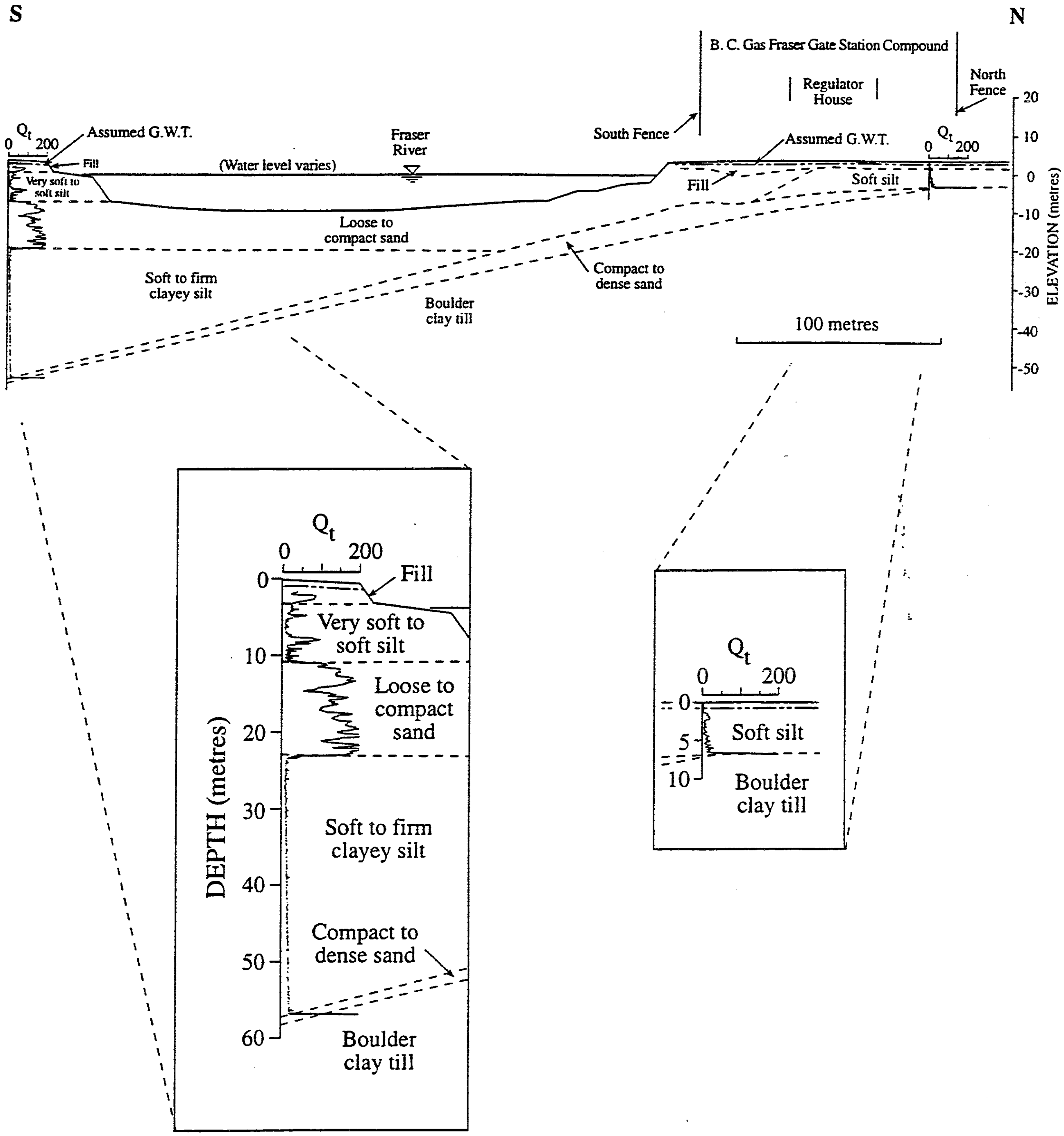

Fig.4. Geological section across the North Arm of the Fraser River, between GSC site 97-4 and the BC Gas Fraser Gate regulating station. The soil stratigraphy was mapped based on CPT data obtained during geotechnical site investigations commissioned by Golder Associates and the GSC.

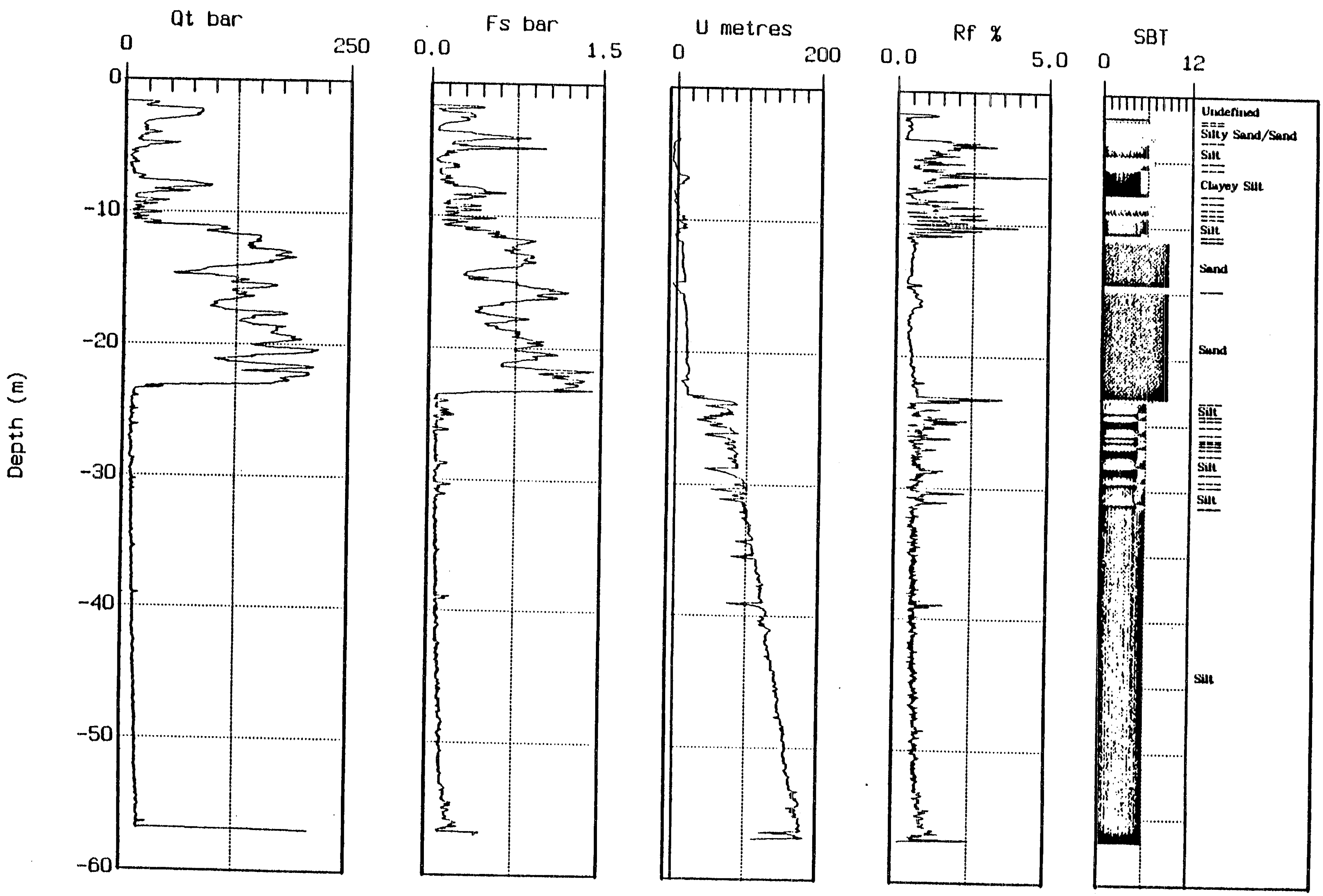

Fig.5. Resistivity cone penetration test result from 97-4, located on the south bank of the North Arm of the Fraser River showing cone tip resistance, sleeve friction, dynamic pore pressure, friction ratio and an interpretation of soil behaviour type, based on CPT classification charts given by Robertson (1990).

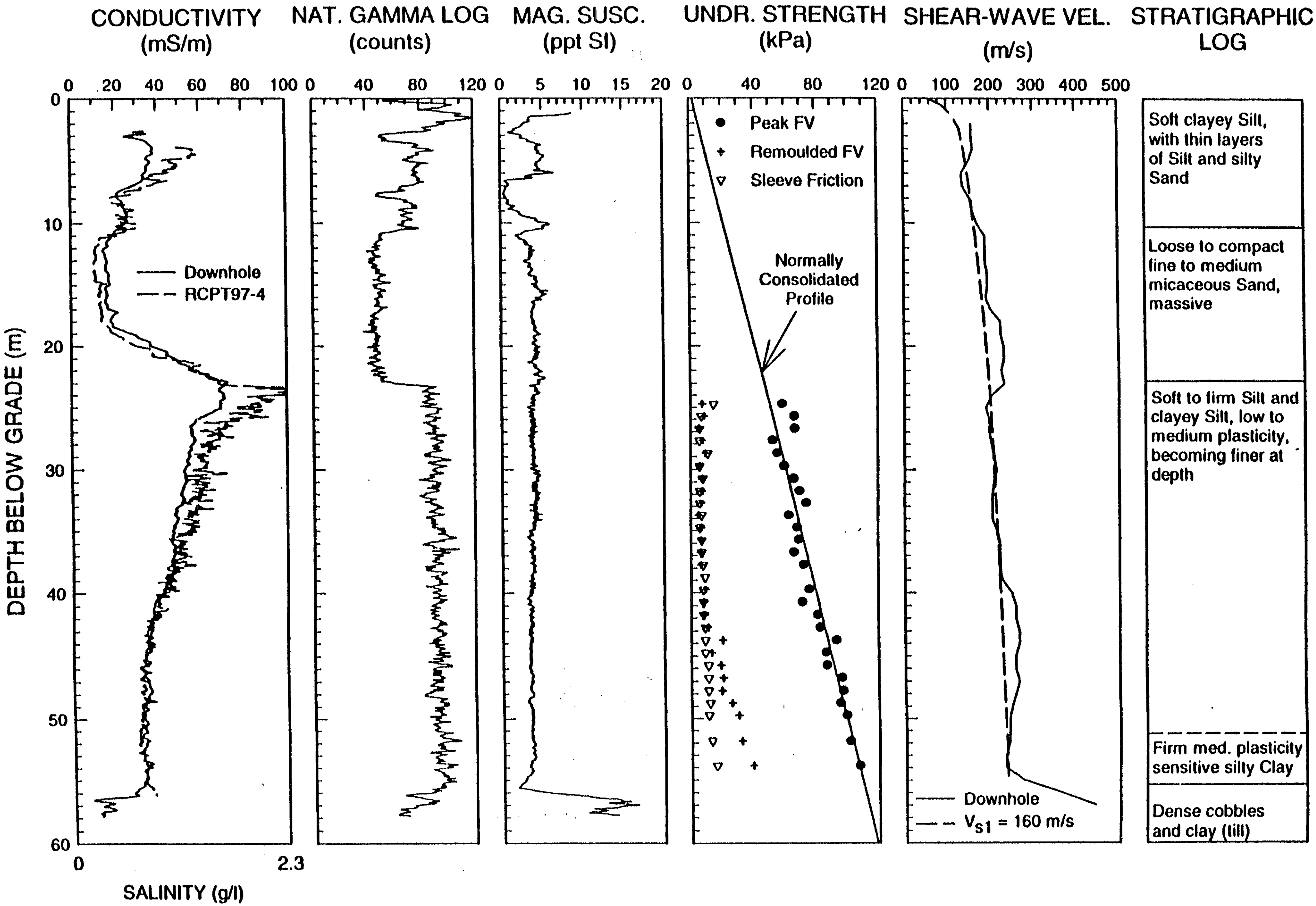

Fig.6. Summary profile of downhole geophysical logging showing conductivity and pore water salinity, natural gamma, magnetic susceptibility and shear-wave velocity data. A stratigraphic interpretation is also shown, which includes findings from the RCPT sounding. Peak and remoulded undrained shear strength from the field vane and CPT sleeve friction are also shown.