Conoco Dynamic Mud Bay Well d-95-D

SOME GEOPHYSICAL PROPERTIES OF THE QUATERNARY- TERTIARY SEQUENCE IN THE FRASER RIVER DELTA, FROM AN EXPLORATION GAS WELL

by
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Abstract

Open hole geophysical logs obtained from a gas exploration well drilled in the southwestern Fraser River delta (Conoco-Dynamic Mud Bay d.95-D) have presented an opportunity to examine some basic geophysical properties of the stratigraphy within the Quaternary and upper Tertiary (bedrock) sequences. Characteristics and stratigraphic correlations of formation electical conductivity and seismic velocities have been derived from some of these logs. Such information is of use in the development of hydrogeological models of the delta, and provide basic geotechnical information required for earthquake response estimations.

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Introduction

Gas exploration drilling has been carried on in the lower mainland of British Columbia and in adjacent areas of the state of Washington for many years. However, in most wells, geophysical logs start at the overburden-bedrock interface and are confined to the sedimentary rock section of interest. In the Conoco-Dynamic Mud Bay d95-D well (see Figure 1 for location) the operators wished to examine the known thick Quaternary sequence in detail, for in-house regional stratigraphic correlations, and to make the interpretations from these geophysical logs available to the geoscientific community, through the Geological Survey of Canada, as a public service.

Two of the available open hole logs from the Mud Bay well, of immediate interest to Quaternary stratigraphic studies of the delta are (i) the induction conductivity log, and (ii) the sonic log, since comparative logs are available from previous GSC borehole studies elsewhere in the delta (Clague et al, 1991; Luternauer et al., 1991; Hunter et al., 1994; Dallimore et al. 1995; Dallimore et al. 1996; Hunter et al., 1997).

The induction log gives direct measurements of bulk electrical conductivity of the formation; in this Quaternary setting, the measured conductivities are directly related to the pore-water salinity (Hunter et al., 1997).

The P-wave sonic log (compressional velocities measured over short vertical intervals sequentially in the borehole) is normally used to interpret fine scale variations in lithology; however, the integrated travel-time output of this log can be used in a manner similar to that of a down-hole seismic log (i.e. the P wave average travel-time from a surface source to a geophone location in the borehole) to give large scale interval velocity variations. The P-wave velocities can be converted to shear wave velocities using an established empirical relationship (Hunter et al., 1996). Estimates of shear wave velocities as a function of depth are critical input parameters for earthquake ground motion amplification modelling (Finn and Nichols, 1988; Lo, et al.,1991; Sy et al., 1991; Harris et al., 1995)

Borehole Geology

The generalized geology obtained from drill cuttings from the Conoco-Dynamic Mud Bay borehole is summarized on the left side of Figure 2; a more detailed description is given in Table I.

Holocene deltaic sands and clay exist to a depth of approximately 190 m below ground surface. The basal fine grained unit probably represents distal deposition from the prograding Fraser River delta.
The Pleistocene surface is characterized by a coarse-grained conglomerate (fining downwards) approximately 70 m in thickness. The lower part of the Pleistocene is characterized by fine-grained interlayering silt and clay beds with thicknesses varying between 15 and 45 m. A basal conglomerate (425-446 m depth) unconformably overlies the Tertiary surface.

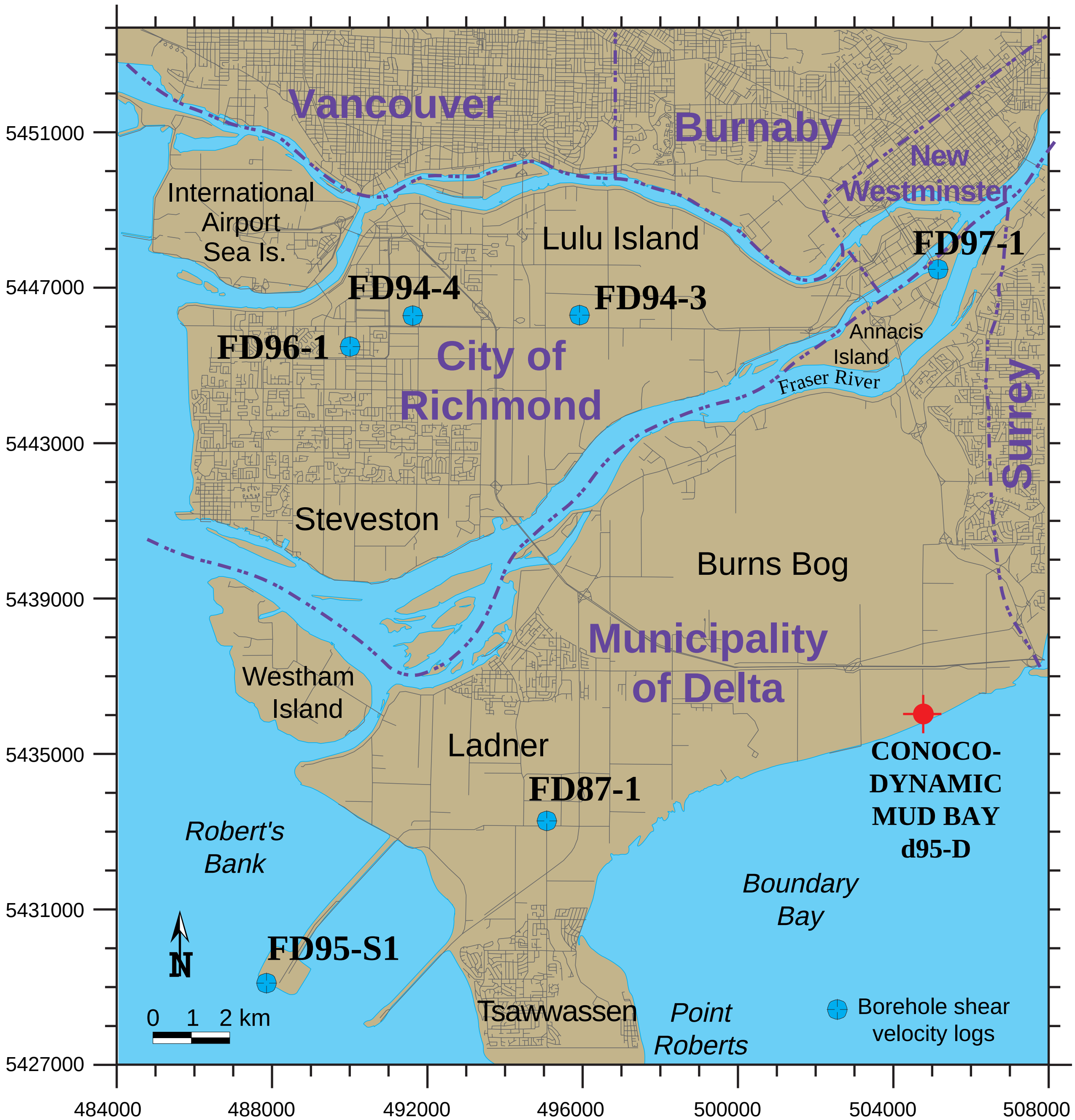

Figure 1. Locations of Fraser River delta boreholes noted or discussed in this paper.

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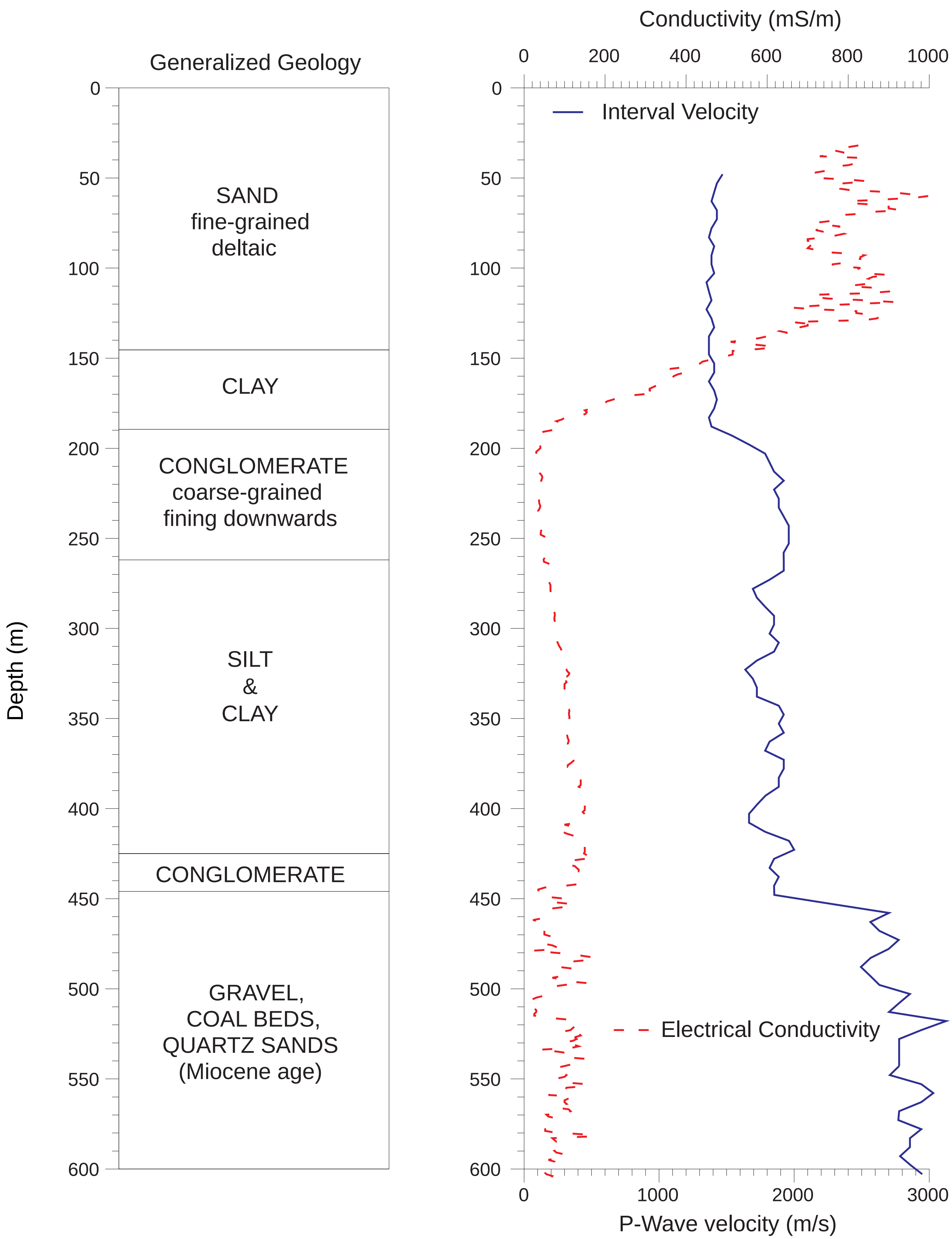

Figure 2. Generalized geology, induction conductivity, and p-wave interval velocities (obtained from the sonic log) for the Conoco-Dynamic Mud Bay exploration well.

Table I
Geological Log for Mud Bay d-95-D/92-G2
(from Dynamic Oil Ltd.)

DEPTH	GEOLOGICAL DESCRIPTION
0-145 m	sand, light buff grey, unconsolidated, salt & pepper, sub angular, fine to medium grained; minor white mica & traces of dark grey rock; volcanic fragments; minor milky quartz; white & clear & some pink feldspar; minor plutonic & volcanic cherts; seismic shows clinoform beds; muscovite is thought to be from the Omenica shists; contains sea water at 30,0000 ppm NaCl from 0 - 150 m.
145-190 m	sands, lithic, as above, with abundant rock fragments; set in a light buff clay which increases downward; contains sea water at 23,000 ppm NaCl at 24o C.
190-260 m	pebble conglomerate with quartz sand, light grey salt & pepper, medium to very coarse grained, unconsolidated; frosted to clear quartz, sub angular; methane gas show up to 1.5% or 15,000 ppm on gas chromatograph from 190 to 205 m; minor rock fragments & milky quartz towards bottom of section; increasingly fine grained downward; typical beach or offshore bar environment; contains a show of methane gas & fresh water at 2,000 ppm NaCl at 302 psi at 200 meters depth; this is 28 psi above sea level pressure.
260-425 m	interbedded siltstone and clays; clay is light grey & micro micaceous with some floating sand grains; the siltstone has very fine quartz with occasional abundant white & black mica.
425-446 m	conglomerate & sand, light grey to medium grey, salt & pepper; very angular rock fragments; may be shards of cobble up to 10% of sample; unconsolidated & may be interbedded with clay which washes out into the mud system.
446-454 m	top of Tertiary; gravel, mostly broken rock fragments; traces of calcite cement; consolidated shards of milky quartz, plutonic & volcanic rock, biotite and feldspar.
454-460 m	shale, grey brown to medium grey, soft, friable & micro micaceous.
460-485 m	sandstone, light grey, clear & frosted quartz, sub angular, unconsolidated but with traces of calcite cement, fining downward as a beach deposit; contains fresh water 2000 ppm NaCl; 2 meters of coal at bottom of section.
485-505 m	shale & coal as above; coal is thinly laminated.
505-520 m	sandstone, light grey; poorly consolidated; fair porosity; with calcite & laolinite cement; carbonaceous; grading downward to very coars grained milky quartz conglomerate towards bottom of section; typical channel sand deposit; contains fresh water at 2000 ppm NaCl.
520-600 m	shale, grey brown to medium grey; very soft; micro micaceous; minor coal interlamination & as thin beds; minor sand from 570-580 m.

Similar Holocene-Pleistocene sequences have been encountered in five other deep geological-geotechnical boreholes drilled elsewhere in the delta (GSC boreholes FD87-1, FD94-3, FD94-4, FD95-S1, FD96-1, see Figure 1 for locations; Clague et al., 1991; Luternauer et al., 1991; Dallimore et al., 1995; Dallimore et al., 1996; Christian et al., 1995) .

The Tertiary surface, at approximately 446 m depth is characterized by the onset of semi-lithified thin beds of gravel, coal, quartz sands and shales, of late Miocene age.

Formation Electrical Conductivity

The formation electrical conductivity log for the Mud Bay well is shown on the right side of Figure 2. High formation conductivities, in the range of 700-1000 mS/m are associated with the upper portion of the Holocene (0-130 m depth). Such high values indicate that the conductivity contribution from porewater salinity is considerable, and that lithological changes are superimposed second-order variations (McNeil, 1990). A well-defined conductivity gradient (decreasing conductivities with depth) occurs between approximately 130m and 190m depth range.

The top of the Pleistocene has a relatively low conductivity of approximately 30 mS/m; conductivities increase gradually with depth within the Pleistocene to a maximum of approximately 150 mS/m; these variations in conductivity probably reflect lithological variations and indicate increasing fines content with depth.

The upper Tertiary is characterized by fine-scale zonation of conductivities between 20 and 150 mS/m, and can be correlated with lithological variations between mudstones, sandstones and coal beds.

Hunter et al. (1997) show a correlation and an empirical relationship between borehole conductivity and measured porewater salinities based on two deep boreholes (FD94-3 and FD94-4) in Quaternary sediments of the Fraser River delta. Figure 3 shows an up-dated correlation based on four such delta holes (see Figure 1 for locations of boreholes) along with the slightly improved empirical relationship. Clearly, high conductivities such as observed in the upper 130 m of the Mud Bay hole are associated with porewater salinity values of 24 g/l or more.

The high conductivities in the upper Holocene and the large conductivity gradient observed in the lower portion of the Holocene has been observed in other GSC boreholes in the delta encountering the Holocene-Pleistocene boundary (Hunter et al., 1997). Figure 4 shows a comparison of conductivities in the Holocene portion of the Mud Bay well with two other example GSC boreholes (see Figure 1 for locations). Most boreholes encountering the Holocene-Pleistocene boundary exhibit large conductivity gradients at the base of the Holocene sequence, although the vertical extent of the gradient differs somewhat from one hole to another. Ricketts (1997) suggests that hydraulic conductivities within the Holocene silts and clays of the delta, are relatively low, but may be relatively high within Pleistocene sediments, with possible existence of artesian pressures. Hence, the interpreted high values of porewater salinity in the upper Holocene materials may represent the depositional porewater salinity, with salt diffusion being responsible for the shape of the gradients (M. Hinton, GSC, pers. comm., 1997). The differing vertical extents of the conductivity gradients may be related to a combination of horizontal

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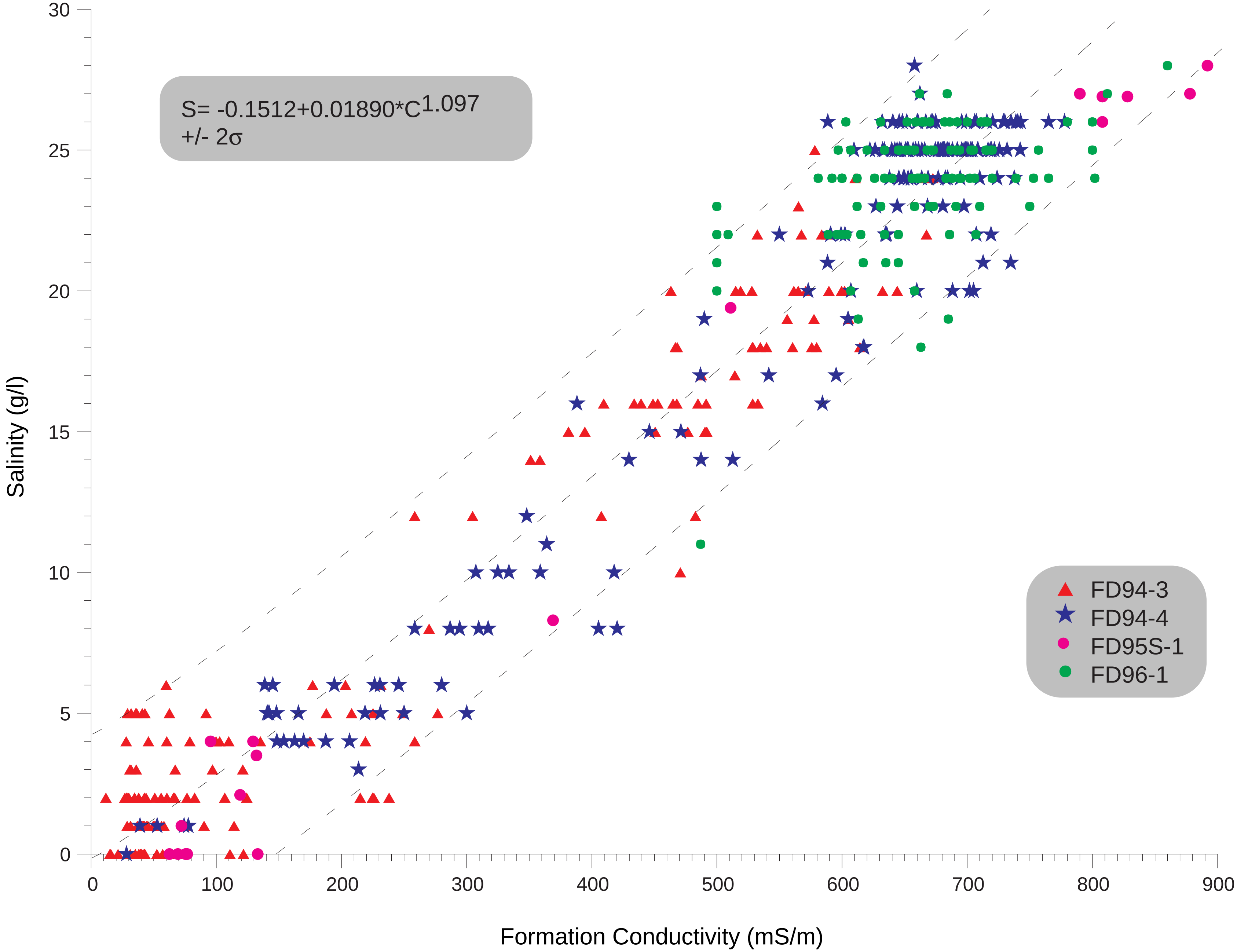

Figure 3. Salinity-formation electrical conductivity data and the best-fitting empirical curve from four Geological Survey of Canada boreholes in the Fraser River delta. See Figure 1 for locations.

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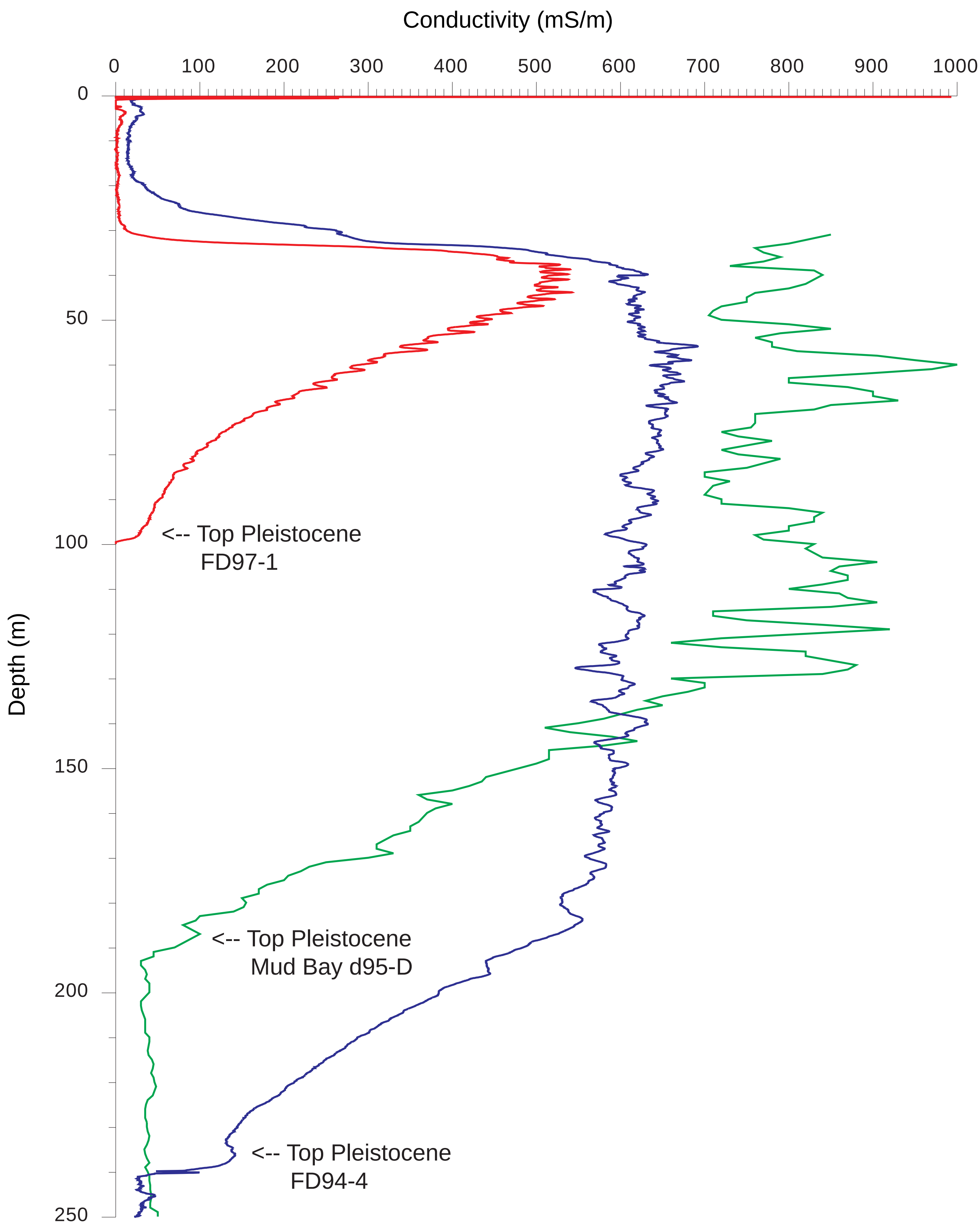

Figure 4. Comparison of borehole electrical conductivity logs for the Mud Bay well and two other representative GSC boreholes in the Fraser River delta.

groundwater flow rate within the Pleistocene materials, porosity and permeability variations across the Holocene-Pleistocene boundary, as well as time of deposition of Holocene materials. Whether or not porewater salinity has changed through some leaching mechanism is of importance in understanding and predicting the occurrence of sensitive clays within the delta (Christian et al., 1997). Perhaps future groundwater modelling studies will resolve the issue.

Seismic Velocities

To obtain a P wave downhole velocity log, the integrated travel-times from the sonic log were digitized at 5 m intervals down the hole. A running 3-point least-squares fit was applied to the data to obtain average interval velocities over vertical intervals of 10m; this type of analysis has been routinely used with delta borehole data (Hunter et al., 1997). The derived velocities are shown on the right side of Figure 2.

From comparative P and S wave downhole surveys in the delta, an empirical P to S velocity relationship has been derived (Hunter et al., 1996) as follows:

$V_S = 0.7455 V_P - 805.4$ m/s

with a standard deviation of V_S on V_P = 68.5 m/s

The P wave velocities and computed shear wave velocities are shown in Figure 5 along with the standard error bars carried through from the P wave least-squares fits. Although the absolute values of the standard error for a 3-point fit may not be meaningful, these are plotted as error bars in order to show relative goodness of fit between velocity determinations. Larger error bars in the lower portions of the borehole indicated larger scatter in the integrated sonic travel-time log resulting from fine-scale velocity variations within the 10 m fitting window.

The velocity-depth curves show that major velocity differences are associated with Holocene, Pleistocene and Tertiary age materials. The P and derived S velocities associated with the Holocene deltaic sediments are relatively uniform, and are typical of those observed elsewhere in the delta (Hunter et al., 1997). An abrupt P (and S) velocity increase is associated with the Holocene-Pleistocene boundary. Minor vertical variations within the P wave velocity structure may be associated with lithological variations or possibly minor amounts of gas in the pore-spaces. Finally, a major velocity increase is associated with the Pleistocene-Tertiary boundary; such Tertiary velocities are typical of more consolidated and semi-lithified sediments.

The velocity discontinuities associated with the Holocene-Pleistocene and Pleistocene-Tertiary geological boundaries are significant for earthquake ground motion amplification modelling studies, for the following reasons:

1) Similar shear wave velocity discontinuity correlations across the Holocene-Pleistocene boundary have been found elsewhere in the delta (Luternauer and Hunter, 1996; Hunter et al., 1997); these present results serve to indicate that such correlations are delta-wide. Such a velocity boundary implies a contribution to amplification of ground surface motion (Shearer and Orcutt,1987) for simple one dimensional elastic earth models. Wherever this boundary occurs within 100 m of ground surface, site resonance periods may be strongly altered during

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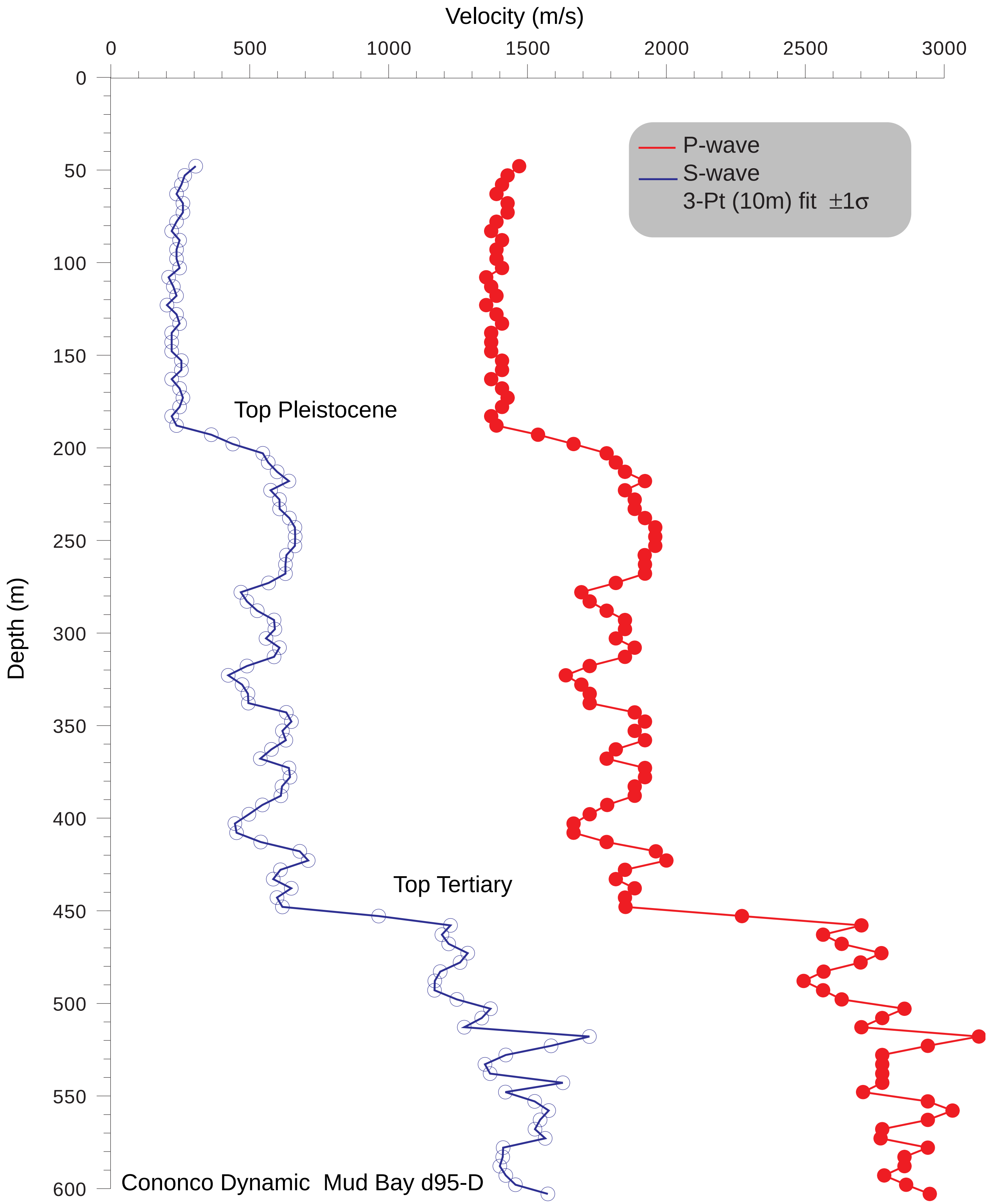

Figure 5. Compressional (P) and derived shear (S) internal velocity logs using 3-point least squares fits to the data over a vertical interval of 10m.

earthquake shaking (Hunter et al., 1997).

2) The P wave velocity results from this borehole are the first direct measurements obtained across the Pleistocene-Tertiary boundary in the Fraser River delta. Again, for simple one-dimensional elastic models (maximum amplitude, end-member type, which ignore anelastic attenuation and its variation with large earthquake strains), the computed shear wave velocity contrast at this boundary also infers very long period resonance effects along with a further contribution to ground motion amplification at surface (Shearer and Orcutt, 1987). The derived shear wave velocity ratio between the top of the Tertiary bedrock and the near-surface is on the order of 5:1. Using an approximate estimate of the density contrast between Holocene near-surface sediments and the Tertiary bedrock of 1.25:1 (Hunter et al., 1997) the (maximum) amplification effect from the top of the Tertiary bedrock to surface would be on the order of 2.5. Such estimates do not include the probable increase of shear wave velocity with depth within the Tertiary which may result in additional velocity-gradient amplification effects (see Hunter et al. 1997).

For ground motion amplification modellers in search of basic shear wave velocity-depth model parameters for the Fraser River delta, the following sources are recommended:

1) the Holocene velocity-depth function given by Hunter et al., (1997);

2) the variations in depths to the Holocene-Pleistocene boundary given by Luternauer and Hunter, (1996);

3) the variations in depths to the Tertiary bedrock surface given by Britton et al., (1995);

4) the derived Pleistocene and Tertiary shear wave velocities as presented in this paper.

Summary

Open hole electrical conductivity and sonic logs from the Conoco-Dynamic Mud Bay d95-D exploration well in the southeastern Fraser River delta have been interpreted to a depth of 600 meters through the Holocene, Pleistocene and upper Tertiary (bedrock) sequences.

Electrical conductivities indicate saline porewater occurs in the upper portion of the Holocene deltaic sequence; a large porewater salinity gradient occurs in the basal Holocene sequence which may result from salt diffusion related to a fresh water aquifer in the upper Pleistocene sequence.

Compressional and derived shear wave velocity contrasts are associated with the Holocene-Pleistocene and Pleistocene-Tertiary boundaries; such contrasts are of importance for earthquake ground amplification modelling studies.

The geophysical logs from this 600 m deep borehole are the first data sets of such measurements obtained from ground surface down to, and, into the bedrock within the Fraser River delta.

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