A CD-ROM COMPILATION OF SHEAR WAVE VELOCITY DATA FOR UNCONSOLIDATED SEDIMENTS IN THE FRASER RIVER DELTA

by

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ABSTRACT

Shear wave velocity-depth data are important input parameters for earthquake ground motion amplification modelling as well as for seismic liquefaction resistance estimates at thick soil sites. The Geological Survey of Canada has surveyed and compiled over 400 regional sites in the Fraser River delta using surface refraction, borehole logging, seismic cone penetrometer and deep seismic reflection technologies. The data are resident in a CD-ROM Open File and are accessed using on-board PC-based software via interactive map displays; screen and hard-copy shear wave velocity-depth plots and location information are available along with easy access to digital data files. Shear wave velocity-depth data are available from surface to bedrock in some areas. Also, the Open File contains an interpretation of significant shear wave impedance boundaries based on geophysical logs from a gas exploration well reaching bedrock, located in the southeastern portion of the delta.

INTRODUCTION

Since 1985, the Geological Survey of Canada (GSC) has conducted surface and borehole geophysical testing in the Fraser River delta in order to delineate and characterize subsurface Quaternary materials as an aid to regional earthquake hazard studies. Such geophysical work has included the application and interpretation of seismic reflection and refraction techniques as well as borehole measurements, and constitutes one portion of the geoscientific studies currently being conducted by federal, provincial, university, and industry research teams. The reader is referred to Clague et al. (1998) for a complete summary of current geoscientific knowledge of the area.

It has become apparent that the thick unconsolidated sediments of the Fraser River delta may be responsible for modifying the ground response to earthquake shaking through amplification and resonance of incident teleseismic earthquake waves; such effects may lead to large horizontal ground accelerations over limited seismic frequencies as well as the possibility of seismic liquefaction of near-surface, water-saturated, non-cohesive sediments. These effects are strongly dependent on the vertical and horizontal variations of shear wave velocity structure within the unconsolidated Quaternary sediments.

Hence, the Geological Survey of Canada has compiled all available GSC shear wave velocity data in the delta, along with other ancillary geophysical data in the form of a new GSC Open File CD-ROM (Hunter et al., 1998a) in order to provide an overview of velocity structure as a guide for geotechnical engineers and earthquake modellers. The CD-ROM is currently at the “beta testing” stage.

Although an attempt has been made to obtain subsurface shear wave velocity data on a regional scale, the reader will note that coverage is currently far from uniform, and future research will be directed towards filling some of the "voids" and examining geophysical structural anomalies in more detail.

ACCESS SOFTWARE

No external software packages are required in order to view the compiled geophysical data plots, since ACROBAT READER access software is resident on the CD-ROM; all active documentation, such as maps, text and plots, are in .PDF (Portable Document Format) with established links between map site locations and data display plots. All site maps contain an unlabelled street map background and both plots can be magnified for inspection; hardcopy prints of any .PDF file can be obtained at any time while the access program is running.

Digital data shown in each of the plots are also resident on the CD-ROM as ASCII files. Although these files cannot be accessed directly while ACROBAT READER is running, text prompts indicating the location of the ASCII files on the CD-ROM are associated with each plot; hence, upon exiting the access software, any ASCII file containing geophysical data can be downloaded to the user's PC.

ACCESSING THE DATA

Upon first running ACROBAT READER from the CD-ROM, a familiar Windows "tool-bar" is presented; to enter the data set, the user must click on the FILE icon and OPEN the DOCUMENT.PDF file. This brings the user to the title page, from which one may choose to examine the TUTORIAL (strongly recommended for first-time users), CONTINUE (on to the main TABLE of CONTENTS) or QUIT (to exit ACROBAT READER).

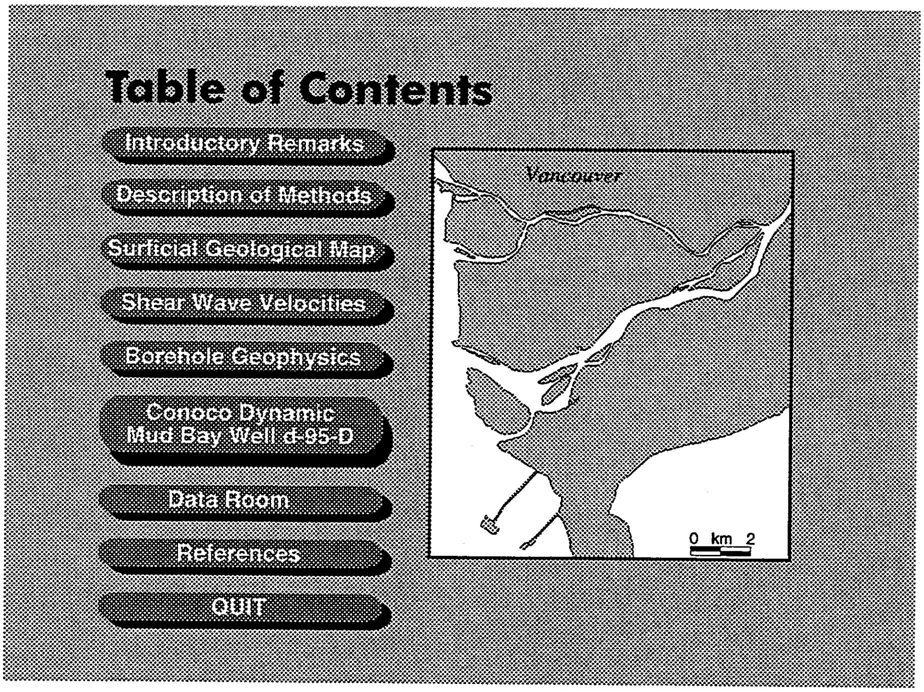

Figure 1. Table of Contents page of CD-ROM for the Fraser River delta survey area

The Main **Table of Contents** (Fig.1) has an outline map of the project area and eight (8) clickable buttons:
***Introductory Remarks:** gives a brief overview of the project aims and component data sets,
***Description of Methods:** detailed description of the geophysical methodology used to obtain the various data sets,
***Surficial Geological Map:** a surficial geology map for the delta from GSC Map 1486A (Armstrong and Hicock ,1976)

The geophysical database is accessed through one of the next three menu buttons:
***Shear Wave Velocities:** various shear wave velocity-depth data sets,
***Borehole Geophysics:** ancillary gamma, electrical and magnetic susceptibility logs and,
***Conoco Dynamic Mud Bay Well d-95-D:** electrical and seismic logs from an exploration well.

The remaining two menu buttons are:
***Data Room:** descriptions of ASCII digital file listings on the CD-ROM,
***References:** a list of cited literature as well as a bibliography of Fraser delta geoscientific publications

THE GEOPHYSICAL DATA BASE

1) Shear Wave Velocities

The main focus of the CD-ROM are the shear wave velocities which have been measured using:

- ***Surface shear wave refraction soundings**
- ***Borehole shear wave velocity logs**
- ***Seismic cone penetrometer**
- ***Shear wave velocity analyses** from conventional seismic data **(Dynamic Oil Co.)**

Clicking on **Shear Wave Velocities** in the **Table of Contents** brings up a location map showing all four data sets mentioned above, along with a menu button for each data set (Fig.2).

Upon selecting a particular data set (e.g. **Surface shear wave refraction soundings**), a map showing the data locations is displayed (Fig. 3). A detailed explanation of the geophysical methodology can be obtained either from each data set map (**M** – click here for description of methods), or from the main **Table of Contents** menu.

By clicking on a survey site shown on any of the four data set maps, the velocity-depth plots specific to that site will be opened. Note that UTM NAD-27 map coordinates of the survey sites are also printed on the velocity-depth plots and that ASCII UTM data location files can be found in DATAROOM directory on the CD-ROM.

<u>Example Surface Shear Wave Refraction Site</u>

At project initiation, surface shear wave refraction sites were designed only to provide shear velocity-depth data from surface to approximately 30-50 m depth (for regional liquefaction resistance studies); surface geophone array lengths were on the order of 100-200 m in length using transversely-polarized, horizontal geophones (at 3 meter spacing along the array) and similar transversely-polarized surface sources (Hunter et al., 1998b). Later, when the importance of identifying the top of high velocity Pleistocene materials at depth was realized, array lengths were increased (up to 500+ m) wherever possible. At most sites, reversed refraction shooting allowed observations of possible apparent velocities due to dipping layers. Such phenomena were not observed within Holocene deltaic sediments, but were commonly interpreted for cases where the top of the Pleistocene (associated with higher shear wave velocities) was observed. In all there are 112 refraction sites within the project area.

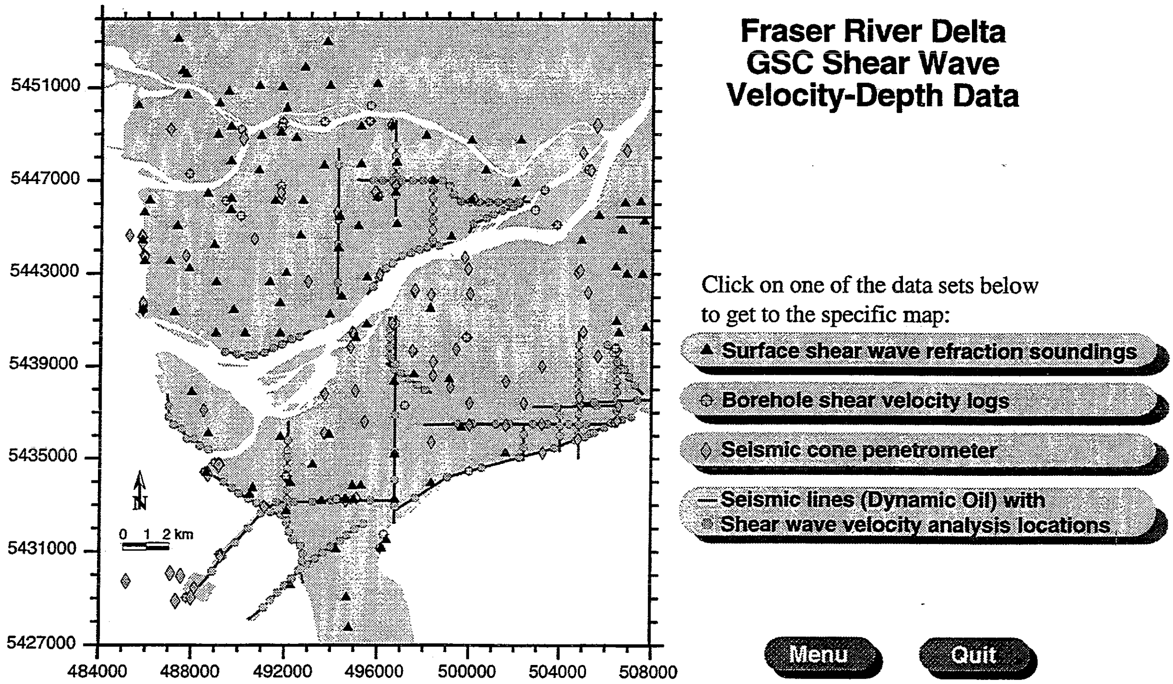

Figure 2. Overview map of compiled shear wave velocity-depth sites. Site locations can not be interrogated on this map.

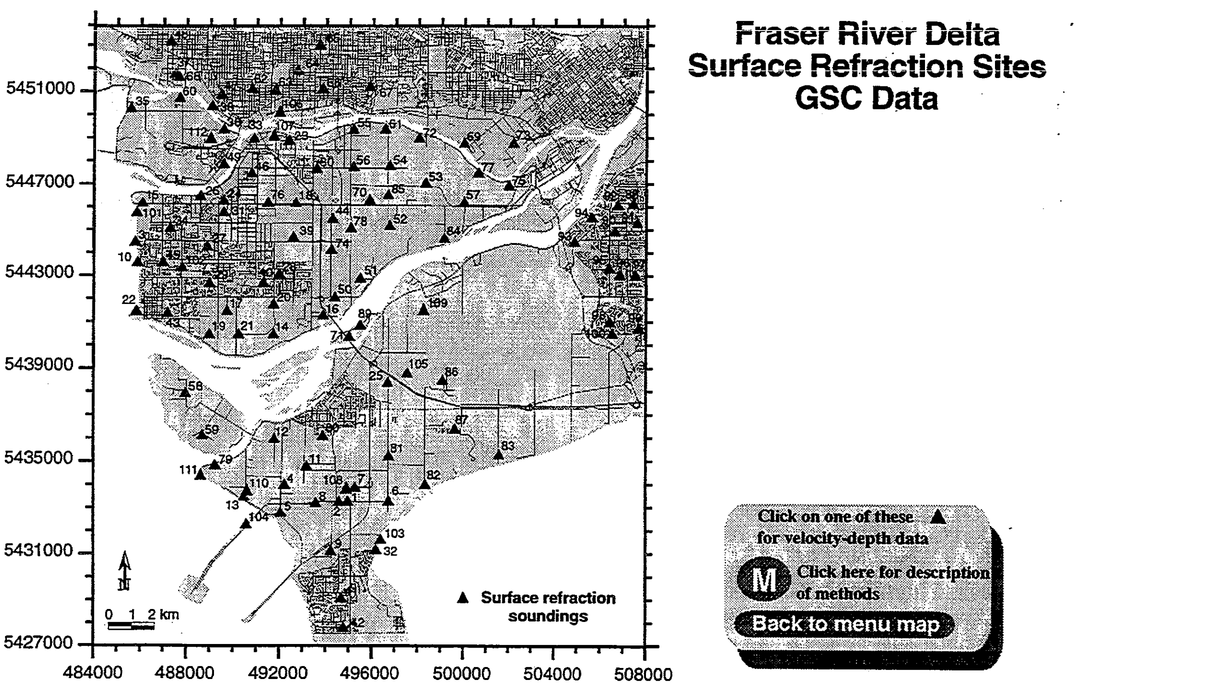

Figure 3. Shear wave refraction sounding site map. Site locations can be interrogated by "mouse-point".

Figure 4 shows velocity depth plots for refraction site #70 (**Table of Contents->Shear Wave Velocities->Surface shear wave refraction soundings->**click **#70** on the site map). This site is located on Westminster Highway between No. 6 and No. 7 Roads, City of Richmond, immediately south of a GSC borehole (FD94-3).

Figure 5 shows the travel-time depth plots for the forward and reverse arrival times of the refracted SH wave. These data were interpreted in two ways: the conventional interpreter-dependent LAYERED-CASE approach, and a "hands-off" computer-based curve fitting and depth inversion routine (known as VELDEP; Hunter, 1971). Both approaches are useful, in that the LAYERED-CASE approach yields a series of abrupt velocity-depth interfaces (with direct interpreter bias), whereas the VELDEP approach incorporates the uncertainty in depth determination due to geophone spacing, yielding a smoothed curve of velocity vs depth (with indirect interpreter bias via fixed and selectable input parameters of the computer routine). It is suggested that the VELDEP interpretation is more amenable to estimating velocity functions within the Holocene deltaic sediments, whereas the LAYERED-CASE interpretation is best for estimation of depth to, and velocities associated with, large seismic impedance contrasts (e.g. the top of Pleistocene sediments).

In the example shown in Figure 4, the "forward" geophone array was shot from south to north (from the highway towards the GSC borehole) and the thickness of low velocity deltaic sediments is approximately 32 m. The "reverse" array shot from north to south (adjacent to the GSC borehole) indicates that the low velocity sediments are approximately 19 m thick. From continuous coring in borehole FD94-3 (Dallimore et al., 1995), it is known that Holocene deltaic sands overly Pleistocene sands, with the boundary identified at a depth of 19.2 m. This sand-to-sand "geological age" boundary still displays a significant shear wave velocity contrast. At other sites, where diamictons associated with the Pleistocene boundary have been encountered, much larger velocity contrasts have been found.

Example Borehole Shear Velocity Log

Downhole shear wave velocity data have been obtained in 44 boreholes to date using a variety of similar borehole-locking geophones and surface shear sources. The reader is referred to Hunter et al. (1998c) for detailed descriptions of the techniques. In general, a sidewall-locked, 3-component geophone pod, firmly in contact with the sediments through grouted PVC casing, was moved successively in either 0.5 or 1 m depth increments down a borehole. At each location, the seismic signal from a horizontally-polarized surface shear source impulse was recorded from the 3-component geophones and interpreted for onset of shear wave motion. The surface-to-geophone travel time vs depth plot was interpreted, by means of running least-squares fits, in terms of shear wave interval velocities.

The example shown here (**Table of Contents->Shear Wave Velocities->Borehole shear velocity logs->**click **94-4** on site map) is from GSC borehole FD94-4 drilled near the intersection of No. 4 Road and Alderbridge Way, City of Richmond. The data acquisition field work was performed under contract by Frontier Geosciences Inc. of Vancouver, and utilized a geophone pod moved in 1 m increments from surface to total depth (300 m); the source was a truck-loaded wooden beam impacted with a pendulum-configured wooden ram. The plot shown in Figure 6 consists of the travel-time vs depth data on the right side of the plot and the interval velocity interpretation at 1 m intervals (in this case using a 9-pt, or 8 meter length, least squares fit) on the left side of the plot. The error bars shown on the velocity plot are derived from the least-squares fits; in this case, as indicated, they are +/- 2 standard errors on the velocity determination.

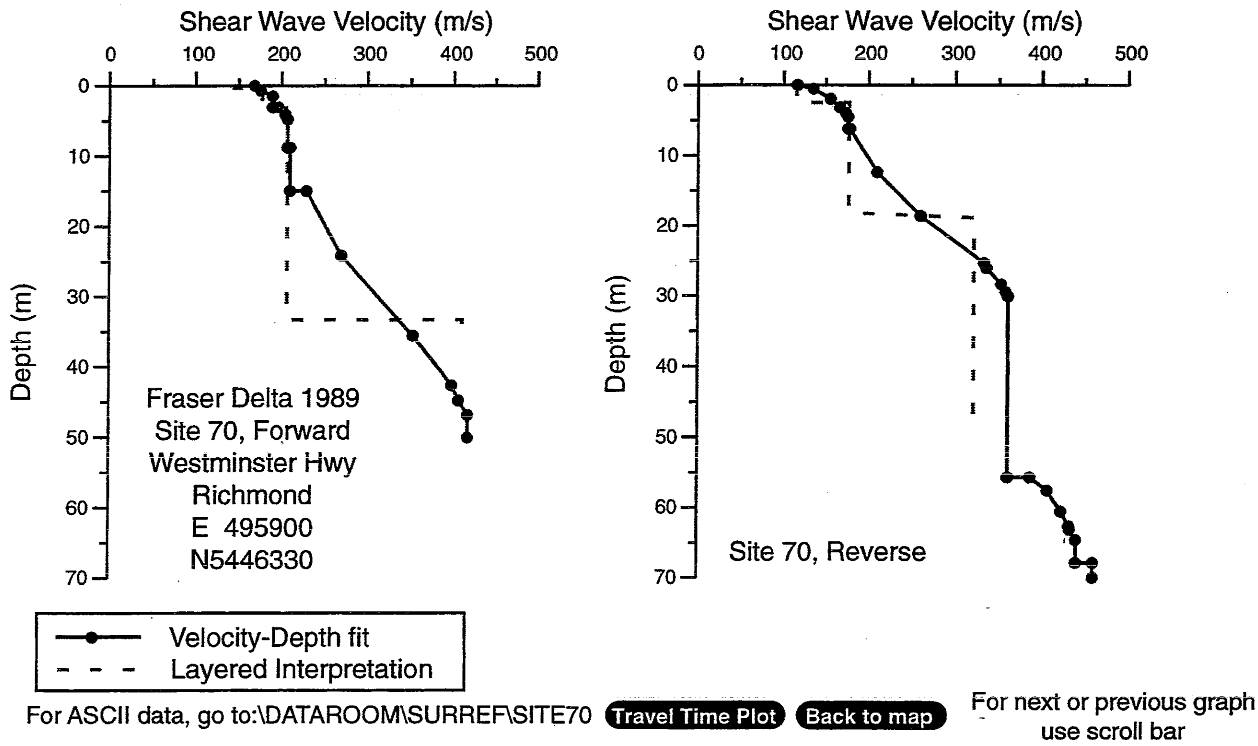

Figure 4. Example shear wave velocity-depth interpretation from a surface refraction site survey.

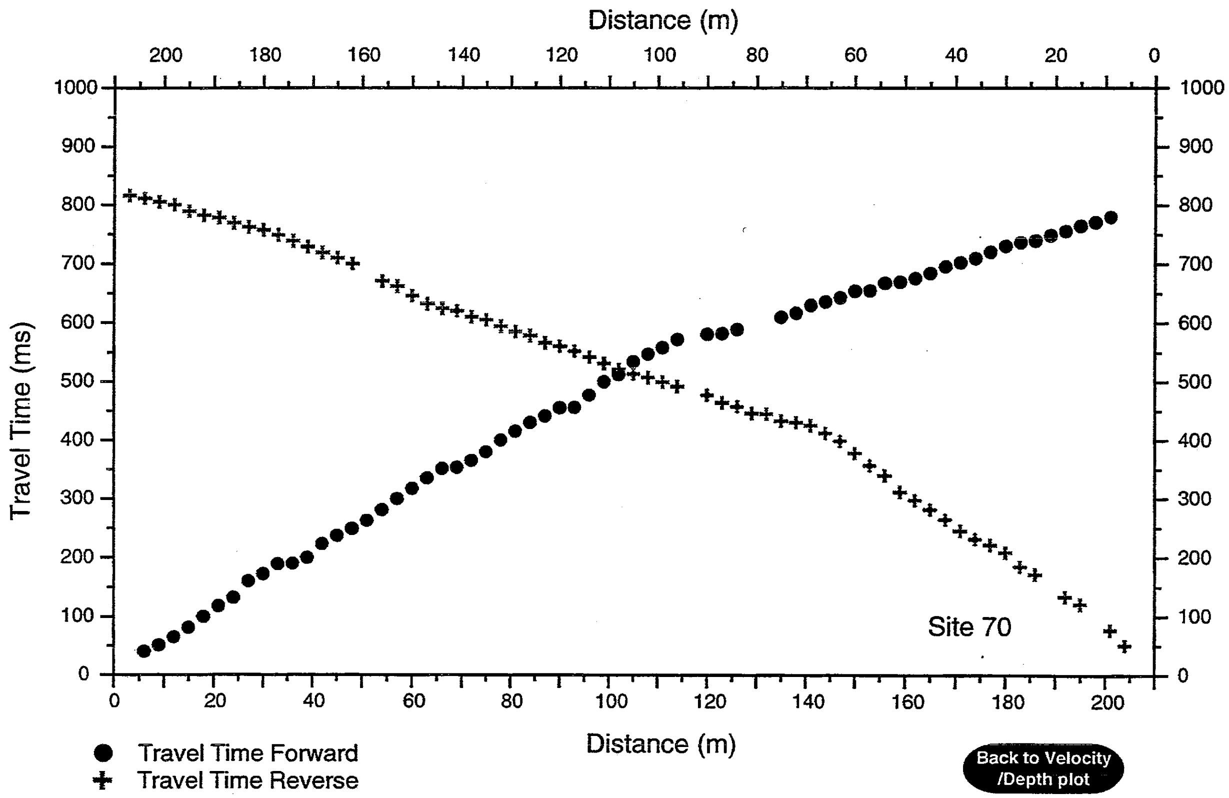

Figure 5. Example shear wave refraction travel-time data for the site show in figure 4.

From continuous sampling in this borehole (Dallimore et al., 1995), it is known that the top of Pleistocene occurs at 236 m depth. Shear wave velocities within the Holocene deltaic sediments increase from 100 m/s near surface to over 450 m/s at depth. The top of the Pleistocene is marked by a large velocity increase (to 800 m/s) associated with an overconsolidated diamicton. Below this, it is interesting to note that a relatively lower velocity is associated with a Pleistocene marine clay at an approximate depth of 285 m. The hole bottomed in overconsolidated diamicton at 300 m depth.

Example Seismic Cone Penetrometer Log (SCPT)

The SCPT, a shear wave velocity measurement technique using geophones or accelerometers installed within a cone penetrometer (utilizing surface shear wave sources) was introduced several years ago (Robertson et al., 1986) and is now considered a routine geotechnical investigative tool. This method was used effectively within the Fraser River delta at locations where other shear wave velocity techniques were not logistically feasible. As well, single cone pushes (without drill-out) to 40 or 50 m depth can easily be achieved in the delta, both on-shore and on the shallow shelf of the delta front, making this technique most cost-effective. All SCPT data in this compilation (87 logs) were obtained under contract by Conetec Investigations Ltd., Vancouver. Only the shear wave velocity-depth data from the cone pushes are given here; the complete compilation and interpretation of the SCPT work will be the subject of a future CD-ROM presentation (H. Christian, GSC, pers. comm.)

The example SCPT shear wave velocity log shown here in Figure 7 (**Table of Contents->Shear Wave Velocities->Seismic cone Penetrometer->**click on **93-1** on site map) is from a cone push done at the BC Hydro Canoe Passage substation at the landward end of the coalport causeway in the municipality of Delta. Details of the seismic cone and the field logistics can be found in Woeller et al. (1993). The standard procedure consists of shear wave travel-time measurements at 1 meter intervals; the shear wave velocities are derived from the interval travel time between two successive vertical cone positions, and values are plotted at mid-point locations. This example indicates a thin, near-surface, high-velocity zone (0-1.5 m depth), probably associated with the prepared gravel pad, below which the shear wave velocity increases uniformly from 80 m/s to >200 m/s at 40 m depth. This velocity-depth gradient (0-40 m) is typical of the near surface Holocene deltaic materials throughout the survey area.

Example Shear Wave Velocity Analysis (Dynamic Oil Co. Data)

Over 125 line-kilometers of deep-sounding seismic reflection data were obtained by Dynamic Oil Company of Vancouver in the late 1980's as an aid to hydrocarbon exploration in the Fraser River delta. The seismic methods employed in these surveys used state-of-the-art, multichannel, reflection geophone arrays along with multiple "vibroseis" vehicles (massive, swept-frequency, P-wave vibratory sources, hydraulically coupled to the earth surface by the weight of the trucks). By using "common-depth-point" overlapping shooting and recording techniques, the large redundancy of digital seismic records were processed to produce good quality seismic reflection sections, despite the urban noise environment. From these seismic sections, reflections defining geological structures within the Tertiary-Cretaceous bedrock favorable to hydrocarbon accumulations can be interpreted. With the array geometries and computer processing used in this work, the seismic sections commonly displayed the top of bedrock as the first prominent reflector on the sections (although several weaker reflection events within the Quaternary section usually are interpretable). A bedrock topographic map based on these reflections has been published by Britton et al. (1995); depth to top of Tertiary bedrock ranges between 200 m and 1058 m within the delta project area. Depth interpretations have been subsequently ground truthed at two locations by exploration well-drilling.

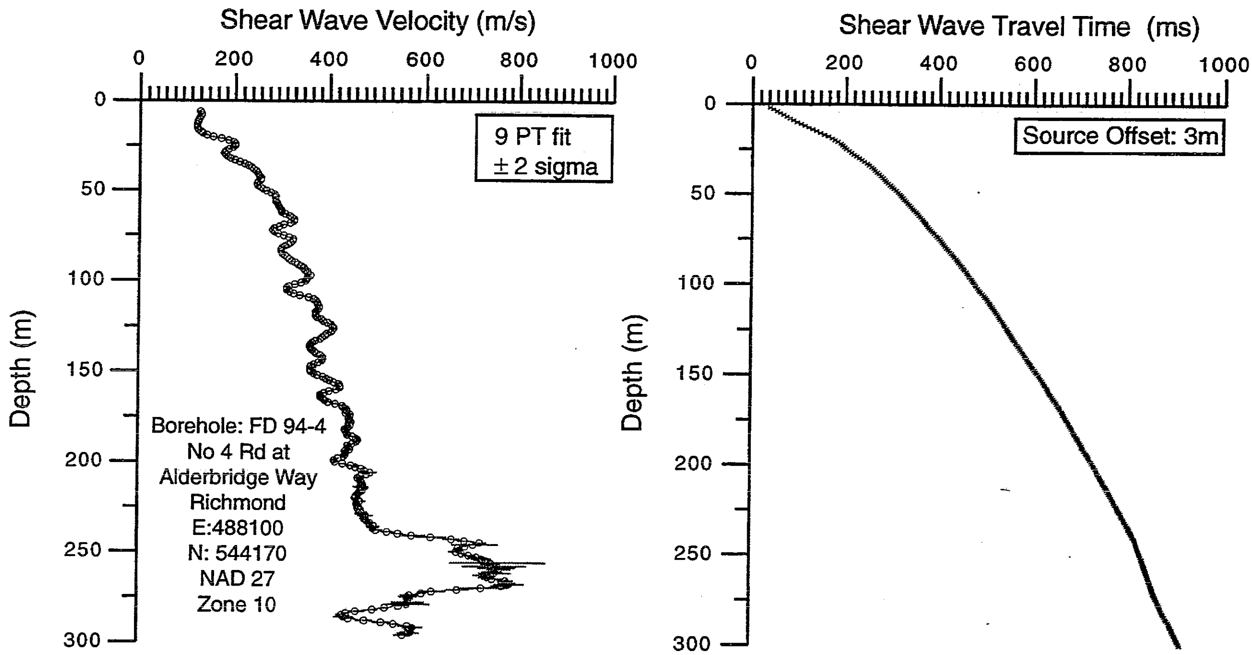

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Figure 6. Example borehole shear wave velocity depth interpretation.

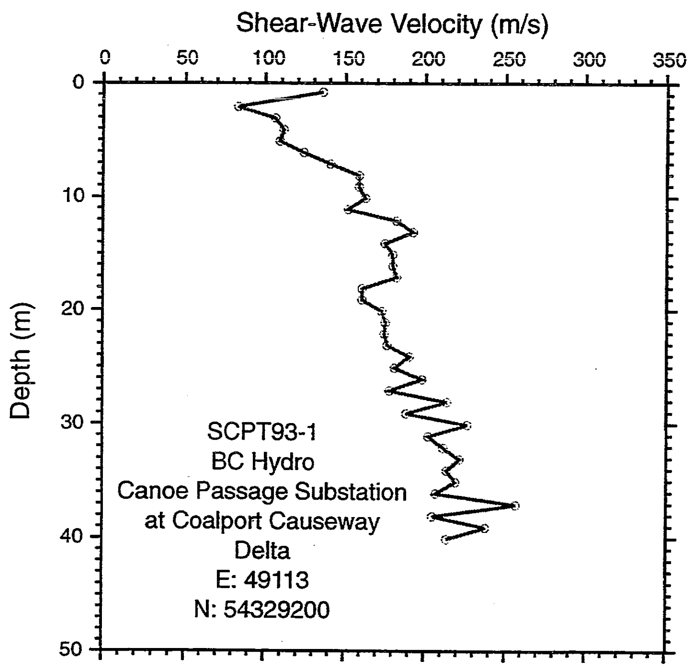

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Figure 7. Example SCPT shear wave velocity-depth interpretation.

As one step in the computer-processing of seismic sections, compressional-wave (P-wave) velocity analyses were done at regular intervals along seismic lines by examination of the travel-times, distances, and amplitudes associated with reflection horizons, from within the overburden, the overburden-bedrock surface, as well as from within the bedrock sequence. These P-wave velocity-depth functions (from surface to 3500 m depth) can be converted to shear wave velocity-depth functions using an empirical relationship developed by Hunter et al. (1996). Further details on this technique, including plots and equations, can also be found within this CD-ROM (**Table of Contents->Description of Methods->Seismic lines (Dynamic Oil) with shear wave velocity analysis locations**). The example velocity analysis shown in Figure 8 (**Table of Contents->Shear Wave Velocities->Seismic lines [Dynamic Oil]...->**click on the northern most point on line **8941** in the south central portion of the site map) was done on the multichannel record from shot point #146 (eg. VA-146) along a seismic line shot in 1989 along 41b Street in Delta. The V_p curve shown here is that produced during routine computer processing of the reflection seismic data. The V_s curve has been derived from the P-wave data.

The notation of the top of Tertiary bedrock (at 630 m depth), is taken from reflection seismic section interpretations of Britton et al. (1995); in most cases, this interpreted depth coincides with large P- and S-velocity contrasts indicated on the velocity analyses. The higher P and S velocities below a depth of 425 m in Figure 8 suggests the presence of Pleistocene material (probably overconsolidated); however the discontinuity at 425 m depth may not necessarily be associated with the Holocene-Pleistocene boundary.

Also, between 95-200 m depth in Figure 8, the P-wave velocity decreases slightly below the value of 1470 m/s. This decrease is probably indicative of the presence of small quantities of gas within the pore spaces of the Quaternary sediments, since compressional wave velocities are a combined function of granular framework and pore-space fluid velocities. Such gas inclusions do not affect shear wave velocities to any degree, since these are primarily transmitted through the granular framework only; hence, the derived S-wave velocities shown here in this depth range may be erroneously low. The user is cautioned to carefully examine the V_p vs depth curve of any site for possible velocity reversals that are carried over to the derived V_s plot; these may or may not represent true reversals of formation shear wave velocities.

All site plots (182 in all) are standardized with a velocity axis range to 4000 m/s and a depth axis range to 1000 m. The depth range was selected to show optimal resolution of the data within the depth range of most potential users. In most cases, velocity-depth information is available to a depth of 3500 m in the ASCII data files.

2) Borehole Geophysics

Natural gamma, electrical conductivity (induction) and magnetic susceptibility logging data have been obtained in over 50 GSC boreholes in the delta using the GEONICS EM-39 logging system. This logging system is commonly run in a 5-6.5 cm diameter PVC-cased borehole since no galvanic contact with the formation is required. These ancillary logs have been included with the CD-ROM compilation in order to provide additional lithological and porewater chemistry information of use to geotechnical investigators.

The primary natural gamma radiation response from surficial sediments comes from radiactive isotopes of potassium, uranium, and thorium. Variation in the amount of radioactive potassium with variation in fines content is thought to be the main reason for the success of this passive monitoring tool as a qualitative lithological indicator. All gamma logs in this compilation were run with the same sonde, and, with few exceptions, all boreholes were cased with similar

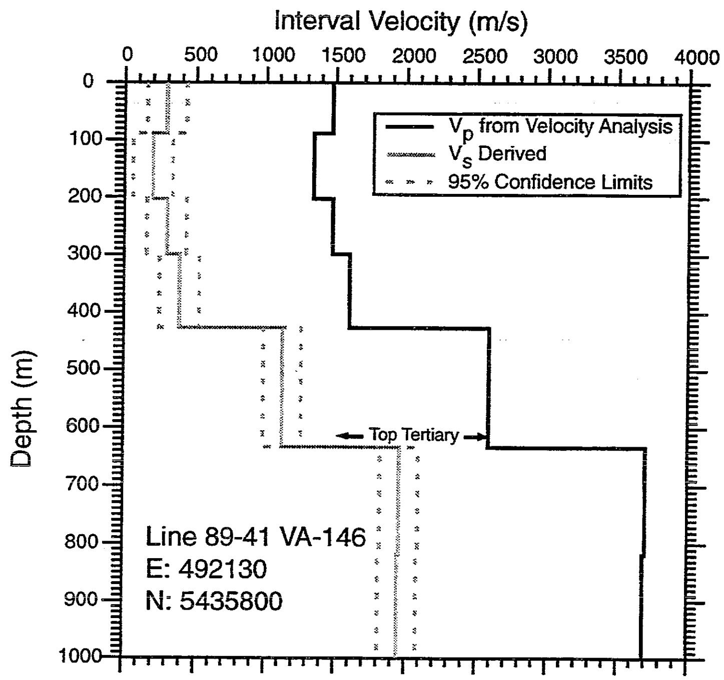

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Figure 8. Example of a P wave and derived S wave interval velocity-depth curve from seismic reflection data.

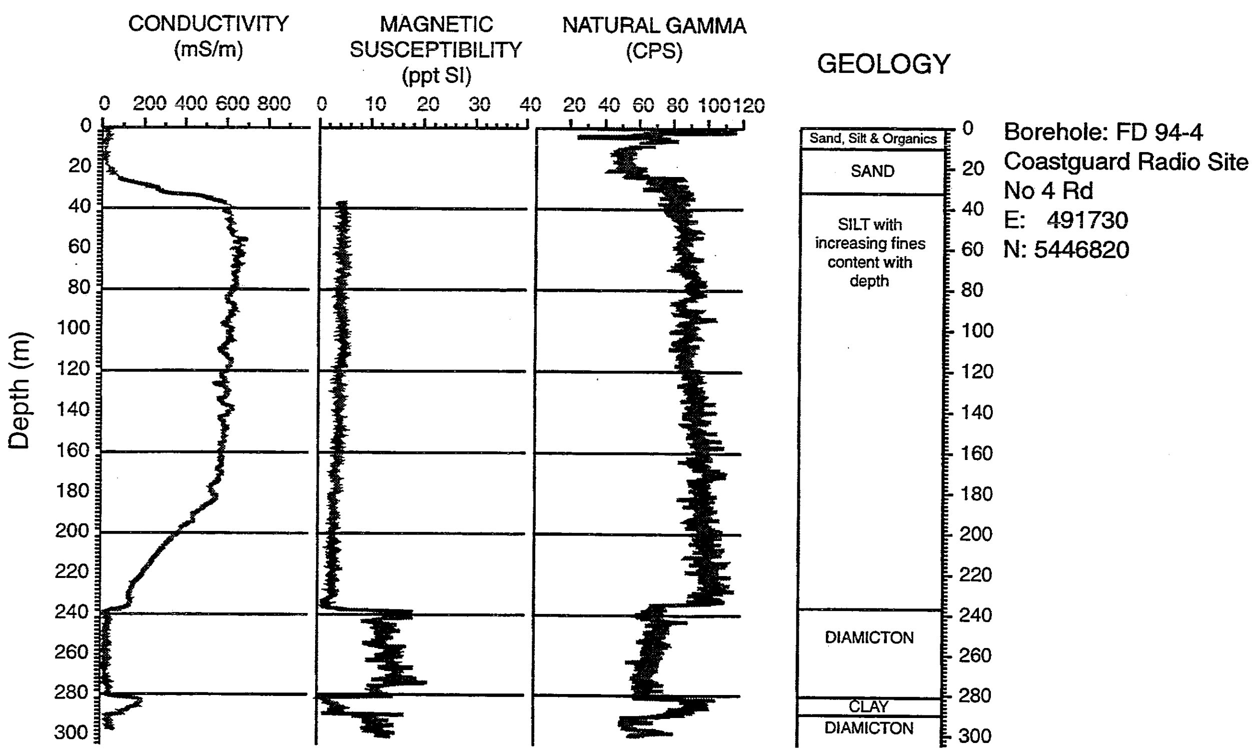

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Figure 9. Site 94-4 borehole geophysics and generalized geological log

diameter PVC. Hence, comparisons of gamma count levels between boreholes are possible. Within Holocene sediments, gamma counts below approximately 60 counts per second (CPS) generally are associated with medium to coarse sand; gamma counts above 100 CPS are generally associated with silty clays. Similar generalizations can be made for Pleistocene sand, silt, and clay; diamictons generally yield gamma responses reflecting the main grain size of the matrix.

Borehole measurements of electrical conductivity variations within Quaternary sediments of the Fraser River delta have been related to variations in porewater salinity (Hyde and Hunter, 1998). Electrical conductivities of porous Holocene deltaic sands can exceed 1200 mS/m reflecting a porewater salinity similar to seawater; yet such sands can also yield values as low as 10-20 mS/m, indicative of fresh interstitial water. Electrical conductivity gradients (hence porewater salinity gradients) commonly occur in basal Holocene silty-clay sediments, immediately above the Pleistocene surface. Of current interest is the sensitivity of these materials and the role of salt leaching in such processes (Christian et al., this volume); borehole electrical conductivity measurements may be an aid in such studies.

The magnetic susceptibility of magnetite is much larger that that of most other heavy mineral grains that occur within Quaternary unconsolidated sediments. Hence in the fluvial deltaic setting of the survey area, the magnetic susceptibility sonde can be viewed as a lithological mapping tool, in a general sense. That is, fine grained materials such as silts and clays yield very low susceptibility values, whereas, gravels most often give relatively high values (if the gravel source is rock with iron-rich mafic minerals). It is interesting to note that in the Fraser River delta some sands are magnetite rich, and some are not. It is found that Pleistocene sands and diamictons show relatively high magnetic susceptibility values, whereas, Holocene deltaic sands show very weak responses. Hence in this setting, it is suggested that the magnetic susceptibility tool can help to delineate the Holocene-Pleistocene boundary (McNeill et al., 1996).

The example borehole geophysics log suite given in Figure 9 (**Table of Contents->Borehole Geophysics->**click on **94-4** on the site map) is that of GSC borehole FD94-4 near the corner of Alderbridge Way and No.4 Road in Richmond (see also Figure 6 for shear wave velocity data). The three geophysics logs can be referenced to the generalized geological log (from continuous coring) shown on the right side of the plot.

The conductivity log in the upper 30 m (Holocene sand and surface silts) shows values <200 mS/m, indicating that the formation contains fresh porewater. Saline conditions occur through most of the finer-grained Holocene sequence from 40 to 190 m depth. Between 190m and 237 m depth, a pronounced conductivity gradient indicates an associated salinity gradient withiin the basal Holocene clayey silts, and with fresh porewater within the Pleistocene section.

The magnetic susceptibility log indicates that the Holocene sediments contain very little ferrimagnetic materials. An abrupt increase in mangetic susceptibility response is associated with the Holocene-Pleistocene boundary at 237 m depth where the first diamicton is encountered.

The natural gamma log in the near surface has count rates exceeding 100 CPS indicating the occurrence of overbank silts and clays, with a fining upwards sequence between 10 m depth and surface. The sand sequence between 10 m and 30 m depth is well defined as a low count rate zone. Between 30 m and 237 m depth the gamma log indicates silty material becoming uniformly finer with depth (increasing count rate to 100 CPS and beyond). The diamicton and clay zones of the Pleistocene below 237 m depth are well defined by contrasting gamma count rates.

3) Conoco-Dynamic Mud Bay Well d-95-D

The last data set on the CD-ROM (**Table of Contents->Conoco Dynamic Mud Bay Well d-95-D**) consists of a GSC report describing electrical induction and seismic logs from a well drilled through the Quaternary sediments and into the Tertiary bedrock in the south-eastern portion of the delta. To date, this is the only known hydrocarbon exploration well in the delta with continuous geophysical logs from surface down to Tertiary bedrock; the geophysical contrasts shown in this report (i.e. the Holocene-Pleistocene and Pleistocene-Tertiary boundaries) are noteworthy for earthquake modellers.

Figure 10 shows the combined generalized geology, electrical induction and interval velocity logs from the well (**Table of Contents->Conoco Dynamic Mud Bay Well d-95-D->**page 4 of the report). The conductivity logs are digitized at 1 meter intervals and the interval velocity logs have been derived from the integrated sonic log digitized at 5 m intervals. From the geological log, the Holocene-Pleistocene boundary has been interpreted to be at a depth of 190 m, and the Pleistocene-Tertiary boundary at 448 m depth.

The shear wave velocities derived from the P-wave interval velocity data are shown in Figure 11 (page 10 of the report). The applied P-S relationship is the same as that used in conversion of Dynamic Oil's reflection seismic velocity analyses, as discussed above. Large shear wave velocity contrasts are associated with both the top of the Pleistocene and the top of Tertiary bedrock. Such interfaces represent significant refraction and reflection boundaries for upcoming earthquake seismic waves, and may produce resonance and gradient amplification effects. The association of similar shear wave velocity discontinuities with the buried Pleistocene surface, from other GSC boreholes in the area, suggests that the Holocene-Pleistocene boundary may represent a large shear wave velocity contrast under much of the Fraser River delta. It is unfortunate that the buried topography of this boundary is not very well known to date, and more geophysical surveying and geotechnical drilling needs to be done to delineate this interface.

SUMMARY

A Geological Survey of Canada Open File consisting of a CD-ROM compilation of shear wave velocity-depth data, and ancillary geophysical data of the Quaternary sediments in the Fraser River delta, is currently at the "beta testing" stage. These data are a contribution to the determination of earthquake ground response of this thick soil area. Interactive maps and plot displays can be examined by the user with the aid of on-board display software. ASCII data files are also available for downloading. Although editorial proof-reading of maps, plots and ASCII files has been attempted, inevitably such a compilation will not be error-free. It would be appreciated if such errors could be brought to the attention of the author.

ACKNOWLEDGMENTS

I would like to acknowledge the support and encouragement of Dr. W.D.L. Finn who first suggested a CD-ROM compilation of GSC shear wave velocity measurements. A number of researchers contributed to the compilation of the data bank including: Dr. J.R. Britton, R.A. Burns, H.A. Christian, S.R. Dallimore, M. Douma, R.L. Good, Dr. J.B. Harris, Dr. J.L. Luternauer, P.A. Monahan, Dr. K.G. Neave, Dr. M.C. Roberts, and D.J. Woeller. The diagrams for this paper (as well as the layout of the CD-ROM) were created by Ms. Chantal Pelletier in a most efficient and exacting manner for which I am most appreciative.

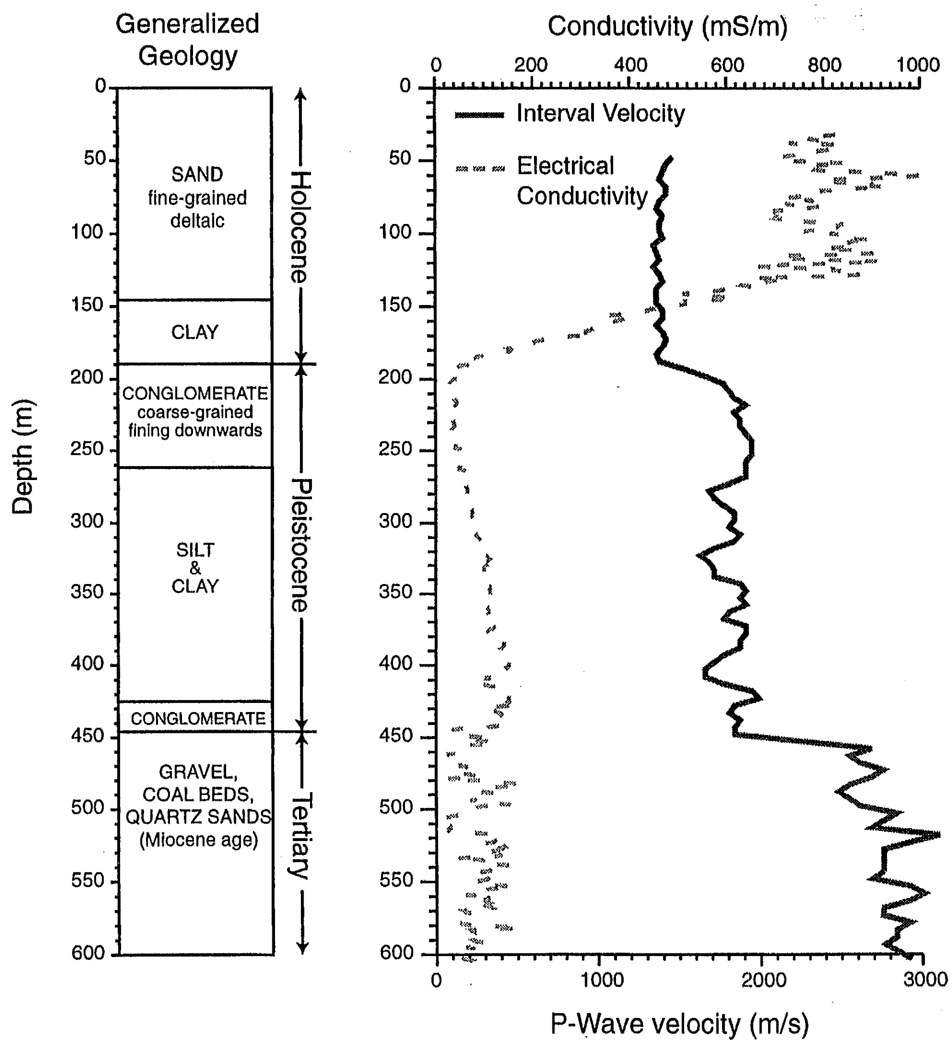

Figure 10. Generalized geology, induction conductivity, and P wave interval velocities (obtained from the sonic log) for the Conoco-Dynamic Mud Bay exploration well.

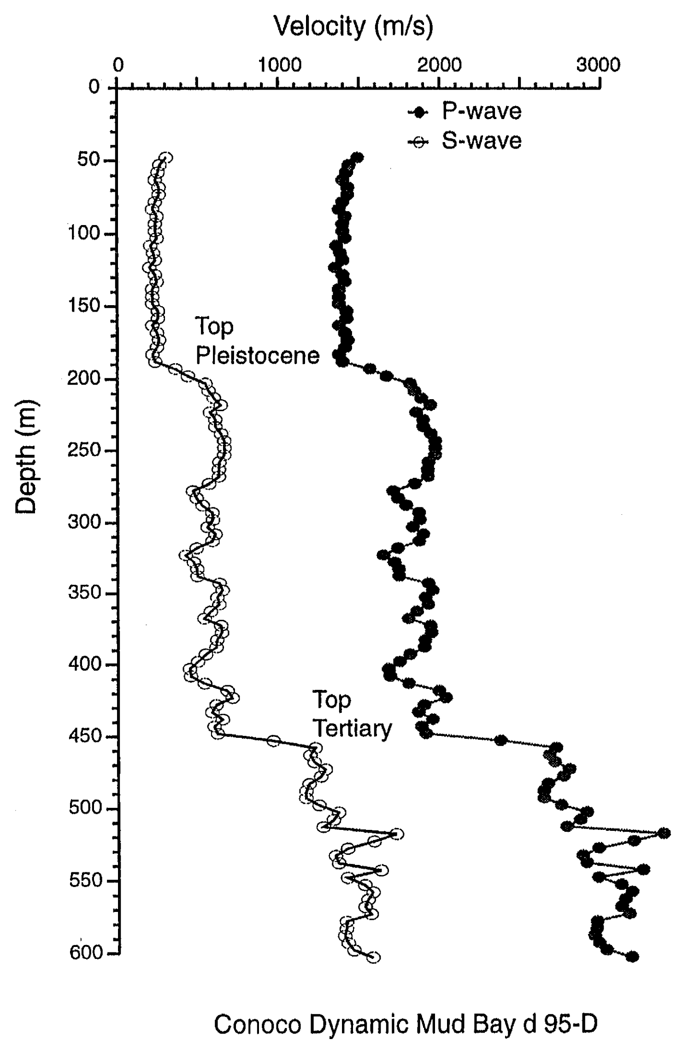

Figure 11. Compressional (P) and derived shear (S) interval velocity logs using 3-point least squares fits to the data over a vertical interval of 10 m.

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