# In-Situ Testing for Characterizing Organically Contaminated Sites: A Case History

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## ABSTRACT

In 1993/1994, the UBC In-Situ Testing Group (ISTG) carried out an in-situ testing program at a wood preserving plant site in New Westminster, B.C., to demonstrate the feasibility of using cone penetration technology as a means of geo-environmental site characterization. The purpose of the demonstration was to evaluate the effectiveness of resistivity piezocone penetration testing used in conjunction with discrete depth water sampling for screening a hydrocarbon contaminated site.

## RESUMÉ

En 1993/1994, le Groupe d'Essais en Place (ISTG) de l'Université de Colombie-Britannique a réalisé un programme de essais sur le site d'une usine de préservation du bois à New Westminster, C.-B. Ce programme visait à démontrer le potentiel de l'utilisation des techniques pénétrométriques dans le cadre des campagnes de caractérisation environnementales des terrains. Le but de la démonstration était d'évaluer l'efficacité du piézocone couplé à un résistivimètre utilisé en combinaison avec l'échantillonage ponctuel de l'eau intersticielle en vue de délimiter une parcelle de terrain contaminée par des hydrocarbures.

## INTRODUCTION

Conventional drilling and sampling are currently the most common methods used to assess site contamination, but they are disruptive to the environment and leave cuttings which require special handling. The time and expense associated with these methods often limit the scope of the investigation and the extent to which the stratigraphy and contaminant plume may be delineated. As such, there has been increasing interest in developing/refining technology that would provide quick and reliable site screening methods that could also track contaminant and groundwater movements.

The piezocone penetration (CPTU) test and the resistivity CPTU (RCPTU) test (Campanella and Weemees, 1990) utilize a direct push technology and provide rapid, high resolution delineation of stratigraphy and determination of in-situ hydrogeological regime without creating cuttings. Both geotechnical and hydrogeological parameters are readily obtained from the testing. Equilibrium pore pressures can be obtained by conducting pore pressure dissipations enabling determination of existing hydraulic gradients and hydraulic conductivity values. Calibration of bulk resistivity measurements to discrete depth water sampling and appropriate analyses enable identification of discrete lenses and/or zones of elevated concentrations of contaminants.

This paper outlines this technology and its use to characterize an industrial site located in the Lower Mainland, B.C.. The test site encompasses an area of approximately 45 acres along the Fraser River. Salish deposits, consisting of deltaic, channel and flood plain sediments of the Fraser River, are most prevalent in the area and at the test site (Armstrong 1956). The ground water table is generally 2 to 3 m below the ground surface and is affected by tidal fluctuations. The test site is a wood preserving/wood treatment plant that has been in operation since the 1930's. Polyaromatic hydrocarbons (PAHs) and phenolic compounds associated with coal tar creosote, a dense non-aqueous phase liquid (DNAPL), and its derivatives are the main contaminants of interest.

This case history demonstrates how the RCPTU can be used and interpreted to provide a geo-environmental characterization of a contaminated site, with respect to stratigraphy, geotechnical and hydrogeological parameters of interest and contaminant location and distribution within the subsurface. Results obtained from the RCPTU program were compared to those obtained from a more conventional investigation. The paper also discusses some practical applications and limitations of penetration technology as applied to hydrocarbon contaminated sites.

## FIELD METHODS

All testing was conducted by members of the UBC In-Situ Testing Group (ISTG). The UBC in-situ testing research vehicle was used as the penetration rig . The methodologies and procedures used in this study have been gaining wide spread acceptance in the geo-environmental field for use in unconsolidated sediments (Karwoski et al 1992, Klopp et al 1989 and Zemo et al 1992).

## Piezocone Penetration Testing (CPTU)

The piezocone, as specified by ASTM D3441, is pushed into the ground at a constant rate of 2 cm/s or about 1 metre per minute. The cone can be pushed using either a modified drill rig or a specially outfitted hydraulic pushing rig. Measurements of tip bearing stress, ($q_c$), sleeve friction ($f_s$), pore pressure at three possible locations, (U1, U2 or U3 for face, behind tip or behind friction sleeve, respectively), temperature (T) and inclination (i) are recorded simultaneously by a PC based digital data acquisition system. All measurements are made by calibrated strain gauges and/or transducers. The cones are also equipped with either accelerometers or seismometers to enable the determination of dynamic soil properties. Readings are commonly taken every 1 to 5 cm in depth. Pore pressure dissipations can be conducted at specific depths of interest.

## Resistivity Piezocone Penetration Test (RCPTU)

The combination of downhole geophysics and penetration technology has greatly improved the speed, quantity and quality of data obtained for geo-environmental site characterizations. The resistivity piezocone test is an adaptation of the standard CPTU. The resistivity piezocone (RCPTU) test consists of a non-standardized resistivity module (Campanella and Weemees, 1990) with surface electrodes at various spacings like 10, 25 and 75mm mounted behind a standard piezocone . The widest spaced electrode set is used for constant peak current 1000Hz excitation and AC voltage is measured across all electrode spacings. This tool allows for measurement of bulk resistivity, $\rho_b$, in addition to all the traditional CPTU measurements. Bulk resistivity gives a qualitative assessment of relative ground water quality since its measurement is dominated by the pore fluid chemistry. Table 1 shows typical values of resistivity and conductivity measurements of soil mixtures and pore fluid based on experience at UBC. These demonstrate the relative size of contrasting values that can be expected from various constituents in the groundwater. Of course, site specific correlations must be determined through water sampling and testing. Resistivity and conductivity are reciprocals related according to Equation (1):

Conductivity (Siemens per metre, S/m) = 1 / Resistivity (Ohm-metres, Ω-m) or

Conductivity (micro-Siemens per centimetre, μS/cm) = 10,000 / Resistivity (Ohm-metre, Ω-m) [1]

## Discrete Depth Water Sampling System

The UBC discrete depth water sampling system consists of a BAT system (Torstensson 1984), which has been modified (Campanella et al 1994). High quality ground water and vapor samples are obtained in an evacuated sample tube through a double ended hypodermic needle from an installed filter tip. Samples are typically collected in 35 to 150 ml tubes. The sample tube is lowered by a cable to the sampling point. The modified BAT used by UBC is 50 mm in diameter and is hydraulically pushed into the ground. Standard AWL size flush joint casing rods are used for the deployment of this equipment. The filter tip can be pushed on its own or down a previously pushed CPTU/RCPTU hole.

The United States Environmental Protection Agency (US EPA) and other such groups have conducted many field trials and comparisons of existing water sampling technologies (Blegen et al 1988). They have recognized the BAT technology as being superior in obtaining high quality groundwater samples for use in screening studies and for geo-environmental characterizations.

Test Procedure

Resistivity piezocone penetration (RCPTU) testing was used in conjunction with discrete depth water sampling as a preliminary method of site characterization. RCPTU bulk resistivity logs are used to determine anomalies across the site which cannot be explained by changes in soil type or stratigraphy. These anomalies are based on comparisons to site specific background or baseline values. Background values are established from on-site experience or from similar geological and geochemical environments. The modified BAT is then used to obtain water samples within the zone(s) of interest. Upon sample retrieval, preliminary chemical analyses can be conducted on site, and the sample can be appropriately stored for further chemical analyses. The filter tip can then be advanced to the next depth of interest, and the procedure repeated.

Testing Program

UBC carried out an in-situ testing program consisting of 13 RCPTU soundings and 2 CPTU soundings (combined depth of approximately 450m) and 12 water samples in three different hole locations. Soundings were located such that results could be checked against those obtained from the conventional drilling and sampling program. Water sampling holes were located to enable a reasonable comparison between site baseline values and values in the midst of the contaminant zone(s). A continuous vibro-core hole was drilled and detailed logging was compared to results obtained from the RCPTU testing. Figure 1 shows a general site layout, marking the location of each sounding in addition to previous test holes.

## RESULTS AND DISCUSSION

Stratigraphy

The stratigraphic sequence is reasonably consistent across the site. However, the thicknesses and location depths of the different layers vary significantly across the site. Figure 2 shows an East-West cross section in the DNAPL area ( see Fig. 1) based on the interpreted cone data.

Generally the stratigraphy can be described as a thin layer of sand and gravel fill (0.3 to 1.5m thick) overlying a soft clayey silt. This compressible silt is underlain by a variable density sand (loose to medium dense) which is sometimes clean but often interbedded with thin layers of sandy silt. With depth, the interbedded layers of sandy silt tend to become less frequent but thicker and more distinct. The sand sequence extends to a depth of 30 to 35m, and is underlain by a lightly over consolidated soft clayey silt. At this interface, there often exists a zone of transition whereby the clayey silt is interbedded with sandy silt.

The ground water table at the site is variable and depends on the tide in the Fraser River. In general the water table is very close to the surface and within the upper few metres.

Geotechnical and Hydrogeological Parameters

A preliminary assessment of several geotechnical parameters of interest (relative density, internal friction angle and SPT-N values) was carried out using CPTINT. CPTINT is a UBC developed software package (CPTINT 5.0, 1993) used to estimate geotechnical parameters based on cone data and well established empirical correlations (Robertson and Campanella 1986). Relative density was found to be extremely variable both across the site and within each hole. It was found to vary from 30% to 100%. The internal friction angle appears to be reasonably consistent in the sands across the site, varying from 39° to 41° . SPT-N values normalized to 1 tsf of overburden, called SPT-N1, tend to vary from 10 to 20 in the sands, 2 to 5 in the clayey silts and 5 to 10 in the silty sands.

The main hydrogeological parameters of interest include hydraulic head, hydraulic conductivity and hydraulic gradient. During pauses in penetration, any generated excess pore pressure will dissipate and its measurement allows the calculation of hydraulic conductivity. If the generated pore pressures are allowed to reach equilibrium the piezometric head can be calculated.

Estimated values of hydraulic conductivity fell in the range of 5E-05 to 8E-06 cm/s for the silty sand, 8E-03 to 6E-02 cm/s for the clean sands and 3E-07 to 5E-07 cm/s for the clayey silt. As these estimates are very approximate in value, they should be used only as indicator values in a qualitative sense. For more accurate values, in-situ measurements of hydraulic conductivity by pump and/or slug testing should be carried out to develop site specific correlations with piezocone estimates.

Estimates of horizontal gradients can be obtained based on location of the water table and piezometric level measurements from adjacent piezocone tests. However, the tides in the Fraser river make the estimate very approximate, at best. By attempting to account for these fluctuations, it was determined that ground water movement occurs in a South to South-West direction (i.e., towards the Fraser River).

An analysis of equilibrium pore pressures from full dissipation records of all the piezocone tests carried out at the site did not detect any upward or downward gradients within the main sand aquifer. However, groundwater tends to flow horizontally in a south westerly direction toward the Fraser River at the site and there is likely a very small downward gradient.

Contaminant Distribution in the Sub-surface

The main zone of DNAPL contamination, as shown in Fig. 1, was identified by the RCPTU soundings and verified by the analysis of discrete depth BAT water samples as well as those obtained from nearby monitoring wells.

Figure 3 shows the CONEPLOT profile for CPT-6. The cone bearing shows the variability of the soils encountered and the correspondence of the penetration pore pressures with hydrostatic conditions indicates a free draining soil. The fine silt layer at 11m is clearly indicated by all parameters.

To interpret the bulk resistivity measurements for an indication of NAPLs, a clear contrast must exist with the natural background resistivity levels (without NAPL). However, that contrast was not as strong as expected at this site and it was not possible to quantitatively correlate bulk resistivity with pore fluid analyses at the current state of tool development.

In examining the bulk resistivity, ($\rho_b$), profiles (see Figs. 2 and 3), some key points to notice are:

1. the sharp drop in $\rho_b$ near the surface infers water level. Since electrical current flows mainly through the pore fluids (i.e. air and the soil skeleton are insulators in comparison to pore fluid), the drop indicates the presence of increased saturation or water table.
2. distinct decreases and increases in $\rho_b$ may correspond to distinct changes in pore fluid constituents, changes in porosity and/or changes in soil grains (if surface conductance becomes significant as in some clays and minerals). The sharp drop in $\rho_b$ at 11m in Fig. 3 indicates a silty or fines layer (and not necessarily a change in pore fluid chemistry) as suggested by the corresponding increase in friction ratio which correlates to a finer soil type.
3. consistency in $\rho_b$ within a given stratigraphic unit suggests essentially no change in pore water chemistry even though stratigraphic variability exists.
4. the spikiness in $\rho_b$ in the sand units in Figs. 2 and 3 suggest high levels of NAPL in thin layers of interbedded sands. At 5 to 11m and 15 to 19m in Fig. 3, where distinct changes in friction ratio are absent, the spikes in $\rho_b$ suggest high levels of NAPL. This information targets depth intervals for pore water sampling.

## COMPARISON TO CONVENTIONAL TECHNIQUES

Figure 4 shows the comparison of stratigraphic logs of two adjacent RCPTU soundings, a conventional drill hole and a continuous vibro-core soil sample. The agreement of the RCPTU profile with the visually obtained vibro-core profile validated the interpretation by the CPTINT software. However, the vibro-core causes soil compaction (which must be estimated) and may lead to mislocations of strata details as for the sandy silt layer at approximately 11m.

## CONCLUSIONS

RCPTU and discrete depth water sampling provided a rapid, cost effective, repeatable and accurate representation of subsurface lithology and requisite geotechnical and hydrogeological parameters. Potential hydrocarbon contaminated zones were identified and likely contaminant transport paths were delineated. Hydrogeologic and analytical data from previous investigations agreed well with the data obtained from this screening study.

While at this site bulk resistivity profiles did not offer a clear quantitative assessment of contaminant concentration because of lack of contrast or resolution, they were used effectively to identify potential problem zones. This was accomplished in two distinct ways:

1. identification of anomalous bulk resistivity zones across the site, as depicted in Figs 2 and 3.
2. identification of discrete stratigraphic layering (i.e. coarse sands overlying finer sediment lenses) that would provide preferential flow paths and 'resting places'for the DNAPLs (e.g. creosote)

Specifically on the test site, the information gained from the in-situ testing demonstration provided a more detailed representation of site stratigraphy than that obtained from the conventional investigation. This helped with the design of the remedial system.

Based on the results of the in-situ testing program and good correlations to data obtained from the conventional investigations, it was shown that resistivity piezocone penetration (RCPTU) testing in conjunction with discrete depth ground water sampling can be used effectively for geo environmental site characterizations.

Screening methods, such as RCPTU, are particularly useful to identify locations for more rigorous testing and permanent installations (e.g. monitoring wells) can be optimized.

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TABLE 1. Resistivity & conductivity measurements of bulk soil mixtures and pore fluid

| Material type | Bulk Resis-tivity $\rho_b$, Ω-m | Fluid Resis-tivity $\rho_f$, Ω-m | Bulk Conduc-tivity μS/cm | Fluid Conduc-tivity μS/cm |
|---|---|---|---|---|
| Sea water | — | 0.2 | — | 50k |
| Drinking water | — | >15 | — | <665 |
| Typical landfill leachate | 1-30 | .5-10 | 10k-330 | 20k-1k |
| Mine tailings site sand with acid drainage | 1-40 | 2-27 | 10k-250 | 5k-370 |
| Mine tailings site sand without acid drainage | 70-100 | 15-50 | 145-100 | 665-200 |
| Industry site: APL contaminants in sand | 0.5-1.5 | 0.3-0.5 | 20k-6k | 33k-20k |
| Industry site: NAPL contaminants in sand | 125 | 48 | 80 | 210 |
| 100% ethylene dichloride (ED) | — | 20k | — | 0.5 |
| 50% ED/50% water in sand | 700 | — | 14 | — |
| 17% ED/83% water in sand | 275 | — | 36 | — |
| BC Place Parcel 2, PAHs (coal gas plant) | 200-300 | — | 50-33 | — |
| BC Place Parcel 2 (wood waste) | 300-600 | — | 33-66 | — |

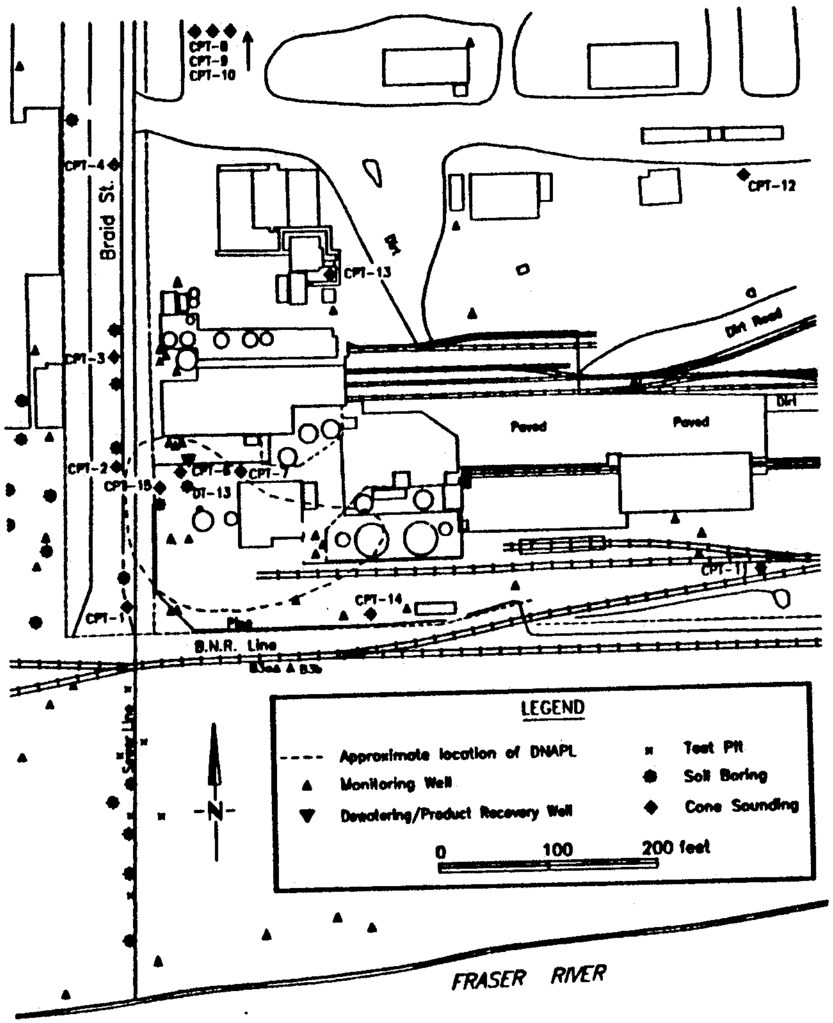


**FIGURE 1. General Site Layout**

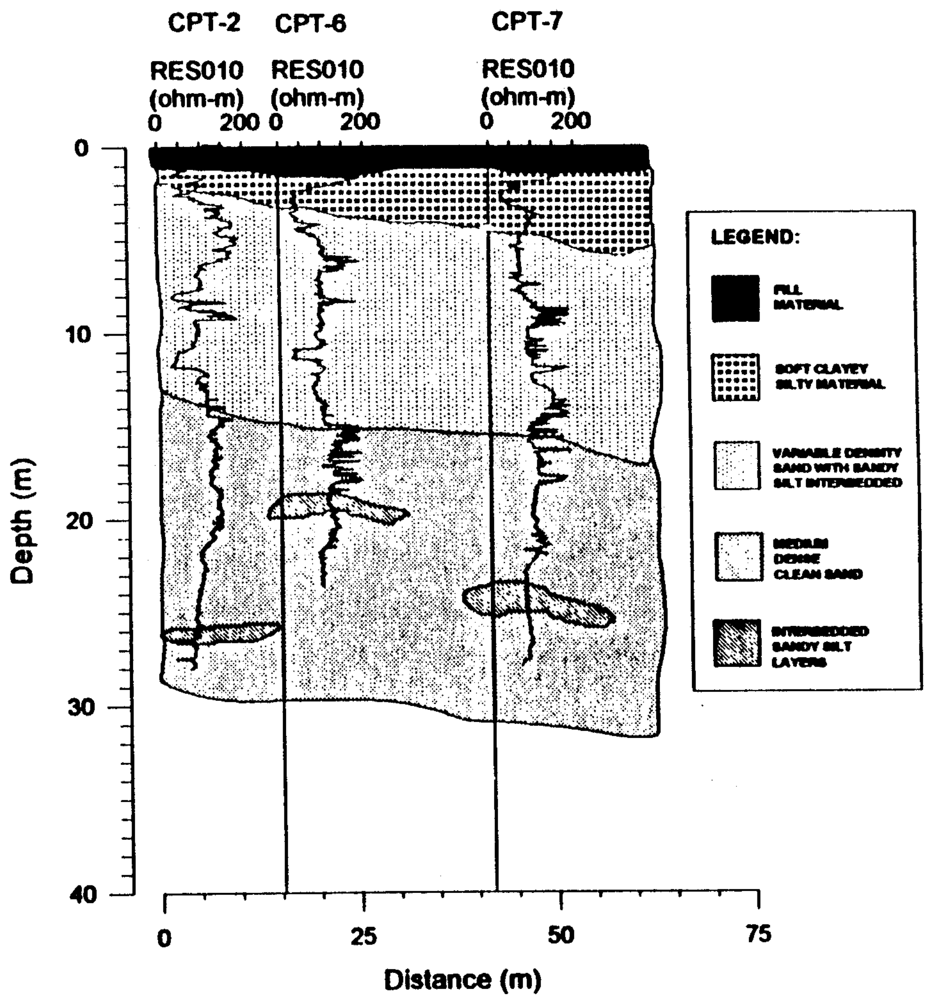


**FIGURE 2. East-West Cross Section - Bulk Resistivity Profiles**

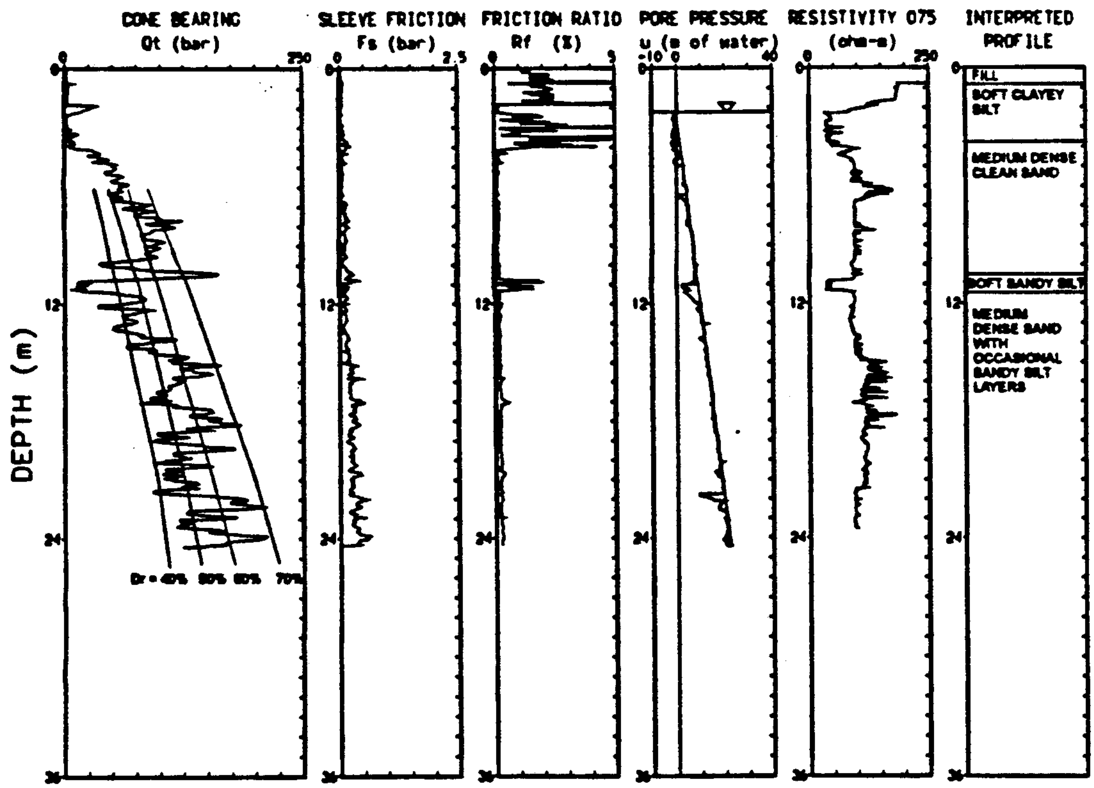


**FIGURE 3. CONEPLOT Profile for CPT-6**

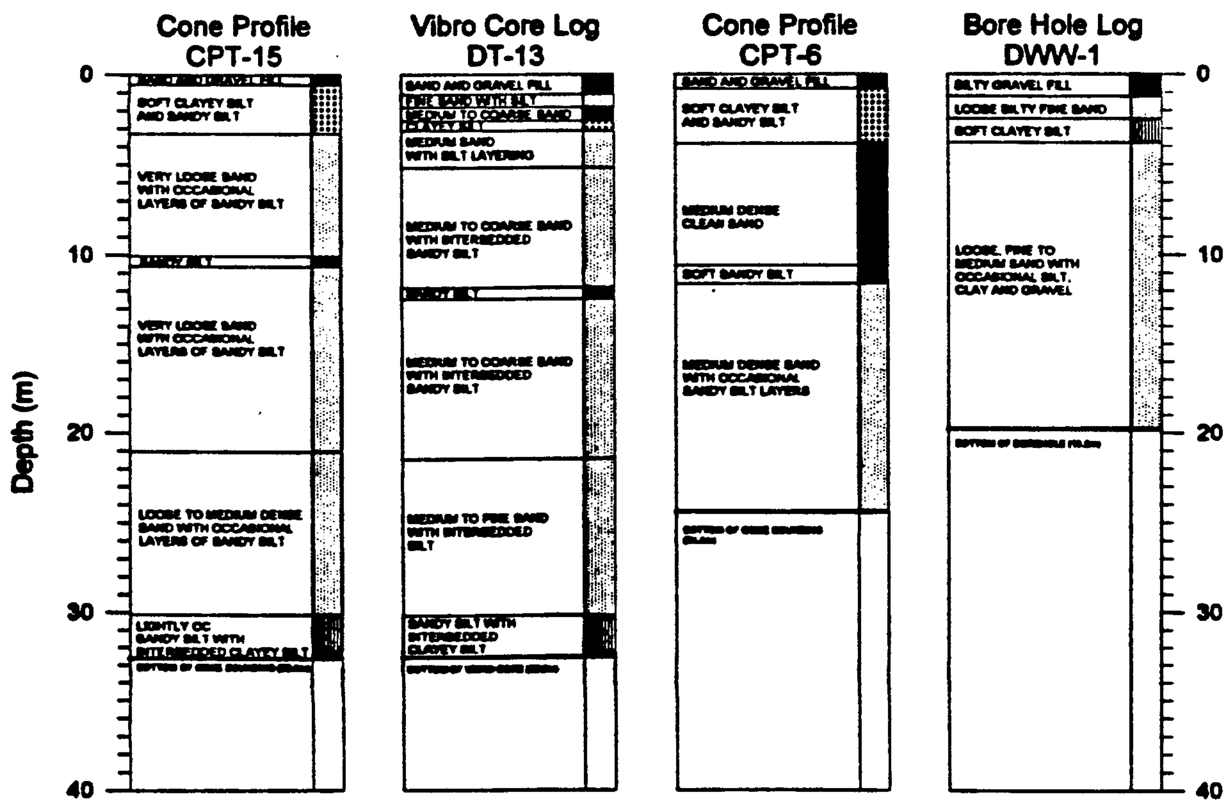


**FIGURE 4. Stratigraphic Comparison**