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Composite geotechnical logs for two deep boreholes in the Fraser River delta, British Columbia

S.R. Dallimore, K.A. Edwardson, J.A. Hunter, J.J. Clague and J.L. Luternauer

With contributions from:

R.A. Burns, M.E. Evans, J. Harris, L.E. Jackson, M. Johns, T. Lewis, M. Leyborne, R. MacDonald, L. Maurice, J. Meldrum, P. Monahan, P.S. Mustard, J. Mwenifumbo, S. Phillips, N. Singh, L. Wang, and Y. Wang

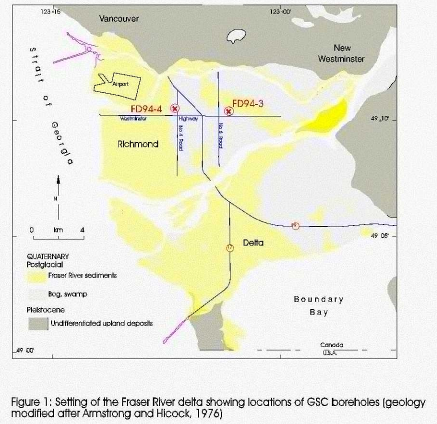

Figure 1: Setting of the Fraser River delta showing locations of GSC boreholes (geology modified after Armstrong and Hicock, 1976)

INTRODUCTION

The Vancouver area, including the Fraser River delta, is situated in one of the most seismically active zones in Canada. Historical earthquake data indicate that the area can experience local earthquakes as large as Richter magnitude 7-7.5. Several studies have suggested that even larger (M8-9) subduction earthquakes are possible along the Cascadia subduction zone off the coast of British Columbia, Washington, and Oregon (Heaton and Hartzell, 1987; Rogers, 1988; Atwater et al., 1995). Because much of the Fraser delta is highly urbanized and is underlain by thick postglacial sediments, a priority of the geotechnical community is to evaluate hazards posed by seismic ground motions. Of particular concern is the possibility of structural damage due to liquefaction of near-surface, water-saturated sediments (Luternauer et al., 1994).

Geotechnical engineers who design new structures or evaluate the need for retrofitting existing structures require knowledge of the susceptibility of shallow sediments to liquefaction, as well as the range of ground motions (e.g., ground velocity and acceleration) that are likely to accompany the largest earthquake that may occur in an area. Preliminary liquefaction susceptibility mapping (Watts et al., 1992) has demonstrated that nearly the entire Fraser delta plain (Fig. 1) is underlain by sediments that, because of grain size, density, and ground water conditions, are particularly prone to liquefaction. To date, seismic ground motion modelling in the delta has focused primarily on the effects of seismic amplification (Byrne and Anderson, 1987; Finn and Nichols, 1988; Lo et al., 1991; Sy et al., 1991). This work has shown that for some geological and seismic conditions, ground motion amplification at the surface may be considerable, increasing the potential for liquefaction during an earthquake. A full evaluation of these effects requires comprehensive characterization of the sequence of unconsolidated sediments overlying bedrock and knowledge of the geometry of the sediment/bedrock interface.

In the spring of 1994, the Geological Survey of Canada addressed the need for deep geotechnical and geological data for the Fraser delta by drilling boreholes to a depth of 300 m at two sites (fig. 1) with contrasting geology. This report presents preliminary logs for the two boreholes displaying geological, geotechnical and geophysical data collected during drilling and later. Research to further characterize the geological framework at these sites, and ground motion modelling are continuing and will be reported in subsequent publications. It should be noted that the main purpose of the project was to collect deep high-quality geotechnical data. Shallow geotechnical and geophysical data at these and many other sites on the Fraser delta have been obtained through vibrasonic drilling, cone penetration testing, and downhole geophysical logging (Monahan et al., 1993; Hunter et al., 1994; Woeller et. al., 1993a, 1993b, 1994).

GSCFD94-3

Latitude 49° 10' 23.5" N
Longitude 123° 03' 21" W

Drilling period: March 15-22, 1994

Borehole GSCFD94-3 is located within the city limits of Richmond just north of Westminster Highway between No. 6 and No. 7 roads (Fig. 1). Previous GSC seismic refraction surveys, shallow vibrasonic drilling, and industry seismic reflection data suggested that Holocene sediments at this site are thin and overlie a thick sequence of Pleistocene sediments. Chronostratigraphic data and biostratigraphic studies on samples of drill core collected as part of this study point to a Holocene/Pleistocene boundary at a depth of about 19 m (see geomagnetic data and radiocarbon ages on borehole logs). Bedrock, which was originally interpreted to rise to within 300 m of the surface based on industry seismic reflection records, was not encountered.

GSCFD94-4

Latitude 49° 10' 32"N
Longitude 123° 06' 48"W

Drilling period: March 24-29, 1994

Borehole GSCFD94-4 is located within the city limits of Richmond on No. 4 Road north of Westminster Highway (Fig. 1). This site was chosen because regional geophysical and geological data indicated that the Holocene deltaic sequence was exceptionally thick there. The Holocene/Pleistocene boundary occurs at a depth of approximately 240 m, based on biostratigraphic and chronostratigraphic data (see radiocarbon ages on composite borehole logs).

DRILLING PROGRAM

Drilling was done by Foundex Explorations Ltd. of Surrey, B.C., with a top-drive Simco 5000 truck-mounted drill rig (Fig. 2), a wireline PQ-3 coring system, and bentonite-based drilling mud. Each borehole was continuously cored, but recovery differed according to ground conditions. Core was retrieved with a 3-m-long spring-loaded core barrel, with a retracting inner tube assembly designed to adjust the position of the core barrel shoe relative to the drill bit as ground conditions changed. Where difficult coring conditions were encountered, a conventional PQ-3 core barrel was substituted for the retractor barrel. Undisturbed Shelby tube samples were taken at strategic horizons with either a hydraulic piston sampler or a fixed piston sampler. A blow-out diverter system was utilized during drilling because of the risk of encountering shallow gas.

Collection of high-quality core samples for detailed characterization of material properties was a major priority of the project. Core logging was carried out in two phases. Geotechnical engineers supervised the drilling and made initial observations on drilling conditions, soil consistency, and gas release from the core. Another group of sedimentologists then split the core lengthwise, photographed the core, described sedimentological features, and took samples for a suite of follow-up laboratory tests. Moisture content, salinity, magnetic susceptibility, and natural remnant magnetization were determined at the core sites in a temporary field laboratory.

Figure 2: Foundex Simco 5000 drill rig used for field program

COMPOSITE BOREHOLE LOGS

Composite borehole logs for GSCFD94-3 and GSCFD94-4 are presented as Sheets 2 and 3, respectively, of this Open File report. The logs were prepared using the graphics program CORELDRAW. The nature of the testing (either in situ downhole measurements or laboratory determinations on core samples) is indicated on each log. Details on borehole parameters are given in the following sections.

Lithologic and geotechnical logs

The lithologic log provides a detailed sedimentological description of each borehole and identifies intervals of no core recovery. The geotechnical log records engineering properties of the sediments, as well as drilling conditions. Because the terminology and classification schemes used by geologists and engineers differ, two separate graphical representations and associated text descriptions of the core are provided. Descriptions in the geotechnical log follow recommendations outlined in the Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 1978), whereas descriptions in the lithologic log follow the nomenclature of Reineck and Singh (1975). Differences between these two schemes stem largely from different descriptions of grain size and sorting. The geotechnical distinction between silt and clay, for example, is made on the basis of grain size and plasticity characteristics (see legend on each log), whereas the geological distinction is based exclusively on grain size (*silt* 2-63 μm; *clay* < 2 μm). A low plasticity clay on the geotechnical log commonly is the same as a sandy silt on the lithologic log. The degree of sorting for the sands presented in the lithologic logs follows a modified version of the sorting scale given by Folk (1966).

Laboratory testing

Physical property testing (grain size, moisture content, salinity and plasticity)

Salinity measurements were made in a field laboratory with an optical salinometer on pore water pressed mechanically from the sediments. In some instances, where the water content was low, samples were shipped to the GSC in Ottawa where a high-velocity centrifuge was used to collect the pore water for salinity measurement. Plasticity testing was performed at the GSC Sedimentology Laboratory in Ottawa according to the procedures recommended in the Canadian Foundation Engineering Manual (National Research Council, 1978). Grain size was determined using sieves and a Brinkman Particle Size Analyzer.

Stable isotopes

Oxygen and hydrogen isotopic compositions of pore water samples were determined at the Ottawa-Carleton Geoscience Centre Stable Isotope Facility. Samples of 1-5 ml of pore water were extracted either by mechanically pressing the sediment or by centrifuging. Isotopic compositions are expressed as per mil differences relative to SMOW (Standard Mean Ocean Water). Positive values of ^{18}O and D indicate enrichment in ^{18}O and D relative to SMOW, while negative values indicate depletion of ^{18}O and D relative to SMOW. Repeat analyses indicate precision of better than ±0.2 per mil for oxygen and ±2 per mil for hydrogen.

Geomagnetic inclination

Measurements of natural remnant magnetization were made on oriented cubes of sediment extracted from the cores. Initial measurements were made in the field utilizing a Molspin Spinner Magnetometer. Later, several stages of partial demagnetization were carried out at the Institute of Earth and Planetary Physics at the University of Alberta. Since the cores were not oriented, data presented on the logs are given as deviations from the horizontal plane (inclination). For each sample, the range in magnetic inclination accompanying partial demagnetization is given by a horizontal error bar. Only data from FD94-3 are displayed in this Open File report because all samples from FD94-4 were normally polarized.

In situ testing

Natural gamma

The down-hole, natural gamma logs were obtained with a GEONICS EM-39 logging system. The system uses a sodium iodide crystal to detect natural gamma radiation from in situ sediments. Measurements were made at 2.5 cm vertical intervals at a relatively low logging speed (0.025 m/sec), allowing the use of a high integration rate (time constant of 5 sec) and high precision counting statistics.

The log can be interpreted only in a qualitative sense. Most of the recorded gamma radiation comes from within 30 cm of the detector, thus the diameter of the hole and the type of casing strongly influence the count rate. In general, high count rates are associated with clay and low count rates with sand and gravel. For the Fraser delta boreholes, the statistical counting error is of the order of ± 5 cps. Down-hole variations in excess of this value probably reflect changes in lithology.

Electrical conductivity

The electrical conductivity logs were obtained with a GEONICS EM-39 inductive electromagnetic sonde. This instrument contains transmitter and receiver coils separated vertically by 60 cm. A continuous electromagnetic wave was transmitted at a frequency of about 39 kHz. Both in-phase and quadrature components of the electromagnetic field were recorded, providing a measure of the electrical conductivity of the surrounding formation. The sonde is designed to compensate for near-hole effects such as differences in hole diameter and conductivity of the borehole fluid. However, the thickness of the formation contributing to the measured electrical field can exceed the intercoil spacing, resulting in a strong integration or smoothing effect (i.e., a sharp electrical contact will appear as a gradational change over a vertical distance of 60 cm or more).

Measurements were made at 2.5 cm vertical intervals in the Fraser delta boreholes. Measured conductivity values were corrected for non-linear response of the tool (such non-linearity is only significant at the high range of values). The tool was calibrated in air prior to each run.

Electrical conductivity of porous sediments is extremely sensitive to pore-water chemistry. Variations of conductivity in the range 200-800 mS/m primarily reflect changes in pore-water salinity. In contrast, variations in the range 0-200 mS/m may result from lithological changes in a fresh pore-water environment.

P-wave velocities

Down-hole compressional wave surveys were performed using a GSC 12-channel hydrophone array (Hunter and Burns, 1991). The array consists of 12 Benthos AQ-16 hydrophones and Benthos AQ-300 preamplifiers with 0.5 m spacings. The array was moved up each hole in 2 m intervals. The energy source was a "Buffalo Gun" (Pullan and MacAulay, 1987) which uses 8-gauge blank shotgun shells. The source was positioned 10 m to one side of the borehole at a depth of 2 m.

Twelve-channel seismic records from each of the shots were recorded with a GEOMETRICS R-24 stacking seismograph. First-arrival P wave events were picked for each of the 12-channel records, and velocities were derived from each record set (11.5 m interval); hence zero-time picking errors were eliminated. A Fejer-weighted (triangular window) least-squares fit was applied to each velocity determination. Additionally, because the source was offset from the borehole for casing-wave coupling considerations, a velocity correction for refractive effects was applied to the data.

Down-hole shear wave surveys were conducted by Frontier Geoscience Inc. of Vancouver with a SENSOR NEDERLAND, SM-4, three-component, well-lock, geophone package. The geophone was moved up each hole in 1 m intervals. Recording was done with a Geometrics ES-1225 stacking seismograph. The energy source was a wooden railway tie which was loaded by the weight of a vehicle and struck horizontally with a large sledge-hammer to produce horizontally polarized shear-wave energy. Two records were made at each depth by reversing polarization. To interpret the arrival of shear energy at the geophone package, the two records were superimposed on playback to obtain a "cross-over" arrival time on the seismic record. Record quality throughout the surveys was good and travel-time picking errors were minimal.
To obtain velocities, a running, Fejer-weighted, least-squares fit was made using 11 travel-time data points (10 m interval). No refraction corrections were necessary because the source-to-hole distance was small.

Poisson's ratio

Dynamic Poisson's ratio is an engineering elastic constant that can be derived solely from P and Shear wave velocities. It is often used as a measure of competence of sediment and rock. The relationship is as follows:

$$\text{Poisson's ratio} = (0.5-R^2)/(1-R^2)$$

where R = (P wave velocity)/(Shear wave velocity)

Most unconsolidated sediments have a Poisson's ratio of 0.40-0.5, whereas competent rock has values of 0.2-0.3. The Poisson's ratio logs included in this report were obtained by computing values from the closest depth match between individual P and shear wave velocity measurements.

Relative density

Relative density logs were obtained with a GSC/IFG Corporation prototype spectral gamma-gamma tool using a cobalt-60 source and a 22.5 cm source-detector spacing. This tool measures gamma radiation using a 512 channel spectrometer. The count rate is summed over all channels to obtain relative density measurements. The logs show density variations in the holes assuming constant hole conditions (i.e., no changes in hole diameter or grouting). The tool was not calibrated for the hole conditions encountered in this drilling program, nor for densities less than 1.9 g/cm3. Hence, the scale values are not absolute and the logs can only be interpreted in a qualitative sense.

Spectral gamma-gamma (SGG) ratio

The SGG ratio is derived from the gamma spectra obtained with the GSC/IFG spectral gamma-gamma tool. Count rates were summed over two energy bands, 200-500 keV and 50-100 keV. The ratio of the count rate in the high/low energy bands is shown on the logs.

The SGG ratio is related to the average atomic number of the logged material; high values indicate a high atomic number. In mineral exploration, this ratio is used to identify heavy element concentrations. In overburden studies, the ratio may signal changes in porosity (i.e., a decrease in SGG ratio may reflect an increase in porosity). The Fraser delta logs have not been calibrated and may only be used for interpretation in a qualitative manner.

Temperature

Temperature measurements were made in each borehole some months after drilling using a single thermistor probe designed by the Geological Survey of Canada (Pacific Geoscience Centre). Measurement spacing was 5 m, except near the surface where a closer spacing was used. Measurements were repeated using the thermistor sensor of the IFG Corporation BMP-04 multiparameter tool at a spacing of 0.2 m. Although the IFG tool has a temperature sensitivity of 0.001° C, an absolute temperature calibration was not done at the time of the survey. Instead, the IFG tool was calibrated from the measurements obtained with the GSC tool.

Temperature gradient

Temperature gradient measurements were calculated from the calibrated temperature data obtained with the IFG temperature tool. Gradients shown on the logs were derived from a Fejer-weighted window over a distance of 5 m.

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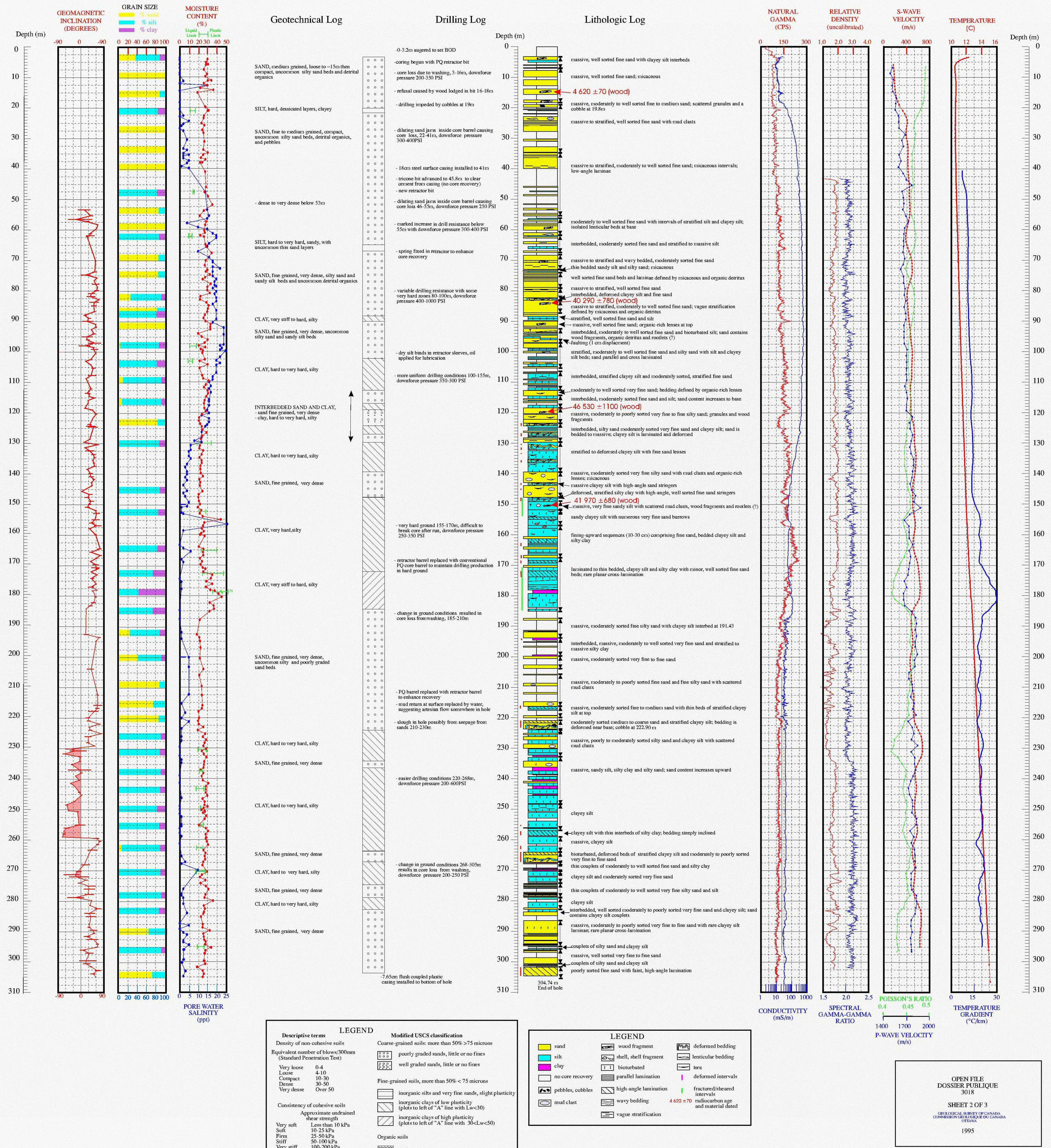
GSC FRASER DELTA 94-3

LABORATORY TESTING — IN SITU TESTING



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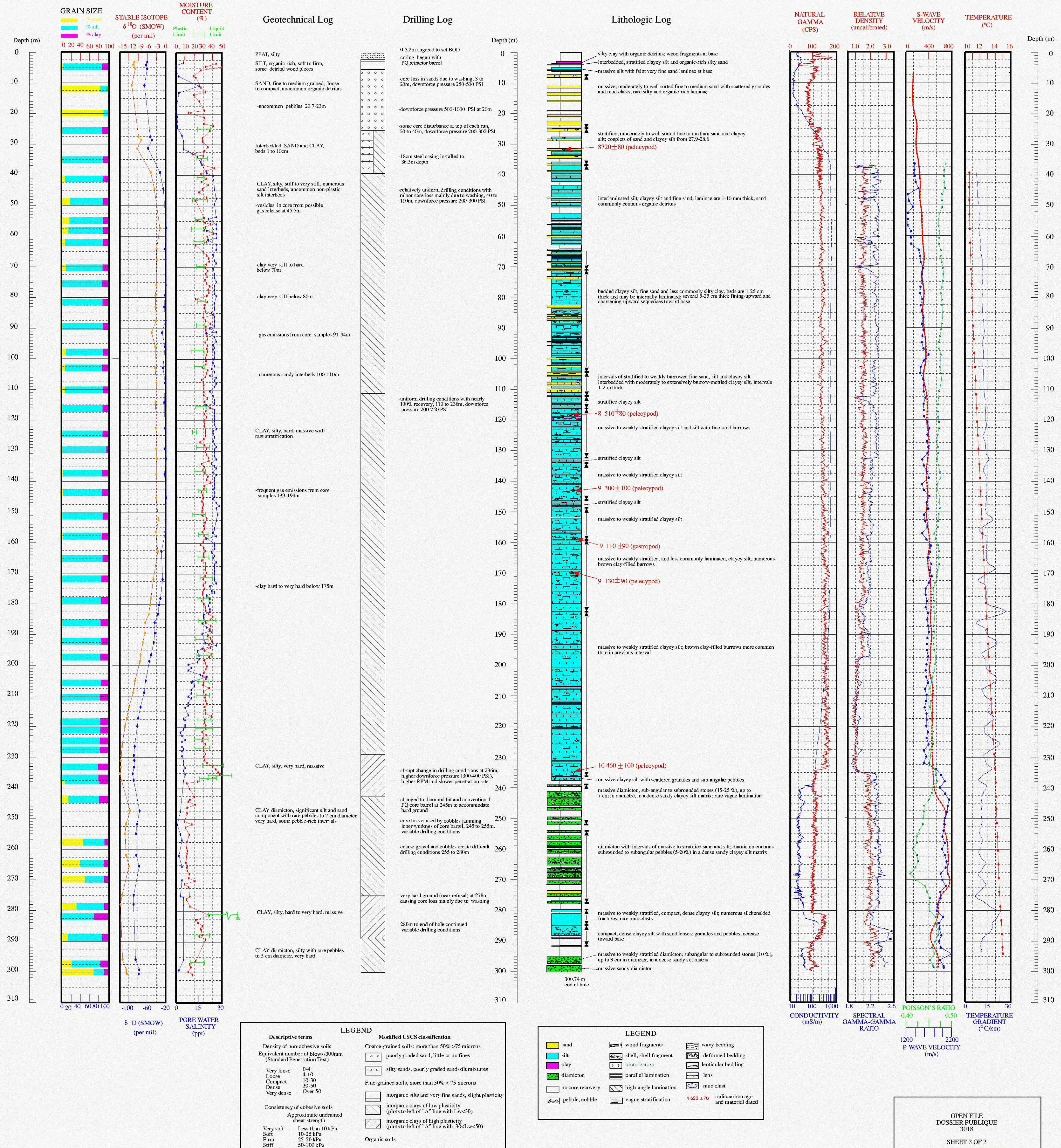
GSC FRASER DELTA 94-4

LABORATORY TESTING — IN SITU TESTING



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