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1.0 Introduction

Water resources on the east coast of Vancouver Island, British-Columbia (BC), are vital to support urban development and agricultural needs, particularly in the Nanaimo Lowlands where population growth has been rapid in the past few decades. Gaining a better understanding of the geology and hydrogeology throughout the region will help protect and sustain the groundwater supply. In collaboration with the BC Ministry of Environment (MoE), Ministry of Forests, Lands, and Natural Resource Operations (MFLNRO), and the Regional District of Nanaimo (RDN) in the characterization of this groundwater resource, the Geological Survey of Canada (GSC) has conducted surface seismic surveys, borehole drilling, core analyses, and borehole geophysical logging to study the geological and hydrogeological properties of the surficial deposits and local bedrock.

The study area extends 30 km south-east from Bowser to Parksville, BC, on the eastern coast of Vancouver Island. This Open File contains the results of the downhole geophysical logging conducted by the GSC in one bedrock and four unconsolidated sediment boreholes within the study area. The objective of this study was to measure a range of in situ chemical and physical properties of the subsurface materials, ultimately contributing towards the GSC's development of a 3D groundwater model of the study area in the Nanaimo Lowlands. The processed logs are presented in Appendix A and digital log data are provided in Appendix C. A detailed description of the geophysical tools is provided in Appendix B.

1.1 Previous GSC Geophysical Surveys in the Nanaimo Lowlands

As part of the current Groundwater Geoscience Program (2009-2014), the GSC is assessing seven priority aquifers across Canada in various geological settings. Over the past five years, the GSC has acquired hundreds of kilometers of high-resolution seismic profiles across Canada for hydrogeological studies using an IVI Minivib source and a 48-sled (144 channel) landstreamer array (Pugin et al., 2009; Pugin et al., 2009b; Pugin et al., 2013). In 2011, the GSC began their investigation in the Nanaimo Lowlands with a high-resolution seismic survey, collecting 17 seismic profiles totaling approximately 40 line kilometers. From these data, three drill targets were chosen; key seismic sections are presented in Knight et al. (2014a).

1.2 Boreholes Logged as Part of This Study

Four Boreholes in Unconsolidated Sediments

Three targets (GSC-BH-HIL, GSC-BH-SPI, GSC-BH-CHR) were drilled in unconsolidated sediment with oversight by GSC staff during the winter of 2012-2013 (see Figure 1, Table 1). Drilling was completed by Mud Bay drilling of Surrey, British Columbia using a rotosonic drill rig to advance the GSC's three boreholes with telescoped casing diameters of 202 to 152 mm (8" to 6") , and continuous core was collected in 10 ft (3.05 m) runs. Drilling fluids were restricted to water and a biodegradable viscosity agent, Extreme Super G gold, to ensure no contamination of the formation waters. Extruded cores were placed in clear plastic bags and packed into wooden boxes. After a preliminary geological assessment on site, the boxes were shipped back to the GSC's core storage facility in Ottawa for detailed geological logging and geochemistry (Medioli et al., 2014; Knight et al, 2014). A fourth

target (BC-BH-QUA) was drilled using an air rotary drill for the MoE, MFLNRO, and RDN near Qualicum Beach in March 2013, and was overseen by SLR Consultants.

Screened PVC piezometers were placed in the four unconsolidated sediment boreholes as either nested (2.5" and 1'' or 1.5") or single (2.5") installations. Screened piezometers were packed in sand and sealed with bentonite above and below the sand pack and back filled to surface with grout or to the upper piezometer where the sequence was repeated. Geophysical logging was conducted inside the 2.5" piezometers which extended to the bottom of the boreholes. A graphical representation displaying the completion details of the wells are shown alongside the geophysical logs in Appendix A.

One Bedrock Borehole

As part of the MoE's observation well network, a 303 ft (92.3 m) borehole was drilled in March 1984 using air rotary methods. The borehole is located on Burgoyne Rd near the town of Coombs, BC, and is listed as OW 287. The borehole diameter is 152 mm (6'') and the drill log records the bedrock as black shale (MoE, 2013).

The borehole has been undisturbed for many years, which is ideal for fluid (temperature and conductivity) logging. In order to conduct downhole geophysical logging, the protective housing containing telemetry antennae and a solar panel was removed, and a new cover was reinstalled after the logging was complete. Water level loggers were removed from the well prior to logging.

Table 1. Summary of borehole geophysical logs collected during the 2013 GSC field work campaign. UTM coordinates are in zone 10 (NAD 83). Unc.Sed.=Unconsolidated sediment, Gam=Natural gamma, Den=Gamma-gamma bulk density, Cond=Apparent conductivity, MagSusc=Magnetic susceptibility, Fl.Temp=Fluid temperature, Fl.Cond=Fluid conductivity, Vp=Compressional wave velocity, Vs=Shear wave velocity.

Borehole	Mat.	Date Logged	Easting (m)	Northing (m)	Maximum Depth Logged (m)	Geophysical Log Suite	Figure
GSC-BH-HIL	Unc. Sed.	Mar 19-20, 25, 2013	397 629	5 463 318	43.8	Gam, Den, Cond, MagSusc, Fl.Temp.	A-1
GSC-BH-SPI		Mar 21-22, 24-25, 2013	382 789	5 469 236	117.0	Gam, Den, Cond, MagSusc, Fl.Temp, Vp, Vs	A-2
GSC-BH-CHR		Mar 22-24, Apr 1, 2013	379 107	5 472 671	127.9	Gam, Den, Cond, MagSusc, Fl.Temp	A-3
BC-BH-QUA		Mar 30-31, 2013	397 787	5 466 463	88.6	Gam, Den, Cond, MagSusc, Fl.Temp, Vp, Vs	A-4
OW287	Rock	Mar 26-29, 2013	441 238	5 480 502	90.8	Gam, Cond, MagSusc, Fl.Temp/Fl.Cond., Optical and acoustic televiewers, heat pulse flow meter	A-5, A-6

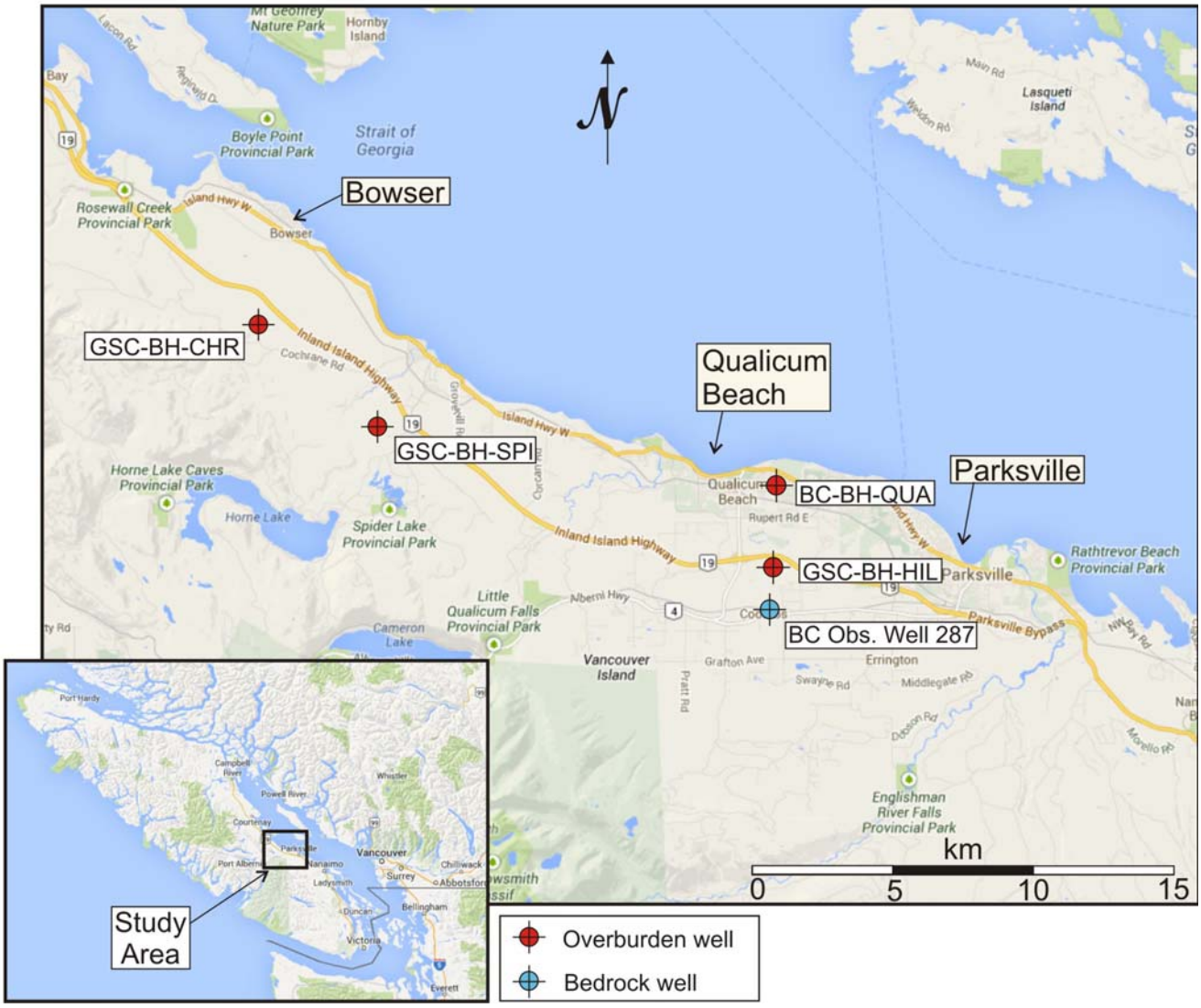

Figure 1. Location map of the boreholes logged by the GSC on Vancouver Island, BC, during downhole logging surveys in 2013 (map image from © 2013 Google).

2.0 Geological Setting

The Nanaimo Lowland coastal zone is a <8 km wide region extending along the eastern side of Vancouver Island. It is dominated by low relief bedrock ridges separated by areas of Quaternary sediment, locally in excess of 100 m, infilling bedrock lows and buried bedrock valleys. Ridges are commonly underlain by Nanaimo Group sandstone and conglomerate beds, and the bedrock lows and valleys are eroded into softer Nanaimo Group shale and along fault zones. The Nanaimo group consists of an upward fining succession of conglomerate, sandstone, shale and coal overlain by shale and thin-bedded shale-siltstone sequences It is attributed to a fluvial deltaic environment that was transgressed by marine waters (Hamblin, 2012 and references therein).

2.1 Surficial Geology

The primary source of information on the surficial geology of the area is by Fyles (1963). A number of authors have reviewed the glacial history of the area, (e.g. Fyles,1963; Clague 2005) and others have worked on aspects of the stratigraphy, chronostratigraphy, sedimentary facies, and process interpretations (Trettin, 2004; Clague 2005 and references there in). Seven regional stratigraphic units are summarized here.

2.1.1 Mapleguard Sediment

The Mapleguard forms oldest Quaternary deposits in the study area and is exposed at the base of a few sea cliff sections where the base of the unit is not observed, notably at Qualicum Beach. It is in excess of 30 m thick and may be spatially extensive in the subsurface (Fyles, 1963; Trettin, 2004). It consists of unfossiliferous interbedded clay, silt, sand, and minor gravel. Trettin (2004) identifies a number of facies changes regionally from previous work and highlights a lower and upper member of predominantly sand and diamicton, respectively. Fyles (1963) suggested a variety of depositional setting including, fine-grained river flood-plain deposits, lake sediment and glacaifluvial deposits. Trettin (2004) infers a more ice proximal depositional relationship with the lower member being glacimarine and the upper member interpreted as a subglacial till.

2.1.2 Dashwood Drift

Dashwood Drift conformably overlies Mapleguard and is < 10 m thick (Armstrong and Clague, 1977). The type section is located at Qualicum (Fyles, 1963; Armstrong and Clague, 1977; Hicock and Armstrong, 1983). It consists of diamicton overlain by mud and gravel. The gravel is a mixture of plutonic rocks derived from the Coast Mountains and volcanic and sedimentary rocks from the east coast of Vancouver Island. Depositional environments include a complex of glacial, glaciofluvial, ice-contact and glaciomarine to marine sediments (Hicock and Armstrong, 1983).

2.1.3 Cowichan Head Formation

Cowichan Head Fm is up to 21 m thick and unconformably overlies the Dashwood Drift (Hicock and Armstrong, 1983). The formation has been divided into a lower member of clayey silt and sand with marine shells, and an upper member of sandy silt and gravel, commonly with reddish oxidized hues rich in fossil plant remains (Armstrong and Clague, 1977). Gravel provenance is from volcanic and sedimentary rocks (Armstrong and Clague, 1977; Clague, 1976). The lower member is interpreted as glaciomarine whereas the upper member is attributed to estuarine and fluvial environments (Armstrong and Clague, 1977).

2.1.4 Quadra Sand

The Quadra Sand may either sharply (erosionally - unconformably) or conformably overlie Cowichan Head Formation and occurs over a broad area in the Georgia Depression, British Columbia and Puget Lowland, Washington (Clague 1976; Armstrong and Clague,1977). It is up to 75 m thick and consists of horizontally and cross-stratified sand of quartz, feldspar, and lithic fragments of granitic provenance (Clague, 1976, 1977). The granitic provenance and well sorted character imparts a white colour to the unit. The sand is diachronous, becoming younger to the south away from its source in the Coast Mountains (Clague 2005). The Quadra sands are interpreted to be proglacial outwash deposited subaerially on floodplains and locally deltaic (Clague et al., 2005). This unit is a significant aquifer unit.

2.1.5 Vashon Drift

Vashon Drift deposits are up to 60 m thick and unconformably overlie either Quadra sand or older units. It consists of sandy diamicton, with local mud rich, and sand and gravel facies (Fyles, 1963). Vashon Drift is interpreted as glacial till and a variety of ice-contact depositional (landform) settings including esker, deltas, and fans (Hicock and Armstrong, 1984).

2.1.6 Capilano Sediment

Capilano Sediment unconformably overlie Vashon Drift and locally, Quadra Sand. The sediment is up to 25 m thick and consists of sand and gravel with minor diamicton. The sediment commonly fine upward (Bednarski, unpublished). It is interpreted as a deglacial succession of coarse glaciofluvial outwash that upwards become more distal.

2.1.7 Salish Sediments (Postglacial – Modern)

Salish sediment are the youngest unit in the area, are generally < 5 m thick (commonly < 2 m) and consist of gravel, sand and mud (Fyles, 1963). Depositional processes are predominantly channel and floodplains along river valleys, deltas related to the modern sea, river and lake levels, and recent mass wasting (e.g. alluvial fans).

3.0 Field Work

3.1 Geophysical Logging

Downhole geophysical logs provide a means of identifying and characterizing lithological units based on variations in their chemical and physical properties. Geophysical logs also augment geological logging by providing information on changes in sedimentary properties that may not be visible in the core, across intervals of missing core, and where boundaries are uncertain due to the logging of cuttings.

In the cased sediment wells, downhole techniques included gamma methods (natural gamma and gamma-gamma density), induction methods (apparent conductivity and magnetic susceptibility), downhole seismic methods (compression (P) and shear (S) wave traveltimes), and fluid temperature logging. In the bedrock borehole, the natural gamma probe, induction tools, fluid tools (temperature and conductivity), heat pulse flow meter, and optical and acoustic televiewers were used. A brief description of the quantities measured in each of these logs, the data resolution, log collection parameters, and the practical interpretation of each log are presented in Table 2.

At each borehole the following sequence of data collection was followed. Water level was measured in each borehole upon arrival at the well site. The fluid temperature tool (and fluid conductivity tool in the bedrock hole) was first lowered into the borehole to collect data on a down run in the undisturbed fluid. A period of 10-20 minutes was allowed for the tools to thermally equilibrate in the top of the water column before the fluid logging began. Following fluid logging, the remaining geophysical tools were run in a random order in the cased boreholes. For the bedrock well, the optical televiewer was run after the fluid tools to avoid clouding the fluid. Subsequent geophysical tools were run in random order. The flow meter was run on a separate day to allow the fluid to stabilize in the well overnight.

Data were acquired using a Mount Sopris logging system with a Matrix console and interchangeable downhole probes (with the exception of the fluid temperature/conductivity and seismic logs). A laptop computer recorded the data using the Matrix Logger Software. The fluid logs (temperature and conductivity) were collected using tools developed at the GSC for high sensitivity gradient measurements, and recorded using in-house software.

Prior to departure for the field, laboratory calibrations were performed with the fluid tools using temperature-monitored baths (0°C and 25°C) and four conductivity calibration solutions ranging between 0 and 12,880 μS. The gamma-gamma density tool was calibrated using specially designed blocks of 1.28 and 2.60 g/cm^3 to provide low and high calibration points for the density measurements. On-site calibrations were carried out with the conductivity and magnetic susceptibility tools prior to each run using known calibration points (low point: 0, and a user selected high point using calibration coils of 95, 460, or 1690 mS/m depending on the conductivity ranges encountered downhole). All logs were corrected for sensor offsets and casing stick ups, and recorded relative to the ground surface.

The seismic surveys were carried out in the cased boreholes using a downhole receiver array and an energy source on the surface, 3 m or 4 m from the borehole collar, depending on borehole depth. The cables supporting the receiver were lowered by hand to the bottom of the hole, and pulled uphole at one metre spacings where measurements were made. Data were obtained for the P-wave surveys using a multi-channel hydrophone array (12 hydrophones at 1 m spacing) in the water-filled portion of the borehole. Shear (S) wave logs were obtained using a clamped, 3-component downhole receiver with 15 Hz geophones. In both cases, the source was a small metal hammer striking a metal plate vertically (P-wave) or at a 45° angle (S-wave). The plate was coupled with the ground by removing the top few centimetres of soil, leveling the plate, and then driving the vehicle onto it. A Geometrics 24-channel Geode seismograph was used and data were recorded on a laptop computer after reviewing each record on screen. The systems and field procedures developed for downhole P- and S-wave logging are described in detail in Hunter et al. (1998).

In the bedrock borehole, the acoustic (ATV) and optical (OTV) televiewers were centralized using a pair of aluminum, four-arm, bowspring centralizers. The maximum horizontal resolution was used for ATV logging (288 pts per revolution, or 1.25 pixels/deg), and OTV logging (720 pts per revolution, or 2 pixels/deg). The logs were collected from the bottom of the borehole upwards to keep constant tension on the wireline at low logging speeds.

For ambient heat pulse flow meter (HPFM) testing, seven target depths were chosen above and below borehole wall enlargements observed in the televiewer images and caliper log, and/or abrupt changes in the fluid logs. To avoid diversion of fluid around the flow meter, the tool was outfitted with rubber diverters which forced all fluid flow through the thermistor column in the tool. The test began with the tool positioned at the deepest target. Once three heat pulse triggers yielded the same value, the test continued, moving the tool to the next target depth. Five-to-ten minutes were required for the fluid to stabilize after the tool was moved to a new location in the borehole.

Flow was not detected under ambient conditions; therefore an active HPFM test was performed using a pump at three depths (10 m, 20 m, and 45 m). Induced upward flow in the borehole can help identify fractures which are capable of transmitting fluid. With the flow meter downhole, a Redi-Flo 2 Grundfos pump was lowered to 10 m depth to investigate borehole wall enlargements observed in the televiewer images between 9.0 and 18.5 m. Before flow meter measurements were started, the pumping rate was adjusted to avoid exceeding the flow meter's upper limit of 4 L/min, while

attempting to obtain steady-state pumping conditions during the test (i.e. to obtain no measurable drop in downhole water levels during the pumping). In practice, steady-state conditions were not achieved, as the borehole did not intersect any highly transmissive fractures. The pumping rate was constantly adjusted to maintain a 2 L/min flow rate and monitored every minute using a graded container and a stopwatch, while water levels were measured in the borehole using a water-level meter. After each flow meter test, the tool was lowered to the next target until "no flows" were detected by the flow meter at 19.0 m. Pump test results are presented on Figure A5 of Appendix A.

The pump was then lowered to 20 m (with the flow meter beneath) to attempt to induce upward flow from minor borehole wall enlargements at sandstone beds observed in the televiewer images at 23.8 m, and 25.15 m. Pumping rates were increased to 4 L/min but steady-state pumping conditions were not achieved. Flows were not detected at either of the identified targets, so the pump was lowered to 45 m meters in an attempt to influence the lower half of the borehole where the fluid conductivity anomaly was observed. As with the overlying interval, at pumping rates of 4 L/min, steady-state conditions were not achieved. During the pumping, a hand-held fluid conductivity meter at surface (calibrated with the same calibration solutions as the downhole tool) was used to measure the conductivity of the groundwater being pumped from the well. Values were consistent with the fluid conductivities measured in the upper half of the well (~700-950 µS) by the downhole fluid conductivity tool. This indicated that fluid was being drawn from the overlying fluid column, not from depths below 45 m. 'No flow' results from the flow meter positioned beneath the pump corroborated these results.

During the pump test, the pump shut off four times due to constantly decreasing heads and difficulty stabilizing the flow. During these periods, water levels were recorded which allowed for an estimate of the well recovery rate in the minutes following the pump shut off.

Table 2. Details of the downhole geophysical logs acquired in all five boreholes.

Downhole Geophysical Log *[Manufacturer]*	**Logging Unit**	**Radius of Investigation** ***[Vertical resolution]***	**Logging Speed**	**Logging Interval**	**Practical interpretations**
Acoustic Televiewer *[Advanced Logic Technology/ Mount Sopris]*	Dual images: Traveltime (millisec) Amplitude (unitless)	Open face of borehole wall; Azimuthal resolution: 1.25 pixel/deg *[Minimum scan height: 0.001 m]*	0.5 m/min	0.003 m	In open rock: structural orientations (strike direction & dip), fracture aperture at borehole wall, reflectivity of bedrock formations (relative hardness)
Acoustic Caliper Interpreted from ATV traveltime data and borehole fluid velocity	mm	Open face of borehole wall [Caliper resolution: 0.0001 m]	0.5 m/min	0.003 m	Wall roughness, fracture aperture at borehole wall

Downhole Geophysical Log *[Manufacturer]*	**Logging Unit**	**Radius of Investigation** ***[Vertical resolution]***	**Logging Speed**	**Logging Interval**	**Practical interpretations**
Optical Televiewer *[Advanced Logic Technology/ Mount Sopris]*	mm	Open face of borehole wall; Azimuthal resolution: 2 pixels/deg *[Minimum scan height: 0.001 m]*	2 m/min	0.002 m	In open rock: structural orientation (strike direction & dip), fracture aperture at borehole wall, true color images in clear fluid indicate geological variations along wall face
Heat Pulse Flow meter *[Mount Sopris]*	Litres/min	Within borehole 0.1 l/min	Stationary readings	Selected based on televiewer, caliper, and fluid log results	Direction and volume of vertical flow
Fluid Conductivity *[GSC]*	Frequency, converted to conductivity μS/cm	Influenced by surrounding materials *[logging interval]*	1 m/min	0.01 m	Anomalies due to groundwater flow; changes in groundwater conductivity, lithology
Fluid Temperature *[GSC]*	Frequency, converted to degrees Celcius (°C)	Influenced by surrounding materials *[logging interval]*	1 m/min	0.01 m	Anomalies due to groundwater flow; lithology (as related to thermal conductivity)
Magnetic Susceptibility *[Geonics/Mount Sopris]*	parts per thousand SI (ppt SI)	0.3 m *[submetre]*	3 m/min	0.02 m	Magnetite (heavy mineral) concentration, lithological boundaries
Spectral Gamma *[Mount Sopris]*	Counts per second (cps)	0.3 m *[centimetres, function of logging speed]*	1 m/min	0.01 m	Relative grain-size, lithological boundaries
Calibrated Gamma-gamma Density (Cs-137 source) *[Mount Sopris]*	Counts per second (cps) calibrated to g/cm^3	0.15 – 0.25 m *[centimetres, function of logging speed]*	1 m/min	0.02 m	Density (when casing coupled with formation), lithology
Inductive Conductivity *[Geonics/Mount Sopris]*	milliSiemens/ metre (mS/m)	0.3 m *[submetre]*	3 m/min	0.02 m	Formation conductivity (grain and/or porewater conductivity), lithological boundaries

4.0 Data Processing

Geophysical log data were imported into WellCAD software for processing and interpretation. As logs were recorded relative to ground surface, depth adjustments were not required during post processing. Induction logs were truncated inside metal surface casings, but were otherwise unaltered. Upward and downward runs were overlaid to check for tool-induced temperature drift and ensure repeatability.

4.1 Unconsolidated Sediment Wells

Gamma logs (natural and active) are highly sensitive to the bonding between formation material and the borehole construction material and casing. Both logs were negatively affected by the boreholes' large grout/bentonite-filled annuli (46 mm on average), variations in the grout, and bentonite seals. This separation between the formation and the tool sensors reduced the effectiveness of the natural gamma log as an indicator of changes in grainsize and mineralogy. The use of potassium-rich bentonite for well seals, however, increased the count levels where seals where present. Therefore, the natural gamma logs are presented alongside the well completion logs to show where the seals surrounding the screens are located.

The gamma-gamma bulk density tool is composed of a 3.7 GBq (100 mCi) cesium (Cs^{137}) source and near and far detectors which measure backscattered energy from the source. The counts recorded by the detectors are converted to densities using the lab calibrations. However, due to the large annular distance between the borehole wall and the detectors, variations in the grout, and bentonite seals account for the variation in density. Therefore, the log has been converted to a greyscale color bar alongside the well completion log, indicating relatively poor (air void) to good PVC coupling with the borehole wall.

Multi-fold P-wave and single fold S-wave travel times were picked using a semi-automatic picking program with a pick-to-pick cross correlation (Ivanov and Miller, 2004). Interval velocities were computed using a derivative requiring two consecutive first arrival time picks. This method selects arrival times through cross correlation using spline interpolation and requires highly accurate arrival times. Due to electromagnetic interference at the Hillier and Cochrane sites from power lines and a substation, only downhole traveltime data recorded at Spider and Qualicum holes could be interpreted.

Logs were interpreted as a complete suite to better identify variations in downhole response. Available geological information from drilling records and core logs was displayed on the figures to assist in the interpretation of geophysical units, identified on Figures A-1 to A-4 (Appendix A).

4.2 Bedrock Well

Geophysical logs were imported into WellCAD software, along with the geological information from the driller's log. Calibrations carried out in the field and/or lab prior to logging meant that little processing was required during the import of the induction and fluid logs.

Heat pulse flowmeter results are presented in bar chart form on Figure A-5 (Appendix A), and in a spreadsheet table in Appendix C. The results of the water level measurements were analyzed to

calculate a recovery rate over 17 and 13 minutes during two pump stoppages. Recovery was measured at 1.9 and 1.8 L/min (respectively), which was lower than the pumping rate, accounting for the dropping water levels in the borehole during the flow testing, and the difficulties reaching steady-state conditions.

Televiewer images were imported into WellCAD and oriented to a common reference (magnetic north) so they could be compared side-by-side. An acoustic caliper was calculated from the traveltime image using a fluid velocity corrected using the fluid temperature log.

5.0 Interpretation

5.1 Unconsolidated Sediment Wells

Lithological Observations

The primary geophysical responses to textural and mineralogical variations were identified from the induction tool logs (magnetic susceptibility and apparent conductivity). Elevated and highly varying magnetic susceptibility values (20 – 80 ppt SI) in the Quadra sands indicate moderate to significant magnetic mineral content. In the underlying diamictons, magnetic susceptibilities were low (10 – 25 ppt SI) and varied little with depth. Several sand intervals in the cores were identified in GSC-BH-SPI, CHR, and HIL for further mineralogical studies.

The apparent conductivity logs were used to identify sedimentological variations in the fine grained diamictons, mud units (and shale bedrock in GSC-BH-HIL and OW 287) underlying the Quadra sand. Apparent conductivities in the sand were ≤20 mS/m, versus ≥20 mS/m in the underlying glacial sediments, up to 75 mS/m in clayey/mud intervals in GSC-BH-CHR. Although these mud intervals contain shells identified as marine bivalves by the Canadian Museum of Nature (Medioli et al., 2014), the *in situ* conductivity levels do not reflect full marine conditions in the porewaters. Marine porewater salinities would be expected to provide a conductivity response on the order of 900 – 1000^{+} mS/m. Note, however, that ancient marine porewaters may have been partially replaced with more recent fresh (non-saline) water from the Quadra sand since sediment deposition.

The velocity logs in GSC-BH-SPI and BC-BH-QUA indicate highly variable P-wave velocities in the diamictons which do not necessarily coincide with the lithological changes interpreted from the induction logs and pXRF spectrometry. Average velocities for both P and S-wave velocities are listed in Table 3. The Vs log in the Quadra sand in GSC-BH-SPI is more uniform, while the elevated standard deviations in the diamictons (GSC-BH-SPI & BC-BH-QUA) reflect their more chaotic nature. This was also observed in the GSC's high-resolution seismic reflection profiles, and suggests a complex and highly variable vertical and lateral velocity character in the diamictons.

Table 3. Average velocities and standard deviation (1σ) for compression (Vp) and shear-wave (Vs) velocities calculated in the Quadra sand and underlying diamicton units.

Material	Vp (m/s)	Vs (m/s)
Sands	insufficient data (4 pts)	480 ± 80 (1σ, 70 points)
Diamicton sequences	2300 ± 600 (1σ, 76 points)	700 ± 220 (1σ, 93 points)

Data Integration for Stratigraphic Picks

Textural and mineralogical boundaries in GSC-BH-SPI and GSC-BH-CHR were also assigned based on changes in the elemental concentrations measured by a portable x-ray fluorescence (pXRF) spectrometer on freeze-dried, sieved samples (<63 μm) collected at ~3 m intervals (Knight et al., 2014b). This technique has been successfully used at the GSC to highlight chemostratigraphic changes in a sequence of fine-grained glacially derived sediments (Knight et al., 2013). Geophysical logs and pXRF-derived geochemistry together significantly enhanced the interpretation of lithological units, often identifying boundaries which were subtle in the geophysical logs alone (Knight et al., 2011; Crow et al., 2012).

Hydrogeological Observations

Hydrostratigraphic unit assignments are based on the core log descriptions classified according to the regional stratigraphy and accounting for aquifer (sand, gravel) and aquitard (mud, diamicton) sediment characteristics. Depths for these unit boundaries were slightly adjusted based on the results of the geophysical logs and the pXRF spectrometry. The hydrostratigraphic units are presented in Figures A1-A4 next to the stratigraphic logs.

Fluid temperature ranges in the boreholes are displayed in Figure 2, along with estimated elevations from Google Earth (© 2013). At the time of logging, fluid temperatures in GSC-BH-CHR and SPI were 0.5 to 2ºC warmer than in GSC-BH-HIL, BC-BH-QUA and OW 287 to the south-east. According to Grasby et al. (2009), there are no known hot springs or geothermal sources in the area. While it is possible that there are differences in geothermal processes between the NW and SE boreholes which influence groundwater temperatures, it is more likely that the temperatures in CHR and SPI are the result of excess heat generated during the sonic drilling process (conducted only two to three months before the downhole logging). Studies by Drury and Jessop (1982) indicate that groundwater temperatures influenced by drilling can take up to a year to dissipate in bedrock. Drilling of BC-BH-QUA was conducted using air rotary methods, resulting in sediment temperatures in agreement with those of the bedrock hole, which has reached equilibrium. Drilling at HIL was conducted prior to CHR and SPI and was carried out over a shorter period of time.

Despite the differences in temperature ranges, trends provide useful information about the geothermal properties of the subsurface. Figure 3a presents temperature logs relative to a main hydrostratigraphic boundary (Quadra sand and Cowichan diamicton), and to depth below ground surface (Figure 3b) to examine whether groundwater temperatures are more influenced by stratigraphy or depth. Temperature gradients in the diamicton range between 0.010 and 0.017 ºC/m. There is however, a negative trend in GSC-BH-HIL (-0.009 ºC/m) which is difficult to explain using this relative depth scale. Figure 3b displays temperature logs relative to depth below ground surface. Here, the negative trend in the diamicton GSC-BH-HIL fits the thermal "bow-shaped" trend of the shale bedrock. This implies that temperature profiles are controlled primarily by the depth below surface, but also, to some extent, by nature of the subsurface materials. For example, GSC-BH-CHR displays a bow-shaped temperature log, which is more pronounced than at SPI and QUA, implying that the heat dynamics at CHR may be different than at SPI and QUA.

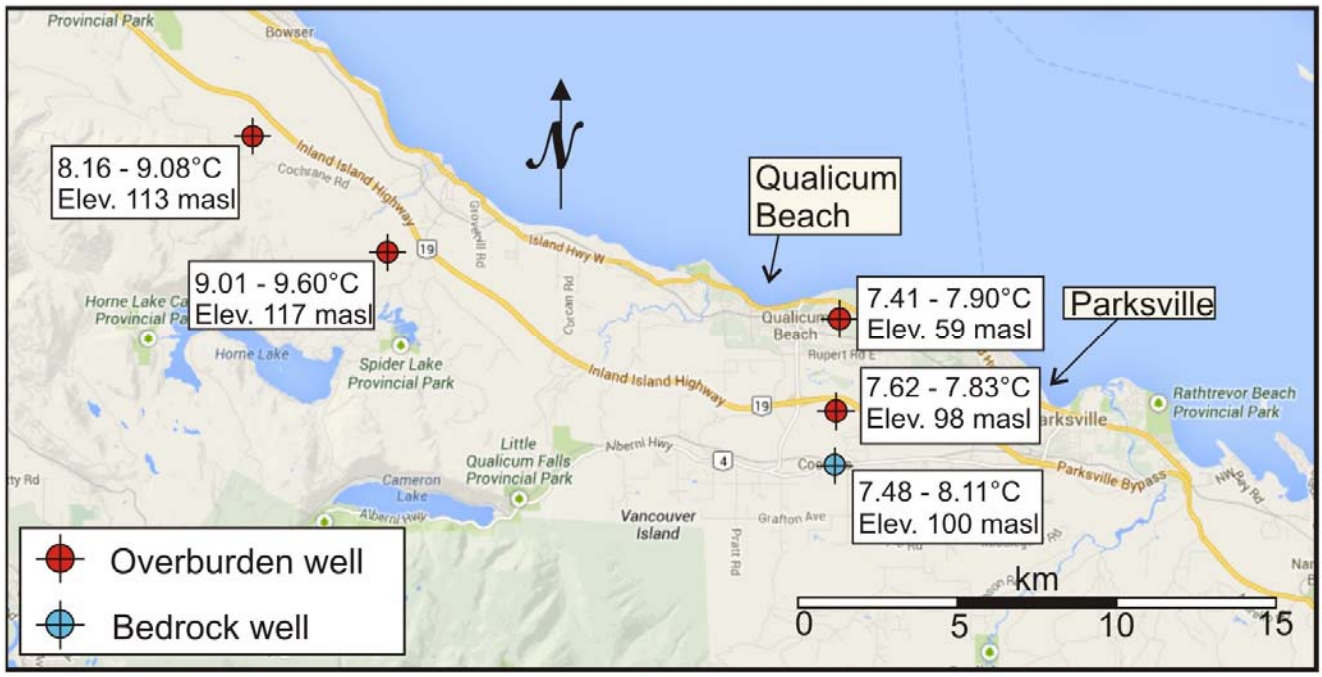

Figure 2. Temperature ranges from fluid logs. Surface elevation approximations from Google Earth (map image from © 2013 Google).

5.2 Bedrock Well

Lithological Observations

Bedrock is described in the water well record as black shale (MoE, 2013) which is assigned to the Upper Cretaceous Nanaimo Group. It likely formed during four major fining-upward deposition cycles, which were increasingly dominated by deeper marine deposition (Jeletsky and Muller, 1970). A simplified geology of the Nanaimo Group indicates a sequence of alternating shale-dominated and sandstone-dominated formations. The shale-dominated formations do, however, contain thin sandstone horizons (Hamblin, 2012).

The natural gamma and apparent conductivity logs indicate that the upper half of the borehole (7 – 46 m) is more homogenous than the lower half. The optical televiewer log indicates this dark-colored interval is shale-dominated, with a few thin (<10 cm) light-colored beds interpreted as sandstone. In the lower half of the well (46 – 92 m), frequent drops in bulk conductivity and natural gamma counts occur. These intervals appear in the optical televiewer log as lighter-colored, coarser grained intervals, and are interpreted as sandstone. The magnetic susceptibility values are low (4.0 – 5.8 ppt SI) and vary little along the entire borehole, indicating that the sandstone does not contain significant amounts of magnetic minerals.

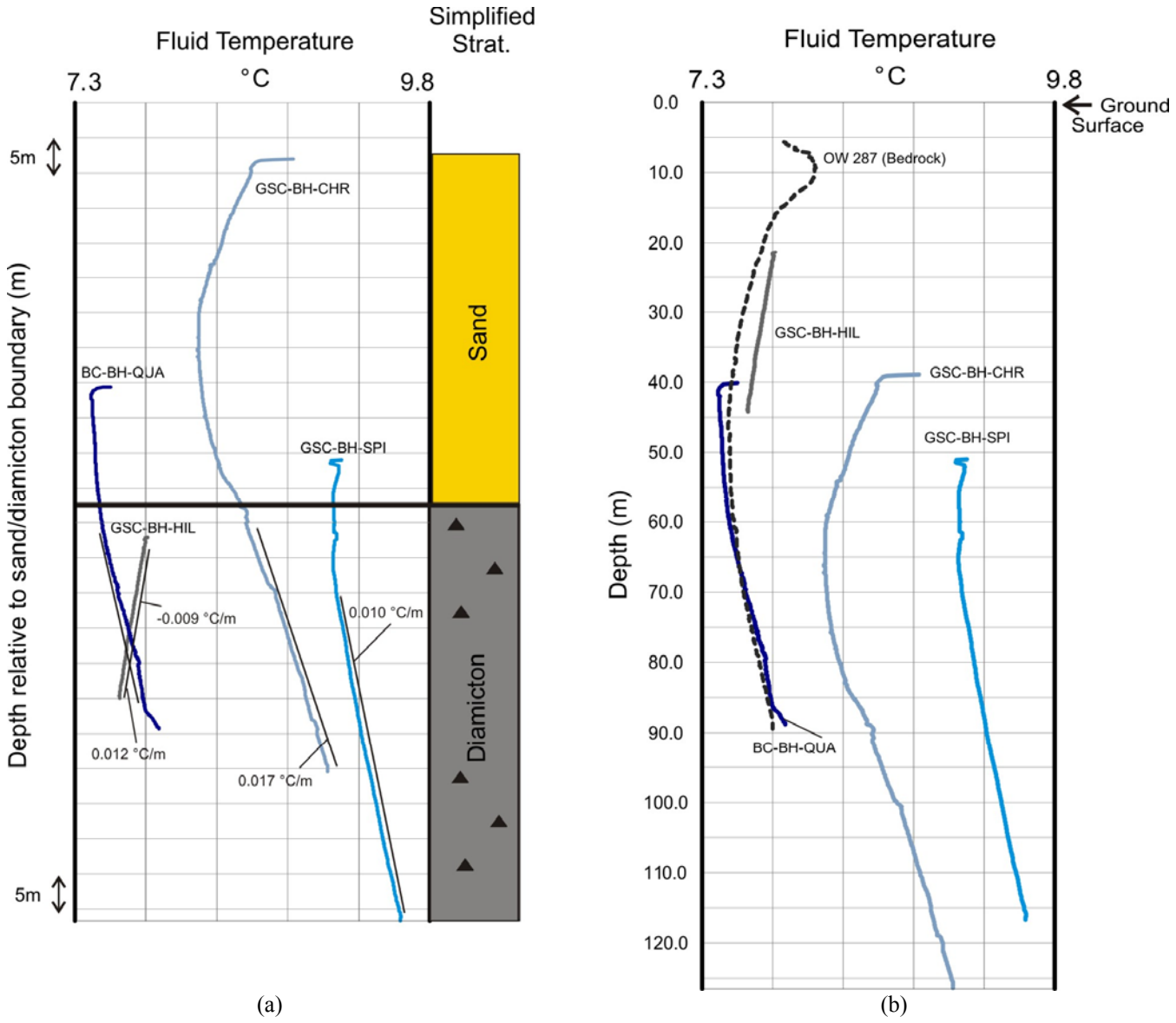

Figure 3. Comparison of temperature logs versus a main lithological and hydrogeological boundary (a), and depth below ground surface (b).

Hydrogeological Observations

Fluid temperatures range between 7.48 to 8.11ºC following a bow shaped arc, with the highest temperatures inside, and immediately beneath, the casing. The variable fluid temperatures inside the metal casing (above 8.80 m) are influenced by mixing with air temperatures, and also by heat conducted through the casing. Below the base of the casing and down to 11.20 m, the temperature remains elevated, corresponding to the most permeable bedrock interval measured using the flow meter. This may indicate that warmer groundwater is traveling through the well in this interval, or may also be due to the metal casing conducting heat from surface. Below 19 m, no induced flow was detected by the flow meter, and the shallow geothermal gradient has become dominant, as indicated in Figure 4 by the dashed orange line.

The caliper and optical televiewer image indicate that a fracture exists at the base of the casing which is a significant source of inflow into the borehole under pumping conditions (Figure 4, see also Figure A-6 for higher resolution televiewer images). Closed high angle joints (dip angles 60 - 78º from horizontal) are visible in the bedrock between 10.2 – 18.5 m. Temperatures in the bedrock display no sudden temperature variations, indicating that any fluid entering the borehole under ambient conditions is occurring at a very slow rate.

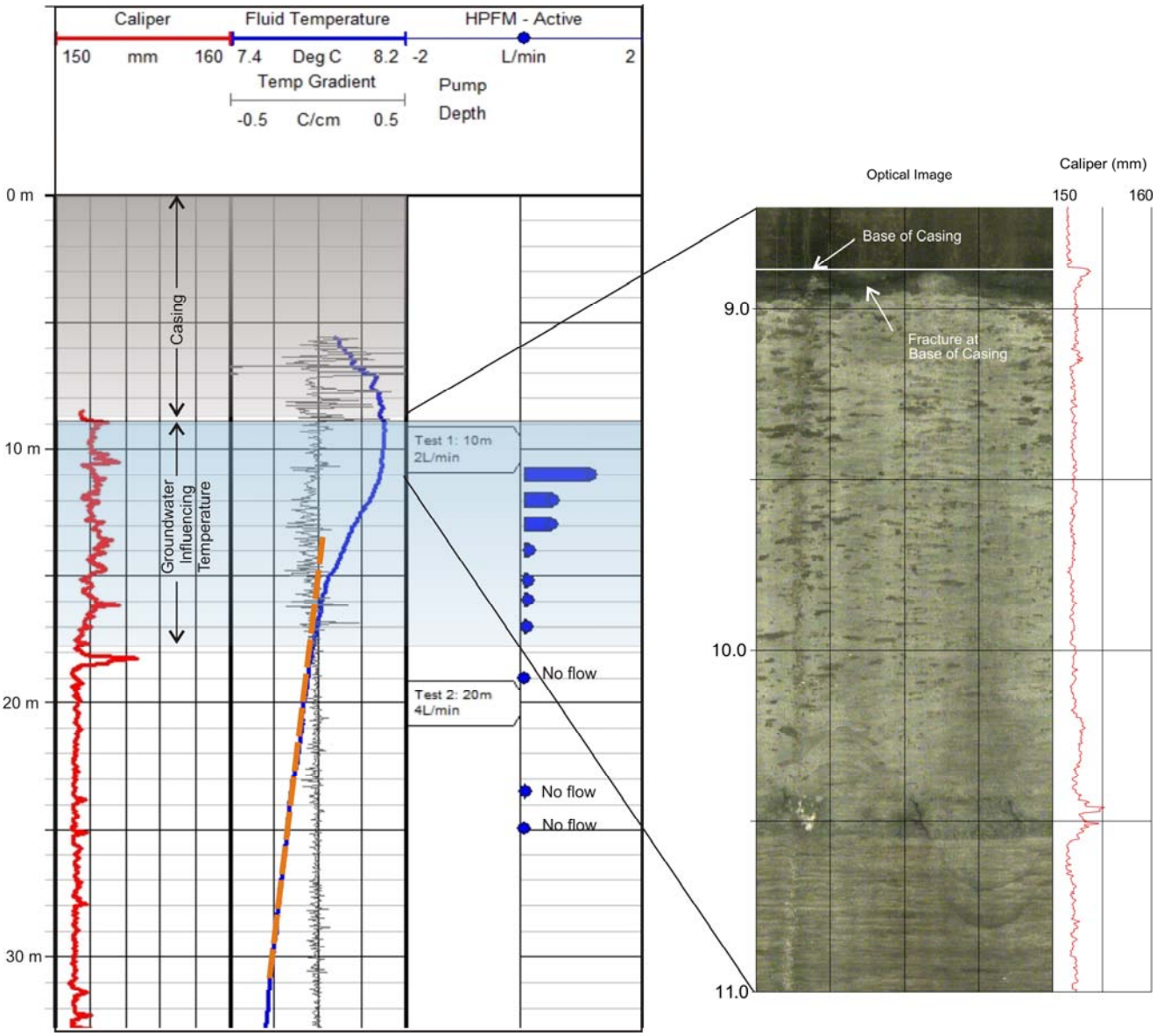

Figure 4. Relationship between fluid temperature and pumped flow meter test results in the upper 20 m of the bedrock borehole. The orange dashed line indicates where fluid temperatures have reached equilibrium with the geothermal gradient. Fluid temperatures between the base of the casing and 18 m depth (blue shading) are interpreted as being influenced by presence of casing, and possibly near-surface groundwater. The caliper and 'unwrapped' optical televiewer image indicate that a fracture exists at the base of the casing which is interpreted as the significant source of fluid inflow during the pump test.

At 46.70 m depth (Figure 3), the temperature reaches its minimum of 7.48ºC, which falls within the predicted temperature range (6 - 8 ºC) of the shallow geothermal field on Vancouver Island at 50 m depth (Grasby et al., 2009). A best fit linear extrapolation of the temperature log from 70 m to 90 m provides a positive slope of 0.005 ºC/m for the shallow geothermal temperature gradient.

Fluid conductivities in the borehole range between 716 and 17,475 µS. Conductivities increase downward gradually until a sudden increase occurs between 47 and 48 m. A gradient of the conductivity log superimposed over the optical televiewer image indicates that these increases are co-incident with a change in geology, identified by a change in bedrock color, frequency of sandstone horizons, and enlargements in the borehole wall indicative of weaker beds. The induction conductivity log, which is designed to be insensitive to borehole fluid and measure the bulk conductivity of the formation beyond the borehole wall, does not increase in the lower half of the borehole. This suggests the fluid conductivity increase is limited to the borehole column, and that the conductive fluids in the borehole are not associated with this geological change. This sudden increase in fluid conductivities may indicate upward migration of a deeper (likely saline) fluid to the 47-m interval due to an imbalance in hydraulic heads associated with the open hole. An open hole can intersect units or fractures with different hydraulic and geochemical conditions, which reach equilibrium over time at a different rate than the natural (undrilled) state. This would need to be confirmed through multilevel hydraulic testing (hydraulic conductivity (K) and head) and geochemical analyses of the groundwater.

Flow meter tests indicated that vertical groundwater gradients were not present in the borehole under ambient conditions at volumes less than 0.11 L/min (the lower limit of the tool). This may be an indication that hydraulic heads in the well have reached equilibrium. Based on the flow profile depicted in Figure 4, the bedrock is productive only in the upper part of the formation. The rock is fairly impermeable below 18 m, and no significant open fractures were observed in the televiewer images.

6.0 Conclusions

Geophysical logging in one bedrock borehole and four unconsolidated sediment boreholes in the Nanaimo Lowlands have provided a suite of logs which have helped in the hydrogeological characterization of the stratigraphy and groundwater properties of the region.

In the sediment boreholes, induction logs (apparent conductivity and magnetic susceptibility) were used to identify changes in the main stratigraphic units. The magnetic susceptibility log revealed elevated and highly varying response in the Quadra sand (20 – 80 ppt SI), and low response (10 - 25 ppi SI) with little variation in the diamictons. The conductivities were relatively low (<20 mS/m) in sands, moderate (20 - 50 mS/m) in diamictons, and elevated (30 – 70 mS/m) in muds, however, these levels are below conductivities expected for pore waters under full marine conditions. The additional information provided by the pXRF spectrometry in GSC-BH-CHR and SPI improved the stratigraphic – hydrostratigraphic classification of the complex diamicton units beneath the Quadra sands. Velocity logs revealed highly variable stiffness in the diamictons, indicating a complex subglacial structure, possibly caused by multiple glacial advance and retreat cycles.

The fluid temperature logs indicated that groundwater temperatures are primarily controlled by depth below ground surface (in equilibrium with the thermal gradient), although material type (i.e. aquitard vs. aquifer) also can influence the temperature gradients.

In the bedrock borehole, lithological variation is well defined by the optical televiewer, natural gamma, and apparent conductivity logs, while the magnetic susceptibility is low and unvarying. The logs indicate that the bedrock is shale-dominated with only a few thin (<10 cm) sandstone beds in the upper 47 m. Sandstone beds are more common and increase in thickness in the lower half of the borehole (47 – 90 m), indicating a possible transition toward a sandstone-dominated formation lies at greater depth.

The fluid temperature log provides a stable baseline temperature profile in the upper 90 m of the ground surface. At the time of logging, the minimum temperature was recorded at a depth of 46.70 m, reflecting the depth to which surface climactic conditions are presently influencing subsurface temperatures. Results of the pumped flow meter tests indicate flow is entering the borehole through a fracture at base of casing; there are no other significant fluid-transmitting fractures evident in the bedrock. Between 47 – 48 m depth, a sudden increase in fluid conductivity occurs which is co-incident with a change in bedrock geology. There is, however, no associated rise in bulk apparent conductivity, implying that the increase is limited to the borehole fluid and not the surrounding formation. This may be a reflection of a deeper (likely saline) fluid which is slowly infusing upwards through the rock due to an imbalance in hydraulic heads associated with the open hole. To infer saltwater intrusion or even connate water migration would require permeability, hydraulic head, and geochemical profiles along the borehole to study the hydraulic conditions, and the composition and age of the fluid (i.e. young waters, versus older connate waters).

In summary, the borehole geophysical logs, pXRF spectrometry, geological cores and seismic surveys provide a framework to interpret existing and future hydrogeological information (e.g., driller's well logs) with respect to the regional hydrogeological context. This will contribute to a better understanding of the aquifer system in the Nanaimo Lowlands study area.

6.1 Implications for regional groundwater modeling

The conductivity and magnetic susceptibility logs, along with the pXRF spectrometry in GSC-BH-SPI and GSC-BH-CHR helped adjust the depths of the hydrostratigraphic unit boundaries for the groundwater model development. The thickness of the hydrostratigraphic units can be quite variable over short distances, as shown by the hole-to-hole variability in the geophysical logs within the Cowichan formation.

The minimum temperature recorded in the bedrock well was at 46.70 m, reflecting the depth to which surface climactic conditions are presently influencing subsurface temperatures. Pumped flow meter tests indicate the diamicton/bedrock surface is a groundwater source; otherwise, the shale bedrock is relatively impermeable, and did not intersect any productive fractures at this location.

Differences in the shape of the bow-shaped temperature logs in the sediment wells imply that the heat dynamics at the GSC-BH-CHR well site are different than at GSC-BH-SPI, GSC-BH-HIL, GSC-BH-QUA, and OW 287.

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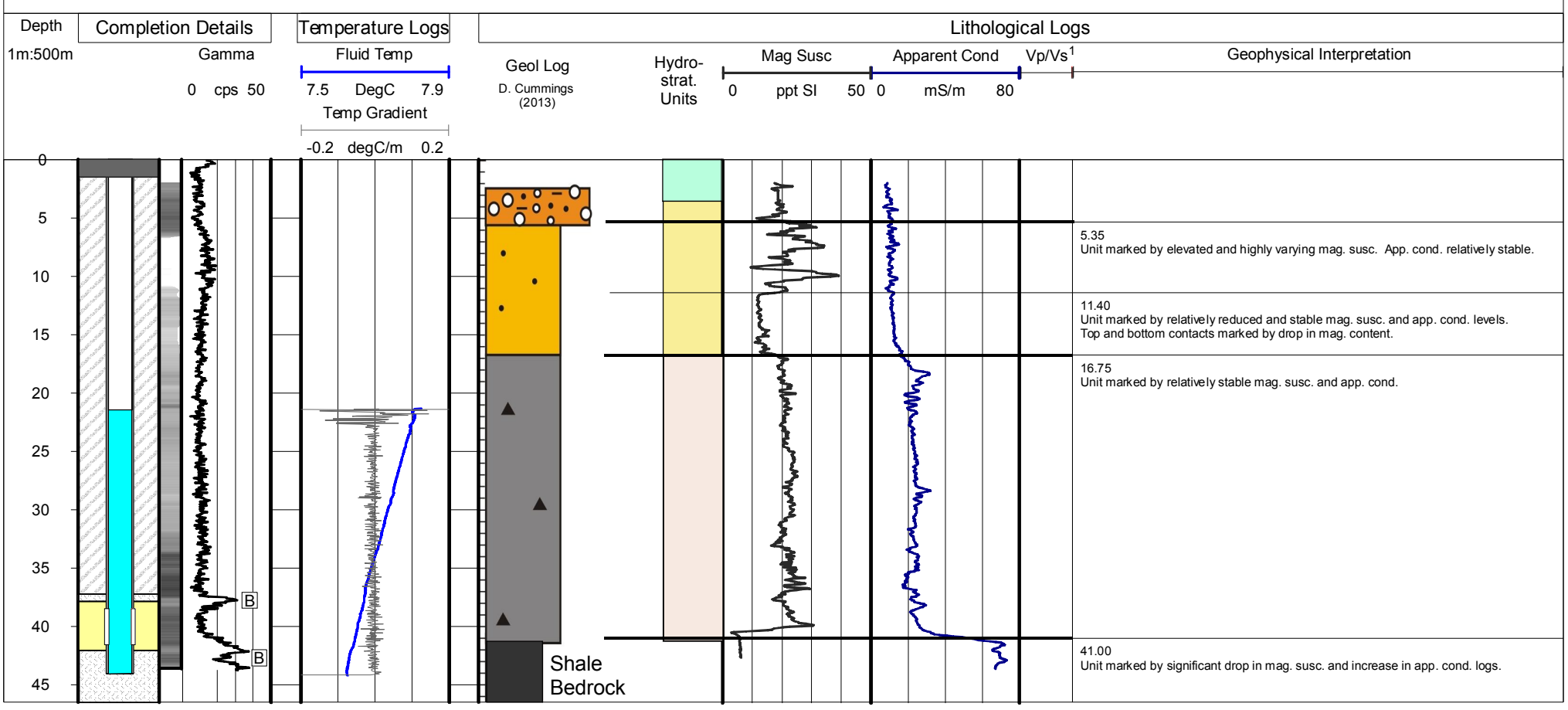
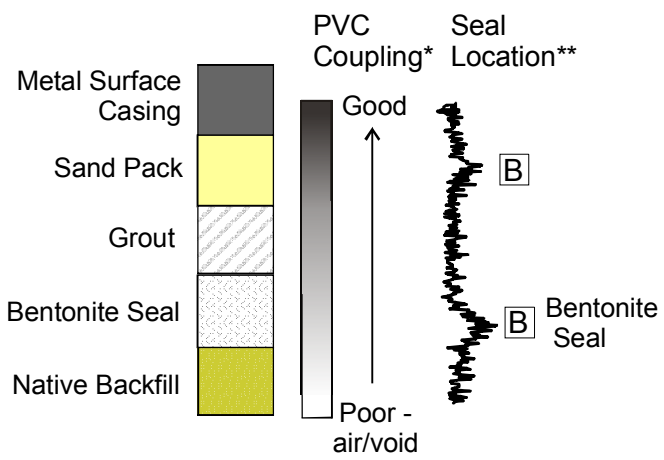
Appendix A

Downhole Logs

Borehole:	GSC-BH-HIL	Easting:	397 629 m	Date Drilled:	Nov 29 - Dec 1, 2012	Date Logged:	Mar 19-20, 2013
Location:	Parksville, BC	Northing:	5 463 318 m	Method:	Sonic	Water Level:	21.36
Project:	Groundwater Asmt	UTM Zone:	10	Diameter:	152 mm	Logged By:	GSC
Study Area:	Nanaimo Lowlands	Datum:	NAD83	Depth:	46.5 m	Log Ref:	Soil Surface

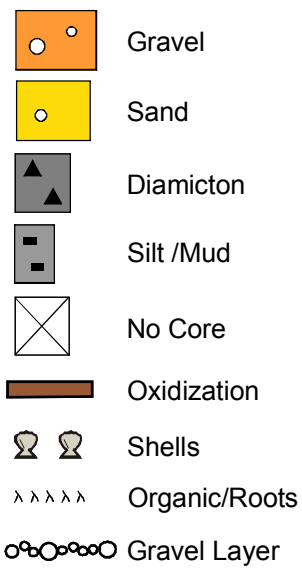


Well Completion Details

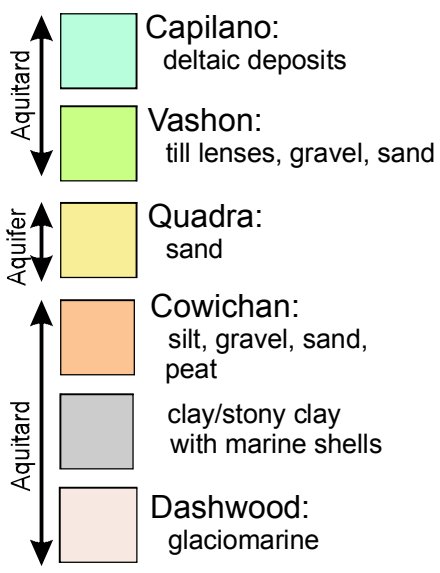


* Scale based on results of downhole density log
** Seal positions based on results of natural gamma log

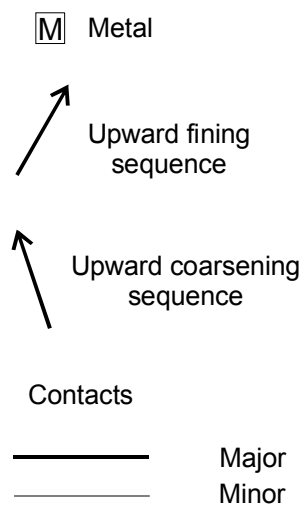
Simplified Stratigraphy



Hydrostratigraphic Units



Geophysical Interpretation



[1] Traveltime measurements affected by electromagnetic noise and broadband urban vibration. Velocity logs not presented.

Borehole:	GSC-BH-SPI	Easting:	382 789 m	Date Drilled:	Dec 3 - 6, 2012	Date Logged:	Mar 21-25, 2013
Location:	Qualicum, BC	Northing:	5 469 236 m	Method:	Sonic	Water Level:	50.95
Project:	Groundwater Asmt	UTM Zone:	10	Diameter:	152 mm	Logged By:	GSC
Study Area:	Nanaimo Lowlands	Datum:	NAD83	Depth:	117.43 m	Log Ref:	Soil Surface

Depth 1m:500m | Completion Details | Temperature Logs | Lithological Logs | Geophysical Interpretation

Gamma 0 cps 50 | Fluid Temp. 9 deg C 9.8 | Temp. Gradient -0.5 degC/cm 0.5 | Geol Log D. Cummings (2013) | Hydro-strat. Units | Mag Susc 0 ppt 50 | Apparent Cond 0 mS 80 | P-wave Velocity ◆ S-wave Velocity ◆ 0 m/s 3000

0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
80.0
85.0
90.0
95.0
100.0
105.0
110.0
115.0

B B B B

M

0.00

5.00
Unit marked by elevated and highly varying mag. susc. levels. These variations are are more pronounced in the lower half of the unit, but a boundary is unclear. Relatively stable and upward decreasing app. cond. values, interpreted as an overall upward coarsening trend.

Interval (34.8 - 49.8 m) contains most highly varying mag. susc. levels in borehole.

54.00
Contact between units is subtle in geophysical logs; upper contact based on increase in magn. susc (interpreted slight upward fining unit).

56.85
Contact between units is subtle in geophysical logs; upper contact based on slight decrease in magn. susc (interpreted slight upward coarsening unit).

62.80
Unit marked by stable app. cond, and very slight upward mag. susc increase, interpreted as subtle upward coarsening. Upper unit transition indicates temperature anomaly suggesting minor fluid movement behind casing.

74.65 Upper contact marked by decrease in app. cond. and mag. susc.

76.00 Increase in app. cond. interpreted as fine grained interval.

77.80
Unit marked by relatively stable app. cond., and mag. susc.

84.65
Increase in app. cond. interpreted as fine grained interval.

85.90

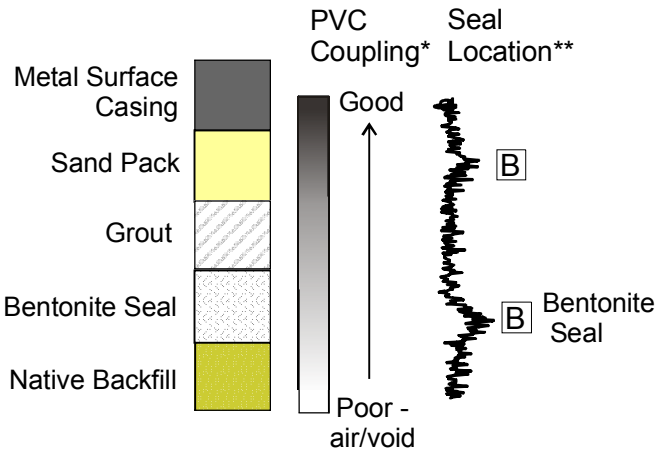
93.00
Increase in app. cond. interpreted as fine grained interval.

97.40
Unit marked by relatively stable app. cond., and mag. susc. Dashed line (104.0 m) identifies the base of an elevated shear wave velocity interval (Vs).

112.40
Increase in app. cond. interpreted as finer grained interval versus overlying materials.

115.00

Well Completion Details



* Scale based on results of downhole density log
** Seal positions based on results of natural gamma log

Simplified Stratigraphy

Gravel
Sand
Diamicton
Silt /Mud
No Core
Oxidization
Shells
Organic/Roots
Gravel Layer

Hydrostratigraphic Units

Aquitard — Capilano: deltaic deposits
Aquitard — Vashon: till lenses, gravel, sand
Aquifer — Quadra: sand
Aquitard — Cowichan: silt, gravel, sand, peat
Aquitard — clay/stony clay with marine shells
Aquitard — Dashwood: glaciomarine

Geophysical Interpretation

M Metal
Upward fining sequence
Upward coarsening sequence
Contacts
Major
Minor

Borehole:	GSC-BH-CHR	Easting:	379 107 m	Date Drilled:	Jan 13-22, 2013	Date Logged:	Mar 22-24, 2013
Location:	Qualicum, BC	Northing:	5 472 671 m	Method:	Sonic	Water Level:	38.89 m
Project:	Groundwater Asmt	UTM Zone:	10	Diameter:	152 mm	Logged By:	GSC
Study Area:	Nanaimo Lowlands	Datum:	NAD83	Depth:	129.23 m	Log Ref:	Soil Surface

Depth 1m:500m | Completion Details | Temperature Logs | Lithological Logs

Gamma 0 cps 50 | Fluid Temp. 8.1 Deg C 9.1 | Temp. Gradient -0.5 degC/cm 0.5 | Geol Log D. Cummings (2013) | Hydro-strat. Units | Mag Susc 0 ppt SI 80 | Apparent Cond 0 mS/m 80 | Vp/Vs[1] | Geophysical Interpretation

0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 65.0 70.0 75.0 80.0 85.0 90.0 95.0 100.0 105.0 110.0 115.0 120.0 125.0 130.0

B B B B B B B B B

M M M

0.00
Unit marked by relatively low magn. susc. levels, and upward increasing app. conductivity.

10.32
Unit marked by relatively reduced (but varying) mag. susc levels compared with underlying unit. App. conductivity relatively stable.

21.70
Unit marked by elevated and highly varying mag. susc. levels. App. conductivity relatively stable.

Interval (63.4 - 84.3 m) contains most highly varying mag. susc. levels in borehole.

88.15
Unit marked by sudden drop in mag susc. and increase in app. cond.

88.80
Unit marked by elevated app. cond. and low mag. susc. levels.

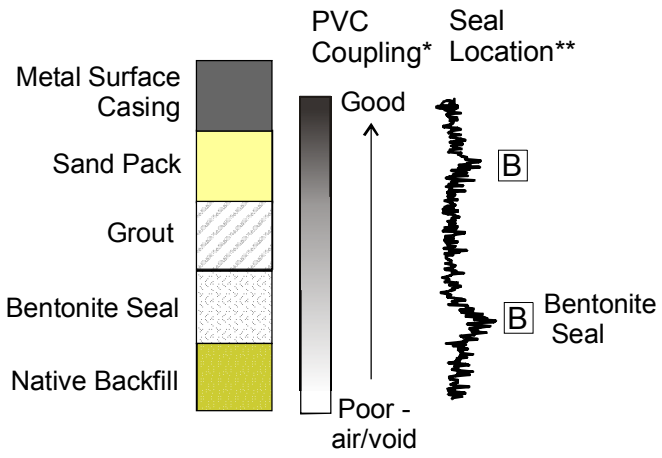
90.14
Unit marked by upward decrease in mag. susc. and increase in apparent cond.

93.69
Unit marked by relatively stable mag. susc., and small increases in app. cond., interpreted as fine-grained interbeds.

98.36
Unit of elevated app. cond.

99.57
Unit marked by relatively stable mag. susc. and app. cond.

Well Completion Details



* Scale based on results of downhole density log
** Seal positions based on results of natural gamma log

Simplified Stratigraphy

- Gravel
- Sand
- Diamicton
- Silt /Mud
- No Core
- Oxidization
- Shells
- Organic/Roots
- Gravel Layer

Hydrostratigraphic Units

- Aquitard — Capilano: deltaic deposits
- Aquitard — Vashon: till lenses, gravel, sand
- Aquifer — Quadra: sand
- Aquitard — Cowichan: silt, gravel, sand, peat
- Aquitard — clay/stony clay with marine shells
- Aquitard — Dashwood: glaciomarine

Geophysical Interpretation

M Metal

Upward fining sequence

Upward coarsening sequence

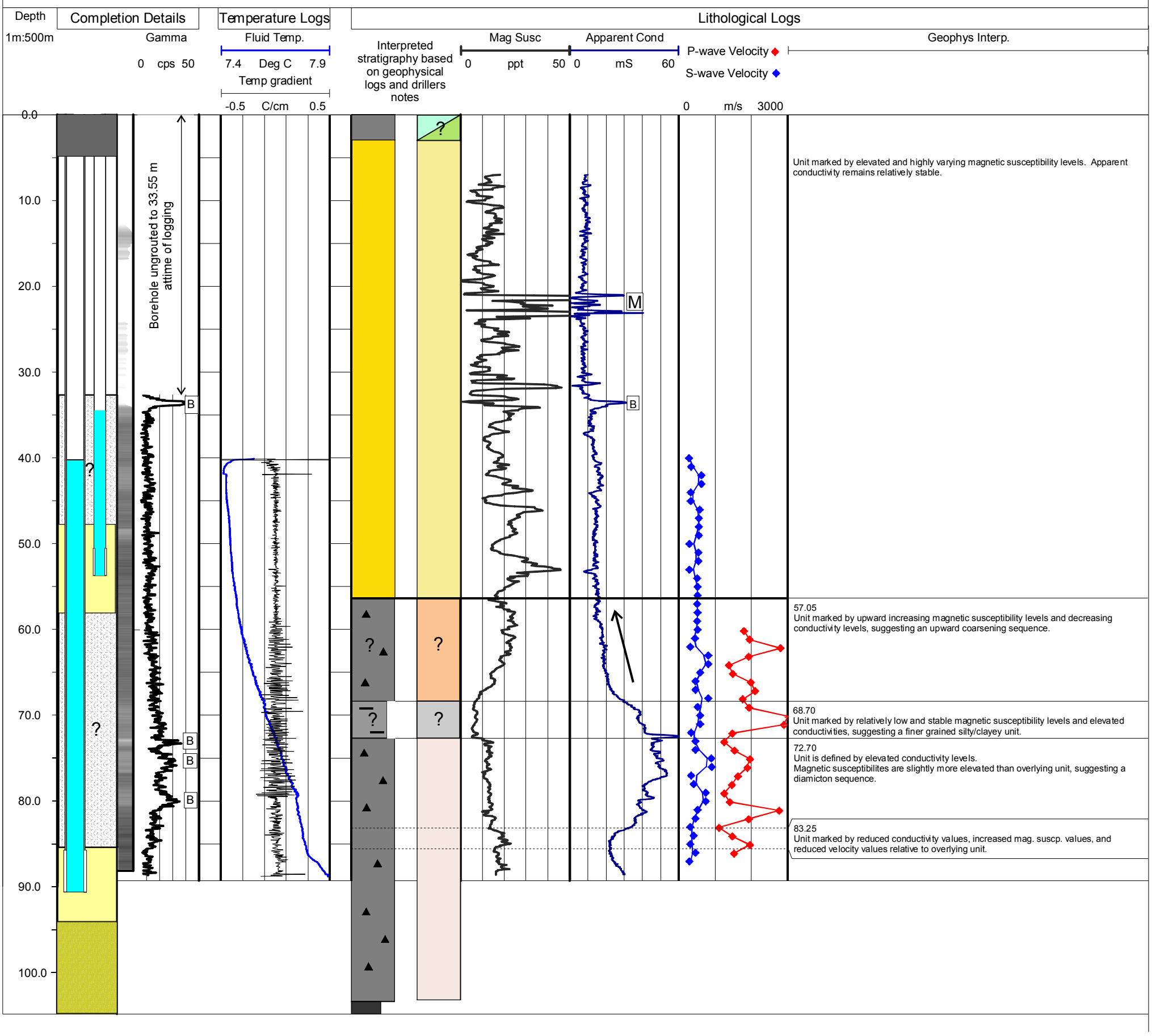
Contacts

Major

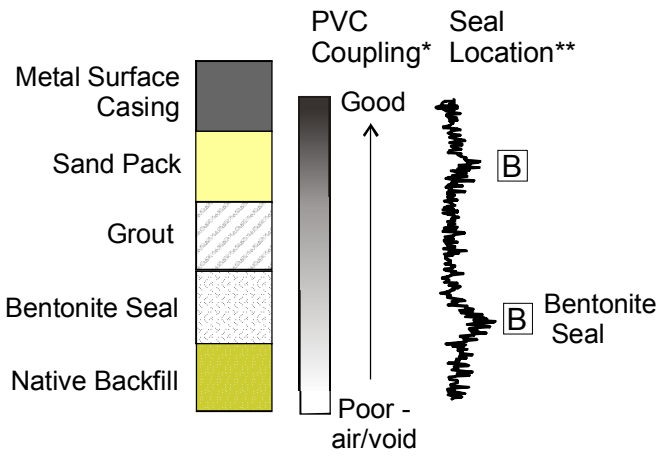
Minor

[1] Traveltime measurements obscured by electromagnetic noise due to near-by power station. Velocity logs not presented.

Borehole:	BC-BH-QUA	Easting:	397 787 m	Date Drilled:	Feb 20 - Mar 12, 2013	Date Logged:	Mar 30-31, 2013
Location:	Qualicum Beach, BC	Northing:	5 466 463 m	Method:	Air Rotary	Water Level:	40.12 m
Project:	Groundwater Asmt	UTM Zone:	10	Diameter:	152 mm	Logged By:	GSC
Study Area:	Nanaimo Lowlands	Datum:	NAD83	Depth:	104.5 m	Log Ref:	Soil Surface

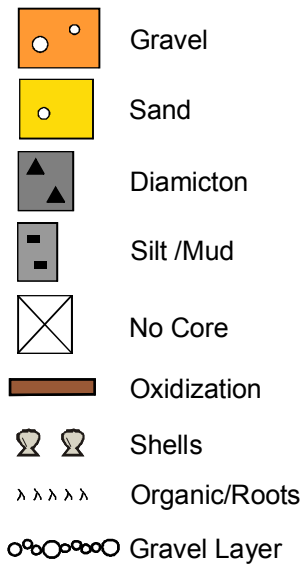


Well Completion Details

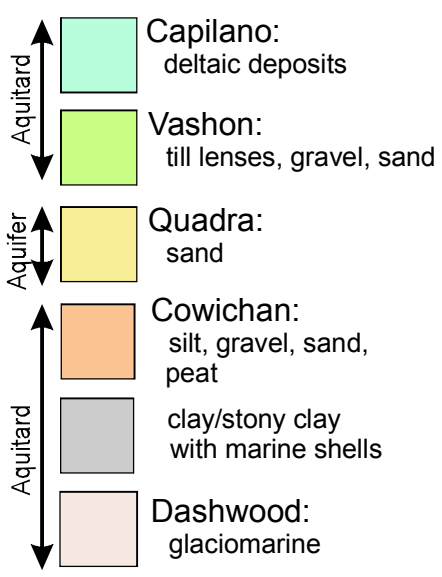


* Scale based on results of downhole density log
** Seal positions based on results of natural gamma log

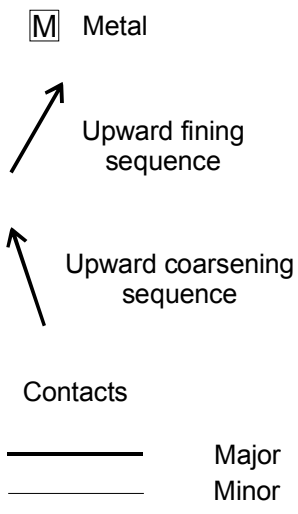
Simplified Stratigraphy



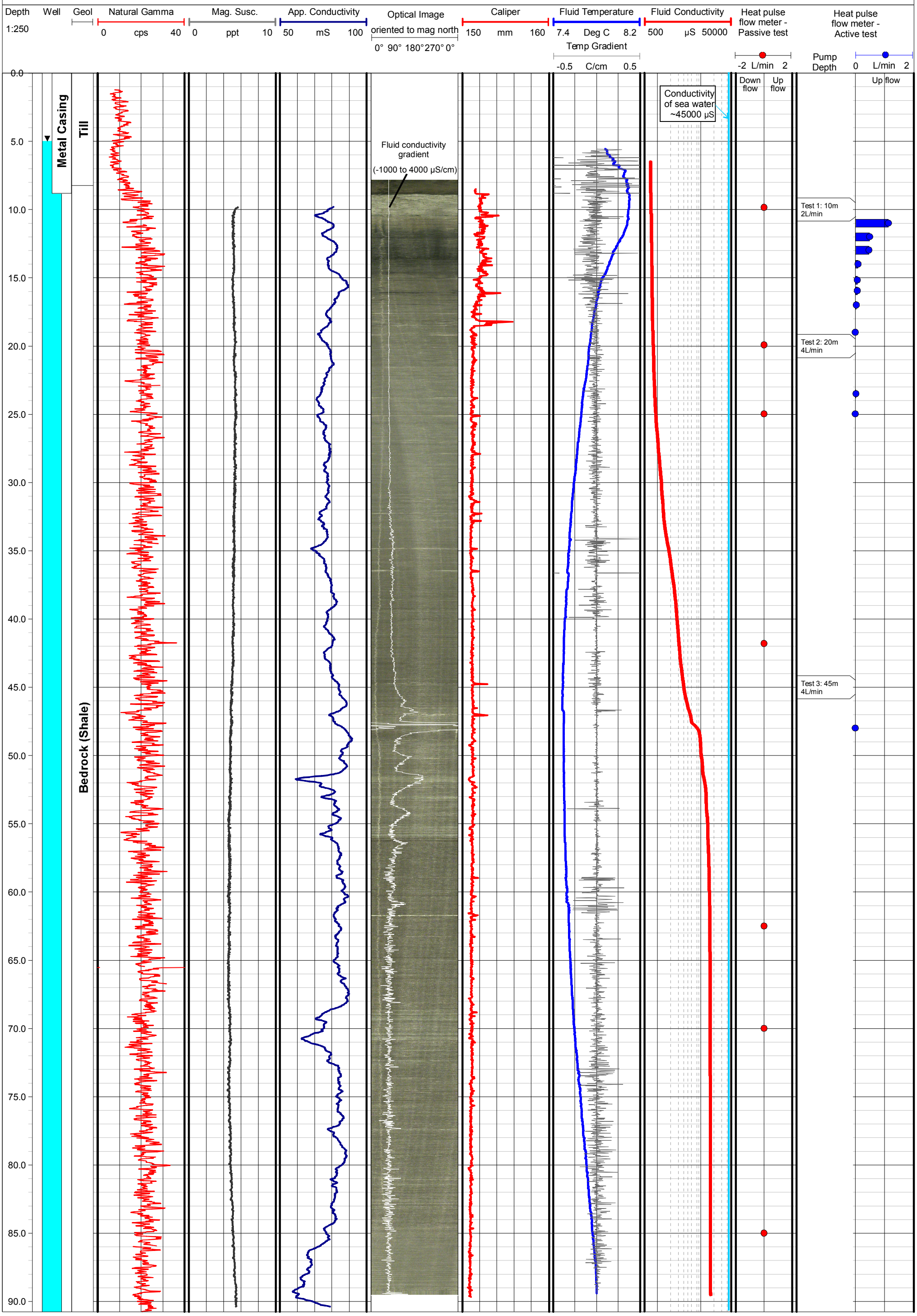
Hydrostratigraphic Units



Geophysical Interpretation



Borehole:	BC Obs. Well #287	Easting:	397 158 m	Date Drilled:	March 1984	Date Logged:	Mar 26-29, 2013
Location:	Coombs, BC	Northing:	5 461 985 m	Method:	N/A	Water Level:	4.94 m
Project:	Groundwater Asmt	UTM Zone:	10	Diameter:	152 mm	Logged By:	GSC
Study Area:	Nanaimo Lowlands	Datum:	NAD83	Depth:	92.35 m	Log Ref:	Soil Surface



Depth
1m:10m
Optical Televiewer Image
Oriented to Magnetic North
0° 90° 180° 270° 0°
Fluid Conductivity Gradient
-1000 uS/cm 10000
Acoustic Caliper
(ATV traveltime)
150 mm 158
Acoustic Televiewer Amplitude
Oriented to Magnetic North
0° 90° 180° 270° 0°
Fluid conductivity gradient superimposed over image to show depths at which significant changes in fluid conductivity occur (see anomaly at 47.6 m)
Base of casing
9.0
10.0
31.0
32.0
33.0

Depth
1m:10m
Optical Televiewer Image
Oriented to Magnetic North
0° 90° 180° 270° 0°
Fluid Conductivity Gradient
-1000 uS/cm 10000
Acoustic Caliper
(ATV traveltime)
150 mm 158
Acoustic Televiewer Amplitude
Oriented to Magnetic North
0° 90° 180° 270° 0°
34.0
35.0
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0
44.0
45.0
46.0
47.0
48.0
49.0
50.0
51.0
52.0
53.0
54.0
55.0
56.0
57.0
58.0

Depth
1m:10m
Optical Televiewer Image
Oriented to Magnetic North
0° 90° 180° 270° 0°
Fluid Conductivity Gradient
-1000 uS/cm 10000
Acoustic Caliper
(ATV traveltime)
150 mm 158
Acoustic Televiewer Amplitude
Oriented to Magnetic North
0° 90° 180° 270° 0°
59.0
60.0
61.0
62.0
63.0
64.0
65.0
66.0
67.0
68.0
69.0
70.0
71.0
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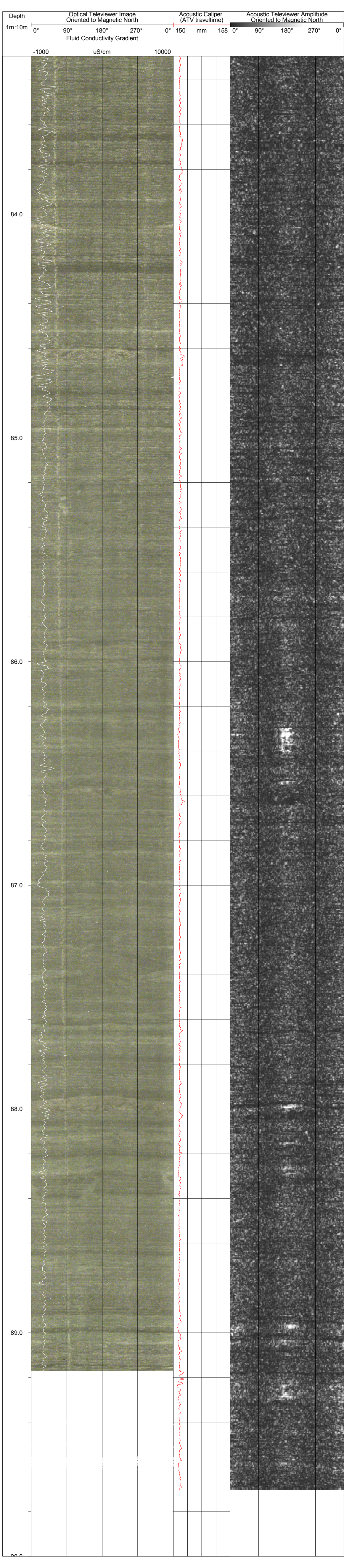
78.0
79.0
80.0
81.0
82.0
83.0


Depth
1m:10m
Optical Televiewer Image
Oriented to Magnetic North
0° 90° 180° 270° 0°
Fluid Conductivity Gradient
-1000 uS/cm 10000
Acoustic Caliper
(ATV traveltime)
150 mm 158
Acoustic Televiewer Amplitude
Oriented to Magnetic North
0° 90° 180° 270° 0°
84.0
85.0
86.0
87.0
88.0
89.0

Appendix B

Geophysical Log Background

Appendix B provides background information on the downhole logging methods used in this project. The tools described in the logging suite are Mount Sopris logging tools, except for the fluid temperature and conductivity which were developed in-house.

1.0 Gamma Methods

Natural gamma logging detects the presence of naturally occurring or man-made radioactive isotopes. The most common naturally-occurring isotopes in rock and soil are potassium (K), uranium (U), and thorium (Th), the most common being potassium in rock forming minerals.

Natural gamma logging tools measure radioactivity by converting gamma rays (photons) emitted from the formation into electronic pulses using a scintillator crystal (detector) in the tool. For total count gamma logging, it is sufficient to count the total number of pulses per second. In spectral gamma logging, the amplitude of the pulse is needed to determine whether the gamma ray energy lies within the range corresponding to the windows for K, U, or Th. At each depth interval, a spectrum (counts per second versus energy levels) is built from the amplitudes of the incident gamma particles (Figure B-1). The counts from each window can be later processed to calculate the weight percent of K, U, and Th in the formation using curves determined from test runs at downhole calibration facilities.

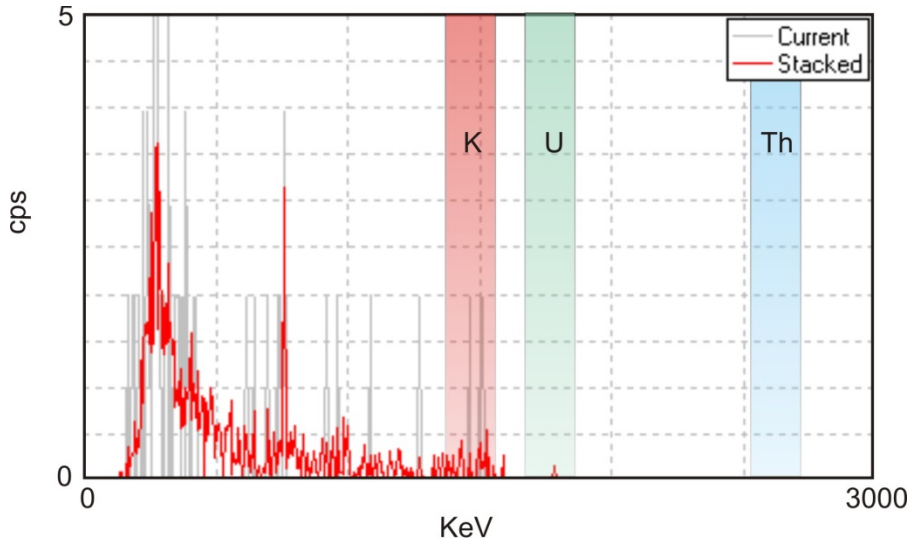


Figure B-1. Sample spectrum indicating total count (200 – 3000 keV), potassium (K), uranium (U), and thorium (Th) windows.

Radioactive decay is statistical in nature and photon emission follows a Poisson's distribution. The standard deviation of the count number will be its square root. The accuracy of the measurement is greatest at high count rates over slower logging speeds. Therefore it is preferable to maintain a very low logging speed.

When overburden units are logged, relative abundances of potassium, and especially uranium and thorium will generally be low, if present. This is particularly true in finer grained soils where the heavier elements were dropped out of suspension earlier in the sedimentary process, although exceptions exist. In soils, therefore, gamma energy is generally found in the lower ranges due to scattering, and can be used as a relative indicator of grainsize. A denser formation will cause the natural radiation to be attenuated more quickly, therefore coarser grainsizes will tend to have a lower

count rate, while softer soils with finer grainsizes (silt/clay) and higher porosity will tend to record higher count levels.

2.0 Electromagnetic Induction Methods

The **apparent conductivity** logging tool uses an alternating current of 40 kHz AC in a dipole transmitter to generate a magnetic field which induces electric fields in the formation. A dipole receiver in turn measures the responding signal, whose quadrature phase is proportional to the conductivity of the materials intersected by the borehole. Additional coils are used to focus the current out into the borehole to reduce the tool's sensitivity to the borehole fluid and improve its vertical resolution.

In soil and rock logging, the apparent conductivity measured is a bulk conductivity, meaning that the grains and pore water both contribute to the total conductivity values. If the pore water is saline or otherwise conductive (e.g. leachate contamination), this will overwhelm the conductivity of the soil/rock matrix. In absence of conductive pore water, the conductivity tool provides a method of identifying variation in stratigraphic units, and tends to mirror the trends of the natural gamma log, where fine-grained materials tend to be more conductive than coarse.

The **magnetic susceptibility** measurement is the ratio between the primary magnetic field and the in-phase component of the magnetic field produced by the host material. Although traditionally used for downhole mineral exploration due to its sensitivity to magnetic minerals (e.g. magnetite, ilmenite, pyrrhotite), the susceptibility tool has been shown to be extremely useful for lithological logging purposes in unconsolidated sediments and sedimentary rocks of low susceptibilities (McNeill et al., 1996).

Although these inductive tools are quite similar, lithological mapping requires a very sensitive magnetic susceptibility logger (in the sub-parts-per-thousand SI) with a high degree of temperature compensation. Therefore, two induction tools are used for the conductivity and susceptibility logging, with slightly different coil configurations and temperature compensation electronics.

Note that the unit for magnetic susceptibility is most commonly SI, but some texts also use the unit CGS. The conversion between these two systems is:

$$SI = 4\pi * CGS.$$

3.0 Fluid Logging Methods

3.1 Fluid Temperature

The GSC conducted borehole research in the late 70's and early 80's on techniques for high resolution temperature measurements on the order of 0.0001°C. The purpose was to investigate the feasibility of recording temperature gradients in fluid-filled boreholes which would reflect the intersected lithology (Bristow and Conway, 1984). The GSC has recently redeveloped a temperature tool based on the original GSC design which could also potentially identify small temperature changes indicative of fluid movement behind casing for groundwater studies, as well as subtle changes in temperature in open rock holes where fluid is entering or exiting the borehole through flowing fractures.

To be effective, the temperature tool must be the first probe to enter the borehole after the fluid has been able to stabilize for at least 24 hours, and the log must be recorded in the downward direction.

Slow logging speeds prevent mixing of the fluid ahead of the probe and allow time for the thermistor to react to slight changes in temperature. Gradient calculations (dT/dz) assist in identifying zones where fluctuations occur over very small changes in temperature.

3.2 Fluid Conductivity

The GSC's fluid conductivity tool is similar in design to the temperature tool, but uses two electrodes in the base (bullnose) of the tool to measure changes in fluid conductivity. The tool's response is calibrated in the lab against four calibration solutions of varying conductivity (deionized water ~0 μS/cm, 178 μS/cm, 1460 μS/cm, and 12880 μS/cm).

As with the temperature tool, the conductivity tool must be among the first probes to enter the borehole after the fluid has been able to stabilize for at least 24 hours, and the log must be recorded in the downward direction. Slow logging speeds prevent mixing of the fluid ahead of the probe and allow time for the electrodes to react to slight changes in fluid conductivity.

3.3 Heat Pulse Flow meter

Many methods have been developed over recent decades to measure vertical fluid flow along an open borehole or well screen for groundwater applications. These methods have included impellers, tracer-release methods, thermal-pulse flow meters, and electromagnetic (EM) flow meters. Thermal and EM vertical component flow meters are quite sensitive in low-flow conditions, permitting high-resolution measurement of the ambient vertical flow in natural or pumped borehole environments. Ambient flow measurements provide information on the direction of the vertical component of the hydraulic gradient and the location of hydraulically active features in fractured bedrock. Measurements made under pumped conditions provide information on the relative differences in the permeability of targeted bedrock zones or fractures.

The heat pulse flow meter used in these surveys (HFM-2293 manufactured by Mount Sopris Instrument Co.) is based on a design by the US Geological Survey to collect measurements in low-velocity flow environments (Hess, 1982, 1986). This flow meter contains a heating grid with equidistant temperature sensors positioned a few centimetres above and below the grid. Rubber diverter petals centralize and seal the probe in the borehole, forcing the fluid to pass through a wire mesh over the heating grid and the sensors. When the tool is in position for a series of readings, a heat pulse is triggered by the user on a laptop computer. The grid heats a lens of water that moves up or down with the flow of the borehole fluid past either the upper or lower sensor. An amplifier detects the difference in temperature between the sensors, and converts the output to a frequency which is sent up the cable and recorded by the laptop. The software records the time elapsed between when the heat pulse was triggered and when the sensor records the peak temperature change, carried by the flow.

If natural flow is not detectable in the borehole (i.e. <0.110 l/min), artificial upward flow can be induced with a submersible pump to determine the relative flow drawn from permeable fractures in the rock mass. Flow rate must be carefully monitored every few minutes on surface using a graded container and a stopwatch, while water levels are measured in the borehole using a water level meter. This ensures the change in flow rate measured by the tool can be attributed to changes in hydraulic conductivity of the rock mass and not to changes in the pumping rate. The pump's flow rate must be carefully adjusted so it does not exceed the tool's upper limit of 4 l/min, and also to equalize the pumping rate with the recharge (i.e. no measurable drop in water level during the pumping). In non-hydraulically conductive boreholes, reaching stability is very difficult, and sometimes not possible. In

these cases, the flow results are converted from a volumetric value, to a percentage of the total pumping rate measured simultaneously at the surface during the downhole flow measurement.

Flow meter measurements are influenced by number of factors, including the construction and degree of development of a well, and the natural hydrogeological conditions: factors which can change over time. Logging conditions during the test will also influence the results. Proper sealing with the tool's rubber diverters is critical, as a poor seal caused by borehole wall enlargements (such as in fractures or washouts) will influence flow determinations. Collecting caliper and fluid temperature/fluid conductivity logs before flow meter logging guides the selection of test intervals. Allowing sufficient time for the fluid to settle after moving the tool in the borehole is also critical, particularly in wells with very low ambient flows.

4.0 Imaging Methods

Televiewers collect high-resolution images of the inside of the borehole wall, using either ultrasonic pulses (acoustic televiewer, ATV), or color digital scans (optical televiewer, OTV). The tools are highly effective in the detection and evaluation of fractures, lithological characterization, dip and dip direction of features for rock mass structural analyses, and casing inspections.

Centralization is key in the collection of high quality images, particularly with the ATV. The tool is kept centered in the borehole with the use of two or more bowspring arm centralizers, made of non-magnetic material, fixed to the tool's housing.

Both tools are equipped with an APS544 orientation sensor, containing a 3-axis magnetometer and 3 accelerometers, to constantly resolve magnetic north and the tilt of the tool. Each line scan contains the direction of magnetic north, and also the tilt of the borehole at that depth. The tool can resolve azimuth with an accuracy of 1°, and tilt to an accuracy of 0.5°. When the travel time and amplitude images are imported into processing software, they can be oriented to magnetic north (or to the high side of the borehole in the case of inclined borings). Once the dip and dip direction of structural features are interpreted, they can be corrected for any tilt of the borehole from vertical.

4.1 Acoustic Televiewer (ATV)

The **ATV** transmits a pulse from a fixed transducer and a rotating focusing mirror, and records the amplitude and travel time of the signal reflected by the borehole wall. The ATV used in these surveys (the ABI40, manufactured by Advanced Logic Technology SA.) records the entire reflected wave train, and processing algorithms allow the software in real time to determine the first reflection from the tool's acoustic window, the bedrock wall, and all other subsequent reflections.

Line scans of the borehole wall are collected in intervals as small as 1 mm, and at a resolution as high as 288 pixels/revolution. The number of pixels per degree will depend on the diameter of the borehole. To collect images this detailed, the tool must be run very slowly (~1 m/min) however a slight decrease in quality (i.e. 2 mm intervals and/or fewer pixels/rev) can allow for a faster logging speed (~2-3 m/min).

The ATV's travel time image can be processed to build a 360° caliper of the borehole shape. This can then serve as a mesh around which the amplitude image can be draped to create a 3D image of the borehole. Features such as open fractures and washouts can be better visualized using this technique.

4.2 Optical Televiewer (OTV)

The **OTV** is designed for optical imaging of the surface of open or cased wells in air or clear water. The tool is equipped with a high sensitivity (charge-coupled device) CCD digital camera with Pentax optics. The stationary camera is located above a conical mirror which spins during logging and captures the reflection of the borehole wall. Light for the recording is provided by an LED ring of user configurable intensity depending on the color of the bedrock.

Line scans of the borehole wall are collected in intervals as small as 1 mm, and at a resolution as high as 1.25 pixels/degree. The number of pixels per degree will depend on the diameter of the borehole. To collect images this detailed, the tool must be run slowly (~1.5 m/min) however a slight decrease in quality (i.e. 2 mm intervals and/or fewer pixels/rev) can allow for a faster logging speed (~2-3 m/min).

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