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1.0 Introduction

Bedrock buried valley aquifers in the Canadian prairies constitute an important groundwater resource in Manitoba, Saskatchewan, and Alberta. These systems are a result of a combination of Tertiary (preglacial) river systems and Quaternary continental glaciations (subglacial and proglacial processes) that have contributed to the erosion, infill, and burial of most bedrock valleys (e.g. Betcher et al, 2007; Toop, 2010; Cummings et al., 2012).

This study focuses on an area extending south-east from the Brandon Hills in Manitoba, to the Manitoba-US border, where properties of the materials filling two buried valleys were measured *in situ*. South of Brandon, the preglacial Yellowstone-Missouri buried valley provides an important water supply for the town of Souris, MB. The Spiritwood buried valley is the largest and most significant of its kind in the region, and is estimated to extend at least 500 km south of Brandon, Manitoba, into South Dakota (Toop, 2010).

This Open File contains the results of the downhole geophysical logging conducted by the Geological Survey of Canada (GSC) in nine boreholes along the inferred lengths of the Spiritwood and Yellowstone-Missouri buried valleys. The boreholes were independently drilled by Manitoba Water Stewardship (MWS), the Town of Killarney, and the GSC. The objective of the surveys was to measure a range of chemical and physical properties of the subsurface materials, and compare these results to those of the surface and airborne geophysical surveys previously carried out in the region by the GSC. These geophysical datasets will ultimately contribute to the development of a 3D groundwater model of the Spiritwood buried valley, and an improved understanding of the geological characteristics of prairie buried valleys.

1.1 Previous GSC geophysical surveys in the Spiritwood buried valley

As part of its current Groundwater Geoscience Program (2009-2014), the GSC is investigating buried valley aquifers in Canada. In 2007, the GSC conducted an initial high-resolution seismic reflection survey within the Spiritwood buried valley in a comparison study with the Medora-Waskada and Pierson buried valleys (Pugin et al., 2009a,b; Pullan et al., 2012).

In 2010, additional geophysical surveys in the region of Killarney, MB were carried out, including an airborne electromagnetic (AEM) survey over a 1062 km^2 area, land-based resistivity, and high resolution seismic landstreamer surveys, to investigate the location and structure of the Spiritwood buried valley (Oldenborger 2010a, b, Oldenborger et al., 2012). Based on the successful results of these surveys, a location was chosen south of Cartwright, Manitoba, to drill a reference borehole (labeled GSC-BH-SW-07) for coring and downhole geophysical testing (Crow et al., 2012).

1.2 Boreholes logged as part of this study

The logging of GSC-BH-SW-07, and eight additional available boreholes in the study area, was carried out by GSC personnel from July 12 - 21, 2011. The boreholes are briefly described below, and locations of the sites are shown in Figure 1, along with the limits of the GSC airborne geophysical survey in the region of the Spiritwood buried valley.

Borehole	Owner	Date Logged	Easting (m)	Northing (m)	Maximum Depth Logged (m)	Geophysical Log Suite	Figure
GSC-BH-SW-07	GSC	July 12-14, 2011	478 604	5 429 101	97.0	Gam, Den, Cond, MagSusc, Temp, Vp, Vs	A-1
TH08-03	Town of Killarney	July 15,19, 2011	456 910	5 454 011	55.5	Gam, Den, Cond, MagSusc, Temp, Vp, Vs	A-2
TH08-02	Town of Killarney	July 16, 2011	457 405	5 452 472	58.0	Gam, Den, Cond, MagSusc, Temp	A-3
TH11-02		July 19. 2011	457 405	5 452 471	58.9	Cond, MagSusc	
DT-10-06 (Souris Gorge - East)	MWS	July 17, 2011	441 238	5 480 502	72.3	Gam, Den, Cond, MagSusc, Temp	A-4
DT-10-04 (Kent Lake)	MWS	July 18, 2011	438 672	5 487 029	22.3	Gam, Den, Cond, MagSusc, Temp	A-5
DT-10-02 (Lang's Valley)	MWS	July 20, 2011	441 234	5 482 172	68.3	Gam, Den, Cond, MagSusc, Temp	A-6
DT-10-05 (Yellowbrick)	MWS	July 18, 2011	440 247	5 488 575	35.5	Gam, Den, Cond, MagSusc, Temp	A-7
DT-10-15 (Brandon Hills)	MWS	July 20, 2011	434 125	5 508 340	62.8	Gam, Den, Cond, MagSusc, Temp	A-8

Table 1. Summary of borehole geophysical logging during the 2011 GSC field work. UTM coordinates are in zone 14 (NAD 83). MWS=Manitoba Water Stewardship. Gam=Natural gamma, Den=Gamma-gamma bulk density, Cond=Apparent conductivity, MagSusc=Magnetic susceptibility, Temp=Fluid temperature, Vp=Compressional wave velocity, Vs=Shear wave velocity.

GSC borehole GSC-BH-SW-07

The airborne and ground-based geophysical datasets collected in 2010 by the GSC provided necessary information to select potential locations for a high quality reference borehole in a prairie buried valley: a GSC "Golden Spike" (Sharpe et al., 2003; Russell et al., 2004; Logan et al., 2008; Knight et al., 2008; Medioli et al., 2012). A number of targets were chosen where overlapping seismic, resistivity, and AEM datasets indicated an incised bedrock valley, at a depth of approximately 100 m, was filled with sand and gravel and overlain by diamicton (glacial till). These sites would provide an opportunity to study the properties of the groundwater-bearing sands and gravels filling the incised valley, and the overlying fine-to-coarse grained sediments which fill the overlying broader valley. Details of the drilling, coring, downhole testing, and portable x-ray fluorescence (pXRF) measurements can be found in Crow et al. (2012) and Plourde et al. (2012).

The borehole was drilled to a depth of 97.54 m with a sonic drill rig in March of 2011. The outer diameter of the hole was 5.5", and was cased with 2.5" schedule 80 PVC pipe to a depth of 96.98 m. A PVC 20-slot screen was installed between 87.83 – 90.88 m. The annulus around the screen was filled with #75 industrial sand (Filter sil) from the base of the hole to 85.78 m, and the PVC was then grouted to surface with a mixture of bentonite grout (Enviroplug) and Portland cement.

The borehole encountered 13.45 m (84.09 – 97.54 m) of interbedded sand, gravel, and diamicton, in the base of a narrow incised valley. Sand and gravel layers include fining upward sequences with minor silt, and clay. This is overlain by 84.09 m (0.00 – 84.09 m) of poorly sorted-to-massive, very stiff, very dark grayish-brown stony diamicton with a silt-rich matrix containing angular to sub-angular carbonate and shale granules and pebbles.

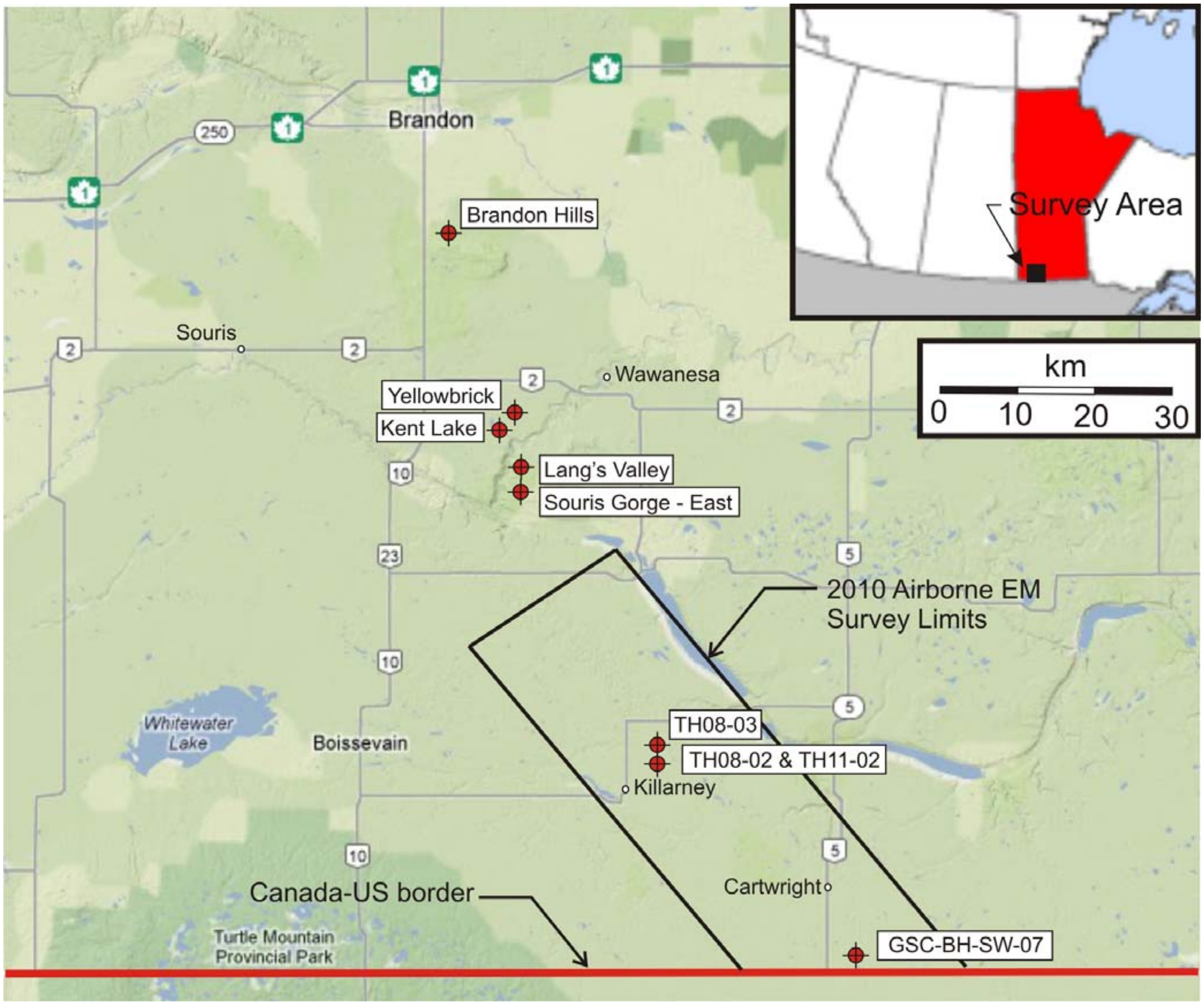

Figure 1. Location map of the boreholes logged by the GSC during downhole logging surveys in 2011 (map image from © 2012 Google).

Town of Killarney test holes TH08-02, TH08-03, and TH11-02.

The GSC was interested in collecting additional downhole geophysical logs within the limits of the airborne EM survey to permit comparison of *in situ*, surface, and airborne geophysical datasets. The Town of Killarney made available two of their monitoring wells which were drilled as test holes during the Killarney-Turtle Mountain Groundwater Assessment study in 2008. Cuttings are described in the driller's reports which are contained in Appendix A of the W.L.Gibbons report (2008).

Test well TH08-02 was drilled to a depth of 190' (57.9 m) but contains a stainless steel screen from 157' – 188' (47.8 – 57.3 m) which is tapered or sealed at its base, preventing advancement of the tools to the bottom of the hole. Therefore, the hole was logged to 57.3 m with the spectral gamma and temperature tools, but could only be logged to 157' (47.8 m) with the induction tools (conductivity, magnetic susceptibility), as readings cannot be taken inside a metal casing. The borehole has an outer diameter of 8" and is cased with a 5" PVC casing. Annular material was not described on the drilling records. TH08-03 was drilled to 354' (107.9 m) into shale bedrock but contains a stainless steel screen from 47.8 – 57.2 m preventing the tools from passing through to the base of the hole. Both boreholes were located on, or within 400 m of, a seismic reflection line collected by the GSC in 2007.

During the time of the logging work, a pilot test hole (TH11-02) was completed adjacent to TH08-02 which extended slightly deeper into the formation (61.3 m) but which didn't have a steel casing, permitting induction logging to the full depth of the hole. The drillers accommodated the testing by inserting a temporary 5" PVC pipe into the 7" diameter borehole.

Manitoba Water Stewardship (MWS) boreholes

In the fall of 2009, Manitoba Water Stewardship drilled a number of wells at 25 sites across the Spiritwood and Missouri-Yellowstone buried valleys. Wells which encountered aquifer materials (gravels and sands) were cased with a piezometer, or temporarily cased with 4.5" PVC for geophysical logging. Five of these wells were logged by the GSC during the 2011 field trip.

The boreholes have an outer diameter of 6.25" and the annular space between the casing and the formation was filled with extruded liquid bentonite. Stainless steel screens were installed in the Lang's Valley, Kent Lake, and Yellowbrick boreholes, and the Brandon Hills and Souris Gorge boreholes were cased with PVC to the base of the borehole. Cuttings were logged on site, and driller's logs are presented in an internal MWS report (Toop, 2009).

2.0 Field Work

2.1 Geophysical Logging

Downhole geophysical logs provide a means of identifying and characterizing lithological units based on variations in their chemical and physical properties. Logs also augment geological core logging by providing information on changes in the formations which cannot be observed in core, or where boundaries are uncertain due to the logging of cuttings.

The downhole techniques used in these surveys include gamma methods (spectral gamma and gamma-gamma density), induction methods (apparent conductivity and magnetic susceptibility), downhole seismic methods (compression (P) and shear (S) wave velocities), and fluid logging (fluid temperature). The suite of logs run in each borehole is shown Table 1. 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. The processed logs can be accessed in PDF and digital form in Appendix A, and a more detailed description of the tools can be found in Appendix B.

Data were acquired using a Mount Sopris logging system with a Matrix console and interchangeable downhole probes (Table 2), with the exception of the temperature and seismic logs. A laptop computer recorded the data using the Matrix Logger Software. The temperature log was collected in GSC-BH-SW-07 using an IFG Corporation fluid temperature tool and logging system due to the narrow size of the borehole casing. For the remaining boreholes, a GSC-developed temperature tool was run. Both tools have been calibrated by the GSC to sensitivities of ±0.005°C or better.

Laboratory calibrations were performed with the density and temperature tools before leaving for the field. Data are recorded in specially designed calibration blocks of 1.28 and 2.60 g/cm^3 (density probe) and temperature-monitored baths (temperature probe) to ensure the tools are working within specification. 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 range encountered in the ground). All logs were corrected for sensor offsets and casing stick ups, and recorded relative to the ground surface. Before logging, downhole water levels were measured and recorded.

The seismic surveys were carried out using a downhole receiver array and a source on the surface 5 m from the borehole collar. The cables were lowered by hand to the bottom of the hole, and pulled uphole at one metre spacings where readings were taken. In the case of compressional (P-) waves, data were obtained using a multi-channel hydrophone array (12 hydrophones at 1 m spacing) in the water-filled portion of the borehole and a small impulsive surface source with 8-gauge shotgun shells. Shear (S-) wave logs were obtained using a clamped, 3-component downhole receiver with 15 Hz geophones, and 16 lb sledgehammer striking a loaded I-beam surface plate as a source. 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 greater detail in Hunter et al. (1998).

3.0 Data Processing

All log data were imported into WellCAD software for processing and interpretation. As logs were depth corrected in the field, shifting was not required. Induction logs were cut off inside metal surface casings and stainless steel screens, but were otherwise unaltered. Upward and downward runs were overlaid to check for temperature drift and ensure repeatability.

Natural gamma total count data were converted to weight percent potassium (K), uranium (U), and thorium (Th) using calibration curves developed at the USGS calibration facility in Denver, Colorado. Due to the very low number of counts in each of these energy windows (generally 2 or less), the calculated weight percent (%) values were not considered statistically significant, and natural gamma data were therefore only displayed as total counts.

The gamma-gamma bulk density tool is composed of a 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 calibrations conducted in the GSC lab with pure blocks of Lucite (1.28 g/cm^3) and aluminum (2.60 g/cm^3). In ideal conditions, the detectors and source are in direct contact with the formation in an uncased borehole. When the tool passes over a void space in the borehole wall (caused by a fracture or wash out), the difference between the near and far detector counts are used to compute a compensation correction over the interval. This correction is based on compensation curves determined for this tool at the US Geological Survey (USGS) downhole calibration facility in Denver Colorado. In cased overburden boreholes where annular material and the PVC casing create a gap between the casing wall and the formation, the compensation calculation overcompensates for the difference between the counts recorded at the two sensors. In these conditions, the far detector produces a more reliable density estimate, as it measures backscattered energy travelling further into the formation. Therefore, the density logs presented in this report are based on the counts recorded by the far detector, with the difference between the near and far detector densities providing a plus/minus range to take into account the annular gap. Where the densities dropped to low levels (less than ~1.6 g/cm^3), it was inferred that the borehole wall was enlarged behind the casing, and these zones are identified on the log figures.

Downhole Geophysical Log ***[Manufacturer]***	**Logging Unit**	**Radius of Investigation** ***[Vertical resolution]***	**Logging Speed**	**Logging Interval**	**Practical interpretations in unconsolidated sediments**
Spectral Gamma *[Mount Sopris]*	Counts per second (cps)	0.3 - 0.6 m *[centimetres, function of logging speed]*	1m/min	0.01 m	Relative grain-size; lithology
Gamma-gamma Density (Cs-137 source) *[Mount Sopris]*	g/cm^3	0.10 – 0.20 m *[centimetres, function of logging speed]*	1 m/min	0.01 m	Density (when casing is coupled with formation); lithology
Apparent 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); lithology
Magnetic Susceptibility *[Geonics/Mount Sopris]*	parts per thousand SI (ppt SI)	0.3 m *[submetre]*	3 m/min	0.02 m	magnetite (magnetic mineral) concentration; lithology
Temperature *[IFG Corp, GSC]*	Frequency, converted to degrees Celsius (°C)	Influenced by surrounding materials *[logging interval]*	1 m/min	0.01 m	lithology (as related to thermal conductivity); anomalies due to groundwater flow (from gradients)
Compressional Wave *[downhole hydrophone]*	m/s	Wavelength-dependent (metre scale) *[metre scale]*	N/A (tools raised by hand between shots)	1.00 m	variation in lithology, relative compaction, identification of reflecting horizons
Shear Wave *[Geostuff Downhole 15 Hz triaxial Geophones]*	m/s				

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

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), after correction for time zero errors had been applied using recordings from a surface geophone. 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.

Logs were interpreted as a complete suite to 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-8.

4.0 Interpretation

4.1 Stratigraphic observations

Based on a review of the three sources of borehole lithological descriptions (GSC, MWS, and drilling reports from the Killarney test wells), six basic material types were described in each of the holes, although they were described using different terms. Broadly, these horizons are:

'Upper' diamicton: The upper-most horizon consists mainly of interbedded diamicton with lenses of fine to coarse sand and gravel, forming near surface aquifers. It ranges in color from **brown** (oxidized, above water table) to dark **grey** (below water table) with a sandy to clayey matrix. The GSC has labelled this Unit D in their analyses of core from GSC-BH-SW-07.

'Lower' Diamicton: This horizon is a very dark gray, stony diamicton with clay rich matrix containing angular to sub-angular carbonate and shale granules and pebbles. This unit generally does not contain the sandy lenses which make up the near surface aquifers, and tends to be very stiff. The GSC has labelled this horizon Units B & C. B tended to be less stony than C.

Sands: Sands were either described as intervals within the upper diamictons (in which case they could contain a silty matrix), or clean sands (as in GSC-BH-SW-07, where it was found in the base of a narrow incised valley).

Gravels: Gravels were more commonly encountered in the lower depths of the boreholes, deposited in incised channels, or directly above the bedrock. The gravels could range from sub-angular to sub-rounded pebbles (2-50 mm) of carbonate and shale, to limestone, shale, coal, quartz, and agate of the Souris gravels and sands.

Bedrock: Bedrock underlying the study region is known to be the shale of the Pierre Formation (Odannah Member). It is typically hard and dark grey, but weathered at the bedrock surface. Borehole tools only reached bedrock in one of the holes.

4.2 Quantitative analyses

Stratigraphic type was interpreted based on the responses of all the logs in the suite, along with a review of the available lithological information. Boundaries between the different horizons were inserted into the "Geophysical Interpretation" column, and the average log value and standard deviation within each depth range were computed using the log processing software. The ranges of average values for the apparent conductivity, magnetic susceptibility, and bulk density logs in each of the material types are presented in Figures 2, 3, and 4, and Table 3. These logs were chosen as they contain quantitative, calibrated values which could assist in the inversion of the airborne survey dataset, and development of the ground water model. Natural gamma is not presented, as count levels vary from tool to tool (unless they are calibrated to API standards in the US, which this tool is not).

During the analyses, there were occasional outliers from the range of average values in each material type. These are shown on the figures as light grey lines, and labeled with the borehole name.

4.2.1 Conductivity

Apparent conductivities range between 35 – 250 mS/m and ranges in each material type are shown in Figure 2. Brown-colored diamictons (generally found in the top ~10 meters of the ground surface) are so colored because they are oxidized above the water table, not fully saturated, and therefore tend to be slightly lower in conductivity. Where the tool enters more saturated conditions in the grey diamicton, the conductivities tend to rise, although there is significant overlap between the two units, meaning there is not a strong distinction between the conductivities of the brown and grey diamictons.

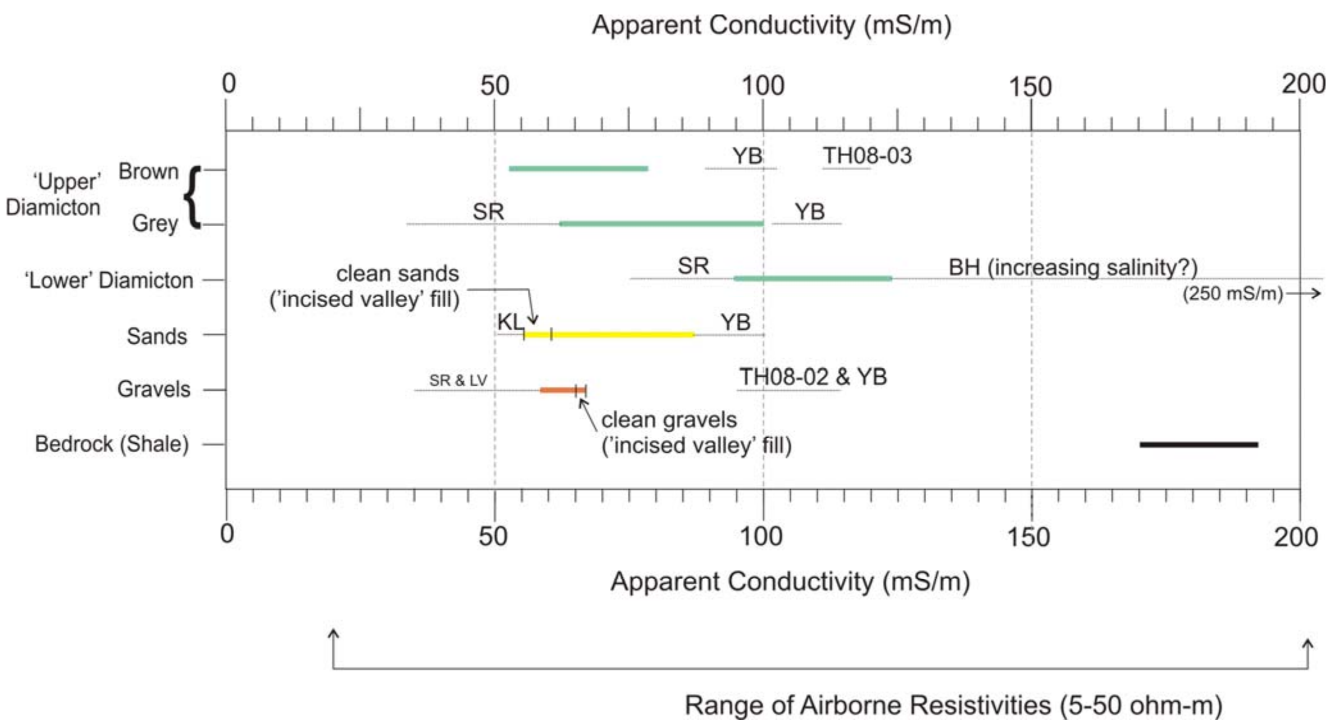

Figure 2 – Ranges of apparent conductivities measured downhole in the study area. Outlying ranges from labelled boreholes are marked with a grey line (SR=Souris Gorge, LV=Lang's Valley, BH=Brandon Hills, KL=Kent Lake, YB=Yellowbrick). Color bars are based on the GSC standard surficial geology legend.

Conductivities are more elevated in the lower diamicton than the upper, where the material tends to be free of sand and gravel layers, and contains a more homogenous silty/clayey matrix. Conductivity response does not indicate porewaters are saline (<~125 mS/m), save possibly in the Brandon Hills borehole, where conductivities rise to 250 mS/m. There is only slight overlap between the conductivity ranges of the 'upper' and 'lower' diamictons, making it possible to differentiate between the sand-bearing upper units and the more homogenous lower unit with the conductivity tool.

Clean sands and gravels in these boreholes exhibit lower conductivities than the diamictons which contain a fine-grained silty-clayey matrix. However, when the sands/gravels are hosted within the diamicton (as inter-diamicton aquifers) or contain small amounts of fine grained matrix, the conductivity response increases. In Figure 2, overlap exists between the conductivity ranges of the 'sands' and the 'upper diamicton' where the materials are interbedded. Because of the large volume of investigation of the conductivity tool, lenses of sand and gravel of less than a meter in thickness tend to produce a reduced, smoothed conductivity response. 'Clean' sands and gravels (found here in narrow incised valley deposits or above the bedrock surface) have lower conductivities because they tend to lack fine grained matrix.

Bedrock is accessible only in the bottom 5 m of the East Souris Gorge borehole, where conductivities are found to be elevated (181 ± 11 mS/m) relative to the other materials deposited above. This implies that materials, such as the sands and gravels, are not composed entirely of shale.

Marked at the base of Figure 2 is the range of resistivities (inverse of conductivities) in the airborne survey dataset. There is agreement in the ranges of the two datasets when the outliers in the low end of the conductivity range are considered (Lang's Valley and East Souris Gorge boreholes).

4.2.2 Magnetic Susceptibility

Magnetic susceptibilities in all materials are very low (<5 ppt SI, Figure 3a), and the responses in the diamicton units are indistinguishable from one another. In the MWS boreholes to the north of the airborne survey area, the Souris sands and gravels are also very low in also susceptibility, indicating little to no presence of Shield materials. The clean sands and gravels in the narrow incised valley (GSC-BH-SW-07) do have a relatively increased response (Δ2 ppt SI) which can be differentiated from the other materials, but the response is still very low (<5 ppt SI). This suggests the clean sands and gravels do not come from an igneous (i.e. Canadian Shield) source, but are sedimentary or carbonate in origin. The bedrock, being very fine grained, weathered, shale is similarly very low in magnetic susceptibilities.

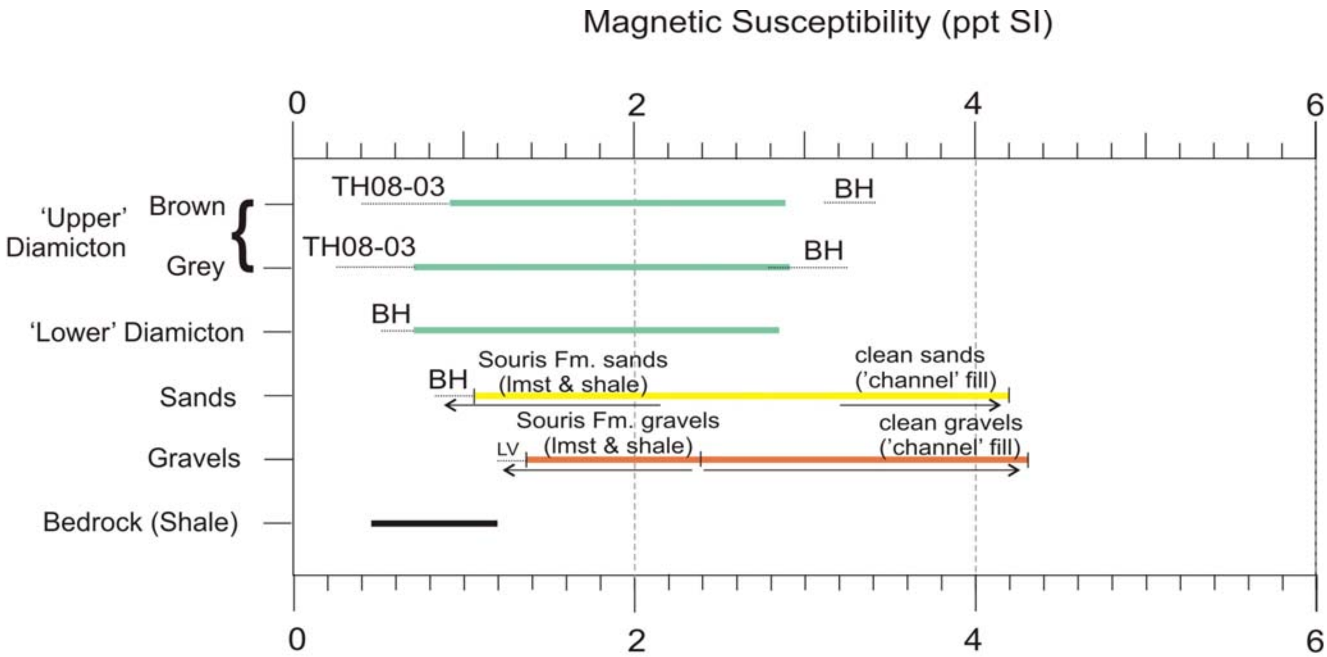

Figure 3a - Ranges of magnetic susceptibilities measured downhole in the study area. Outlying ranges from labelled boreholes are marked with a light grey line (BH=Brandon Hills). Colour bars as per Figure 2.

To illustrate how low the range of magnetic susceptibility readings are in this study, Figure 3b presents measurements made at various other locations in Canada by the GSC using the same type of tool as was used for this survey.

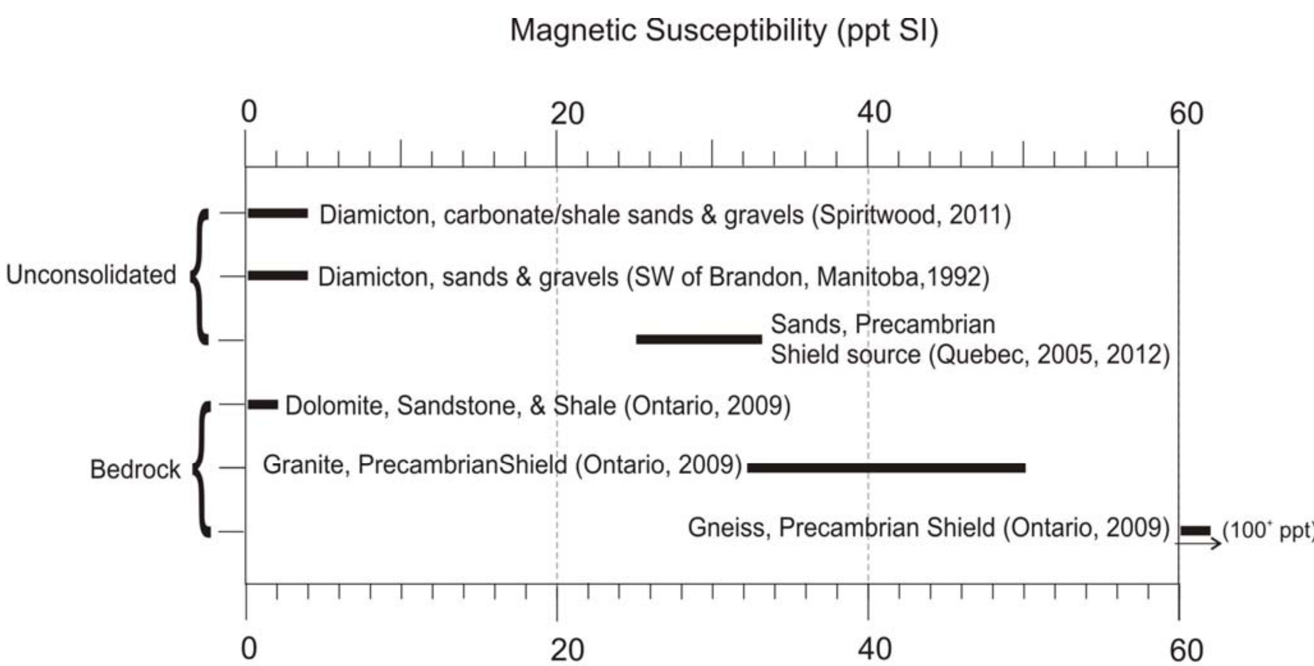

Figure 3b – Range of magnetic susceptibilities in Canadian environments measured by the GSC using the same type of calibrated downhole instrument, illustrating the range in susceptibilities measured when Precambrian granites and gneisses are present.

4.2.3 Bulk Density

The densities measured in the sands and gravels of the incised narrow valley (borehole GSC-BH-SW-07) were the most elevated among all nine boreholes (Figure 4). Lower density sands and gravels (which overlap with diamicton density ranges) likely incorporate lower density matrix material. In Lang's Valley and Souris Gorge boreholes, low density zones in the Souris gravels just above the piezometric water level are attributed to unsaturated conditions, although these results will be further interpreted in a subsequent publication.

Bulk density measurements are strongly influenced by variability in the completion around the borehole, and should be interpreted with other logs to look for indications of borehole wall enlargement behind the PVC. Enlargements in the wall filled with grout (and possibly poorly coupled) is likely the cause of the low density intervals (circled in Figure 4) in the diamictons. These zones occur in, or just beneath, fine grained intervals (often described as clay, and accompanied by an increase in natural gamma counts). Although soft zones were found in the core from GSC-BH-SW-07, a density of less than 1.6 g/cm^3 is not expected in the diamictons based on density calculations made from water content measurements of the core samples (Crow et al., 2012).

Densities in the shale (1.87 – 1.93 g/cm^3) suggest weathered conditions exist at the bedrock surface, as lab values for shale cores average 2.4 g/cm^3 with a range of 1.77 – 3.2 g/cm^3 (Telford et al., 1995).

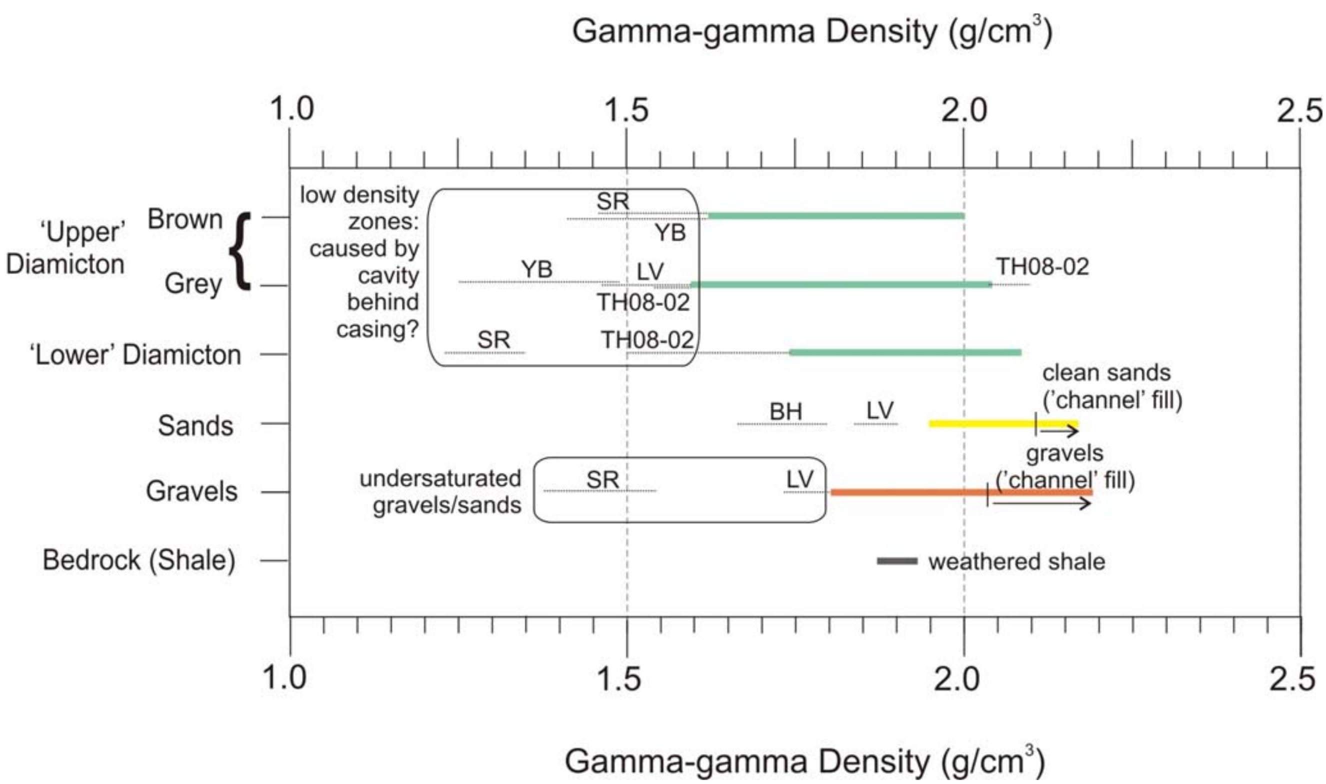

Figure 4 - Ranges of average bulk densities measured downhole in the study area. Outlying ranges from labelled boreholes are marked with a light grey line (SR=Souris Gorge, LV=Lang's Valley, BH=Brandon Hills, KL=Kent Lake, YB=Yellowbrick). Colour bars as per Figure 2.

4.3 Regional continuity of stratigraphy

The heterogeneous nature of the glacial deposits in the study area meant that prominent regional marker beds weren't observed in the logs. As seen, basic unit types share similar ranges of geophysical responses, but exceedances of these ranges occur in some boreholes, demonstrating local variability in the materials. Diamictons bearing sand and gravel layers were present throughout the region, in varying thicknesses, overlying a more uniformly massive diamicton which did not contain detectable sand and gravel units. Only in the northern-most end of the region did this unit have an elevated conductivity (>125 mS/m, Brandon Hills borehole).

Certain signatures are present in similar stratigraphic and depth settings at sites separated by 1 to 2 kms. In the TH-series boreholes outside Killarney, similarities in temperature logs within a near surface sand and gravel layer were observed (Figure 5). This may imply some recharge of warmer surface waters is occurring in near surface (inter-diamicton) aquifers.

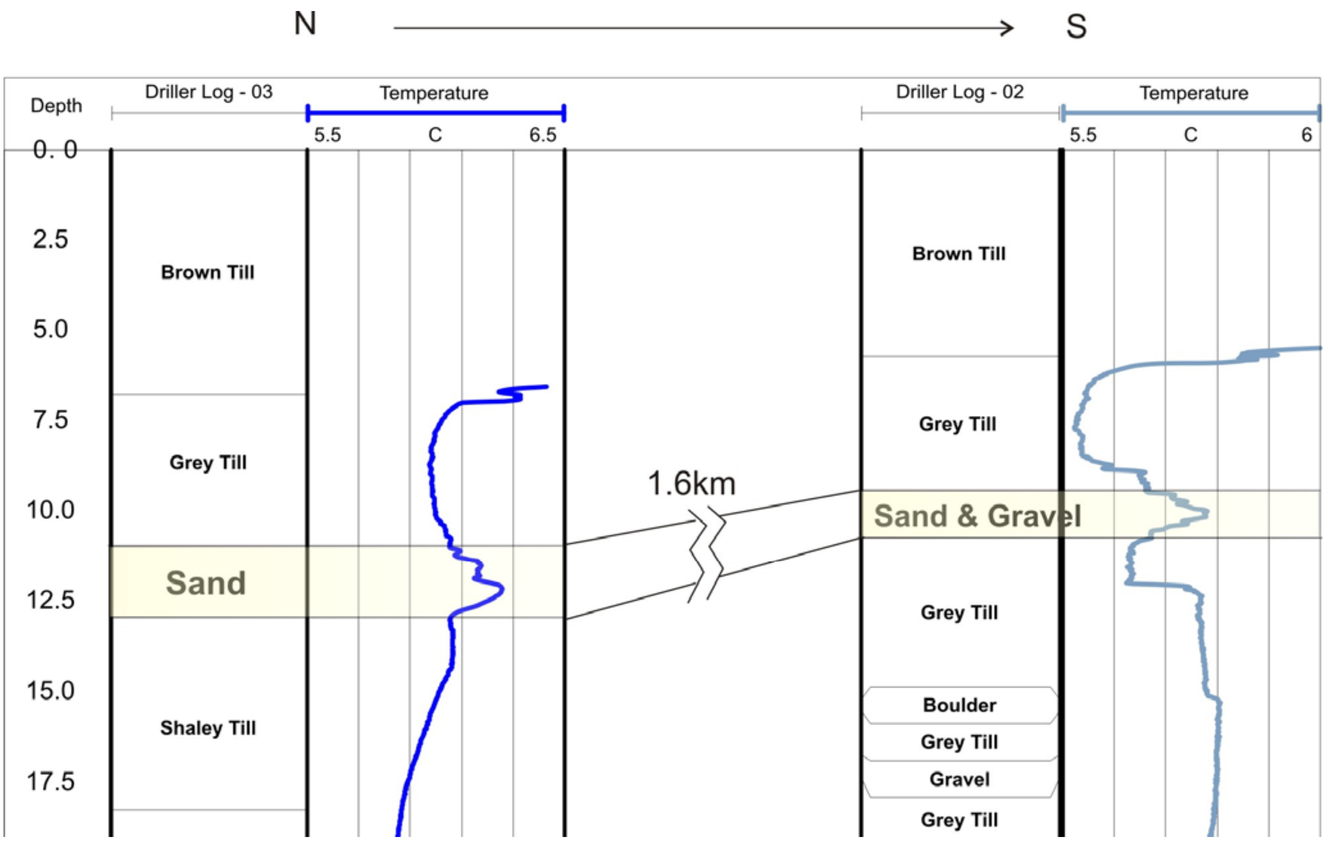

Figure 5 – Correlation of temperature response in a near-surface sandy-gravel aquifer between boreholes TH08-02 and TH08-03.

5.0 Summary

Geophysical logging was performed in nine PVC-cased boreholes located in southwestern Manitoba to investigate the chemical and physical properties of sediments filling two prairie buried valleys. Common ranges of apparent conductivities, magnetic susceptibilities, and bulk densities were interpreted within six basic stratigraphic units encountered in the boreholes (Table 3).

The natural gamma tool was effective in indentifying variation in stratigraphic units and provided otherwise unobtainable information on subtle upward fining or coarsening trends. The active gamma-gamma tool provided bulk density estimates within the materials. However, this tool is very sensitive to variations in the annular region of the borehole (separation between the casing wall and the formation), resulting in a larger uncertainty in density measurements than in open boreholes where the tool is in direct contact with the formation wall. Applications of the bulk density log, including computing estimates of the porosity and saturation in overburden materials (and assignment of error ranges to these calculations), is a topic of future research at the GSC.

Stratigraphic Unit	Apparent Conductivity (mS/m)	Magnetic Susceptibility (ppt SI)	Bulk Density (g/cm^3)	# Boreholes Encountering Unit
Upper Diamicton – Brown	50 – 80	0.9 - 2.9	1.62 – 2.00	7
Upper Diamicton – Grey	60 - 100	0.7 - 2.9	1.60 - 2.04	8
Lower Diamicton – Grey	80 - 125 - 250 (BH)	0.7 - 2.8	1.74 - 2.08	8
Sand incised valley inter-diamicton units	 55 – 60 60 - 90	 3.2 – 4.2 1.1 - 3.8	 2.12 - 2.17 1.95 – 2.12	 1 6
Gravel incised valley other (incl. Souris Grav.)	 65 – 70 60 - 65	 2.4 – 4.3 1.4 – 2.7	 2.01 - 2.19 1.80 – 2.05	 1 6
Bedrock (Shale, weathered)	170 - 195	0.4 - 1.2	1.87 – 1.93	1

Table 3 – Ranges of average downhole geophysical response measured in each of the stratigraphic units. BH=Brandon Hills borehole.

Electrical properties of the formations were measured using calibrated induction tools, producing readings which are averaged over a large bulk volume, ‘seeing’ beyond the annular region of the borehole into the formation. The apparent conductivity response was most effective at distinguishing between the diamicton units, and the magnetic susceptibility was particularly effective at identifying the presence of sand and gravel within the diamicton units. The very low magnetic susceptibility readings in the sands and gravels suggest a carbonate provenance (see Figure 3b).

The use of a high-resolution temperature tool was very effective inside the casing to identify where groundwater was flowing in sand and gravel layers within the diamictons (see Figure 5). This technique could be used to infer where near-surface aquifers have a rapid recharge connection to the ground surface.

Downhole P- and S-wave velocities were computed in two boreholes to assist in the calibration of surface seismic profiles collected in previous years by the GSC (Pugin et al., 2009a,b; Pullan et al., 2012). The heterogeneous nature of the sediments was particularly evident in the seismic logs as the velocities are quite variable in the thick sequences of diamicton.

The acquisition of geophysical logs provides a method of gathering more physical/chemical/lithological information than with cuttings or core logging alone. The logs allow for a refinement of the stratigraphic unit boundaries, and provide further information on the hydrogeological properties of the materials. The analyses of the logs indicate that the induction and bulk density logs provide useful, quantitative information which can be used to distinguish between broad lithological units found in two buried valleys in southwestern Manitoba. This information, along with other GSC geophysical datasets, will contribute toward the 3D groundwater modeling of the Spiritwood buried valley.

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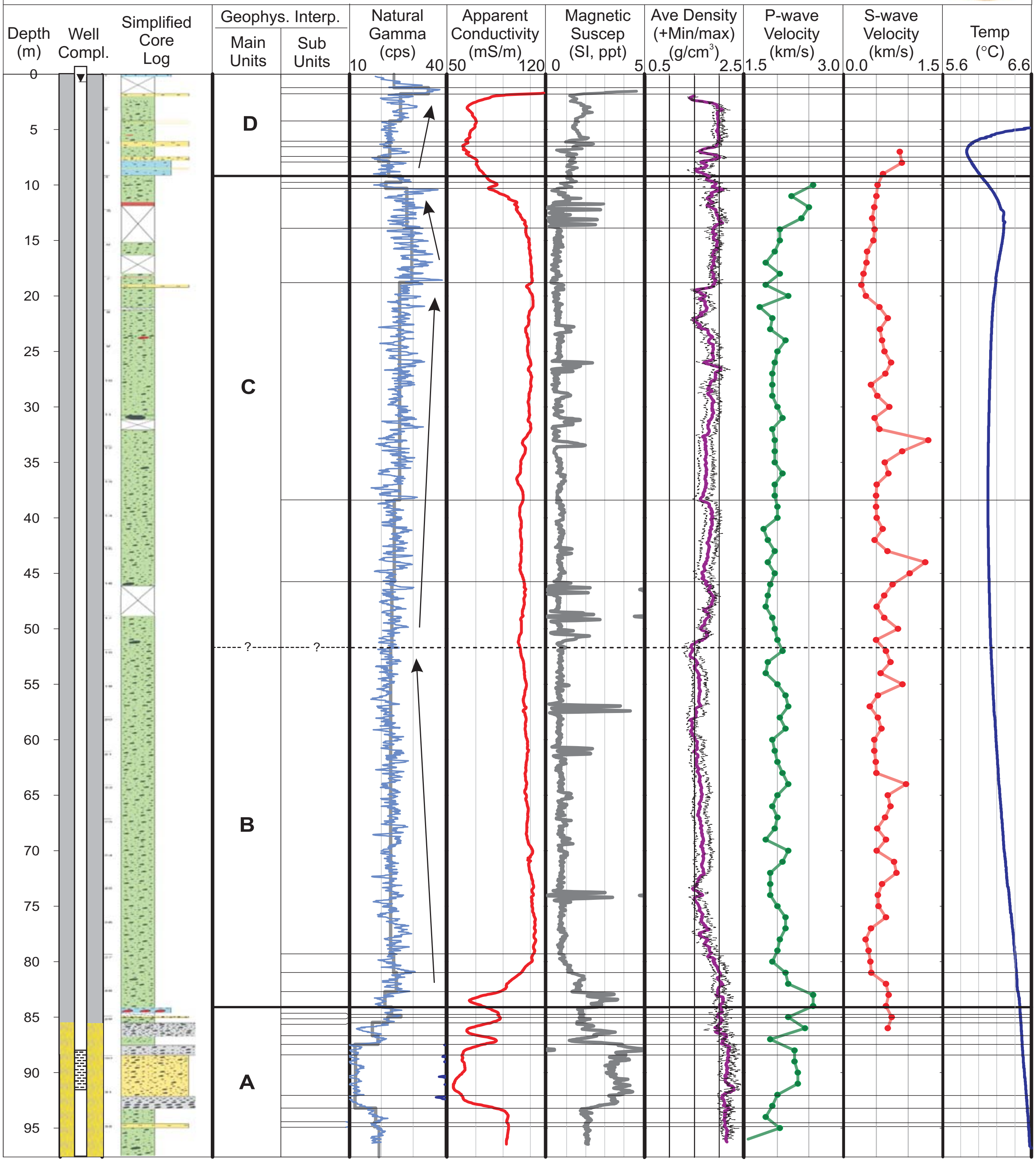
Appendix A

Downhole Logs

Borehole:	GSC-BH-SW-07	Easting:	478 604 m	Date Drilled:	March 17-24, 2011	Date Logged: July 12-13, 2011	
Location:	Cartwright, MB	Northing:	5 429 101 m	Depth Drilled:	97.54 m	Piezometric water	
Project:	Aquifer Assessment	UTM Zone:	14	Method:	Sonic	level: 0.68 m bgl	
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	5.5", 2.5" casing		



Completion Detail

- 2.5" Schedule 80 PVC
- Grout
- 20-slot Screen
- Filter Sand

Core Log

- Silt
- Diamicton
- Sand
- Gravel

Geophysical/Geological Interpretation

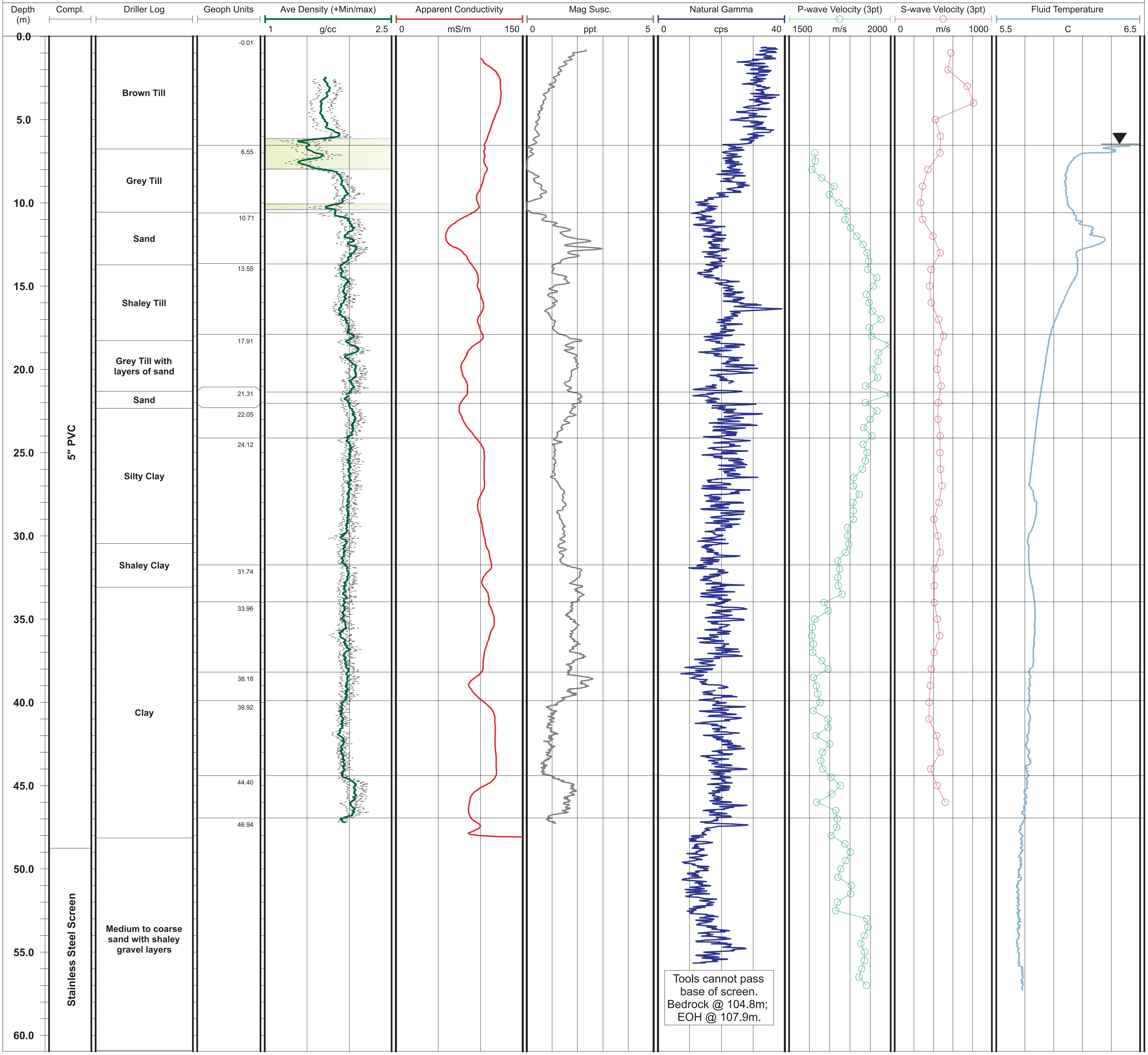
- Primary Unit Boundary
- Uncertain Unit Boundary
- Sub-unit Boundary
- Upward Fining
- Upward Coarsening

Note

Borehole record originally presented in GSC Open File 7079.

Figure A-1

Borehole:	TH08-03	Easting:	456 910 m	Date Drilled:	Oct 20, 2008	Date Logged:	July 15, 2011
Location:	Kilarney, MB	Northing:	5 454 011 m	Depth Drilled:	200 ft (60.96 m)	Piezometric Water Level:	6.55 m bgl
Project:	Aquifer Assessment	UTM Zone:	14	Method:	-		
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	8", 5" PVC		

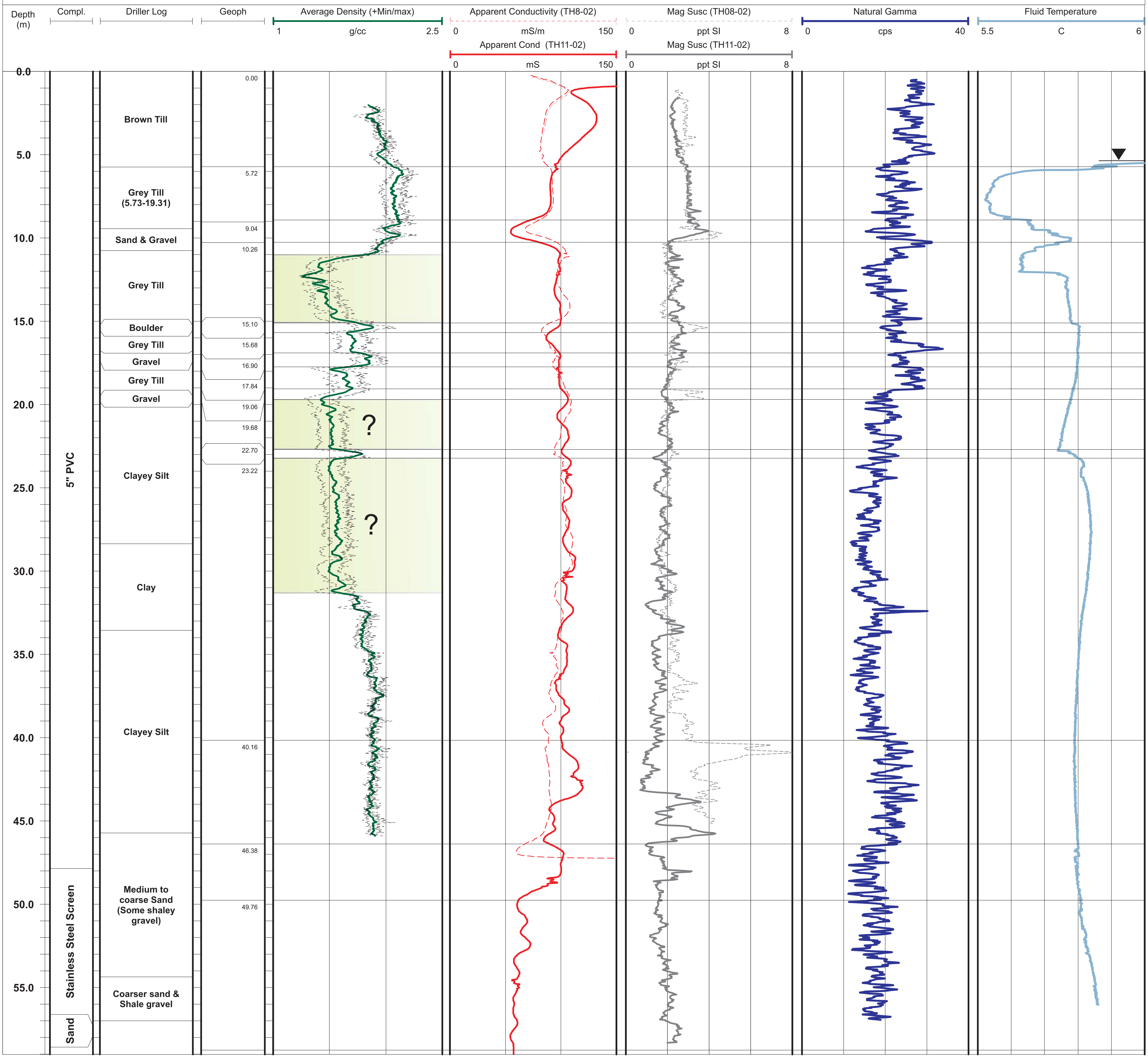


Note

Interval of interpreted enlargement in borehole wall

Figure A-2

Borehole:	TH08-02 / TH11-02	Easting:	457 405 m	Date Drilled:	Oct 17, 2008	Date Logged:	July 16, 2011
Location:	Kilarney, MB	Northing:	5 452 472 m	Depth Drilled:	190 ft (57.9 m)	Piezometric	
Project:	Aquifer Assessment	UTM Zone:	14	Method:	-	Water Level:	5.39 m bgl
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	8", 5" PVC		

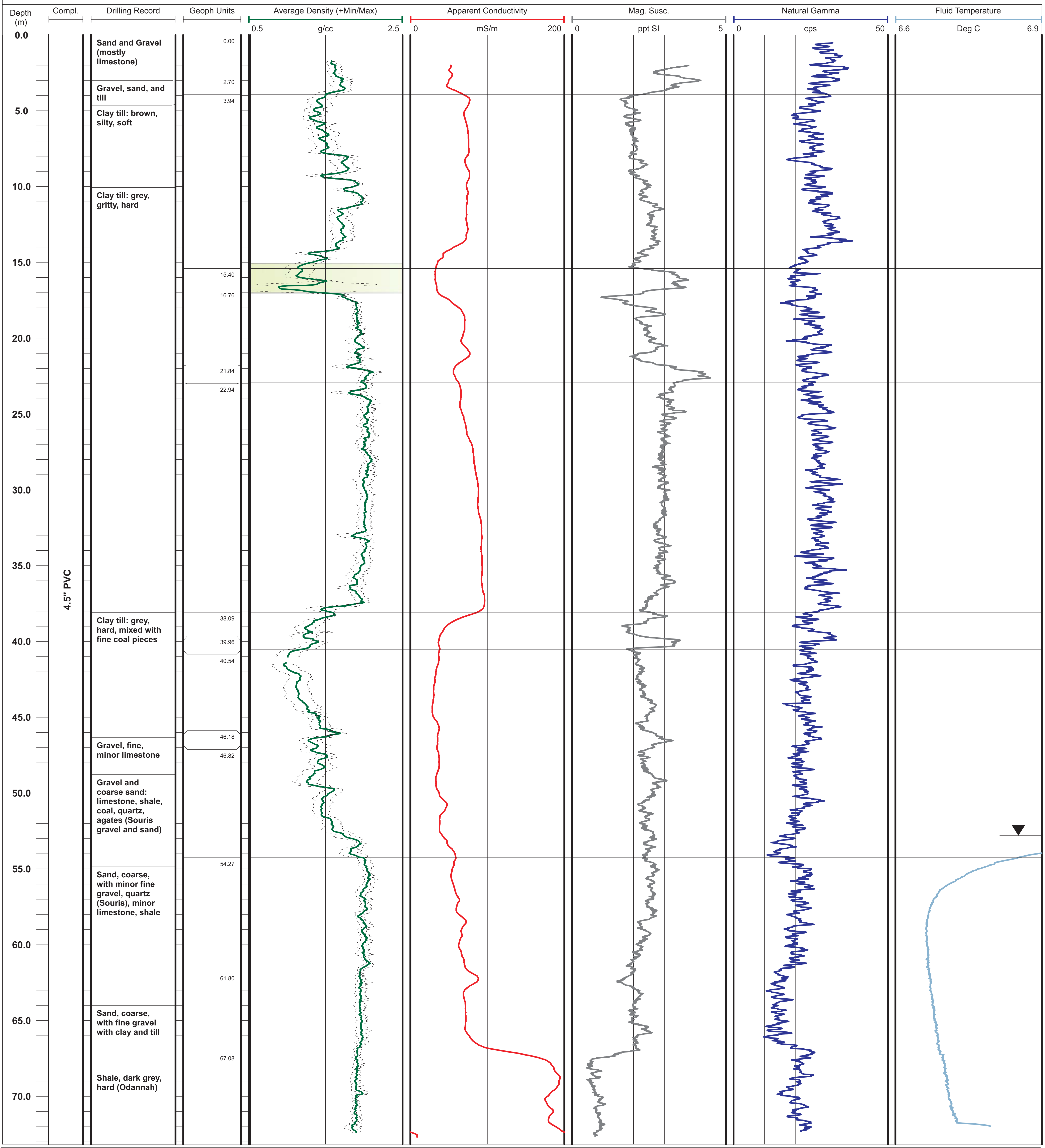


Note

Interval of interpreted enlargement in borehole wall

Figure A-3

Borehole:	DT-10-06 Souris Gorge - E	Easting:	441 242 m	Date Drilled:	Oct 6, 2009	Date Logged:	July 17, 2011
Location:	Brandon, MB	Northing:	5 480 502 m	Depth Drilled:	240 ft (73.15 m)	Water Level:	52.92 m bgl
Project:	Aquifer Assessment	UTM Zone:	14	Method:	Mud rotary		
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	6.25", 4.5" PVC		

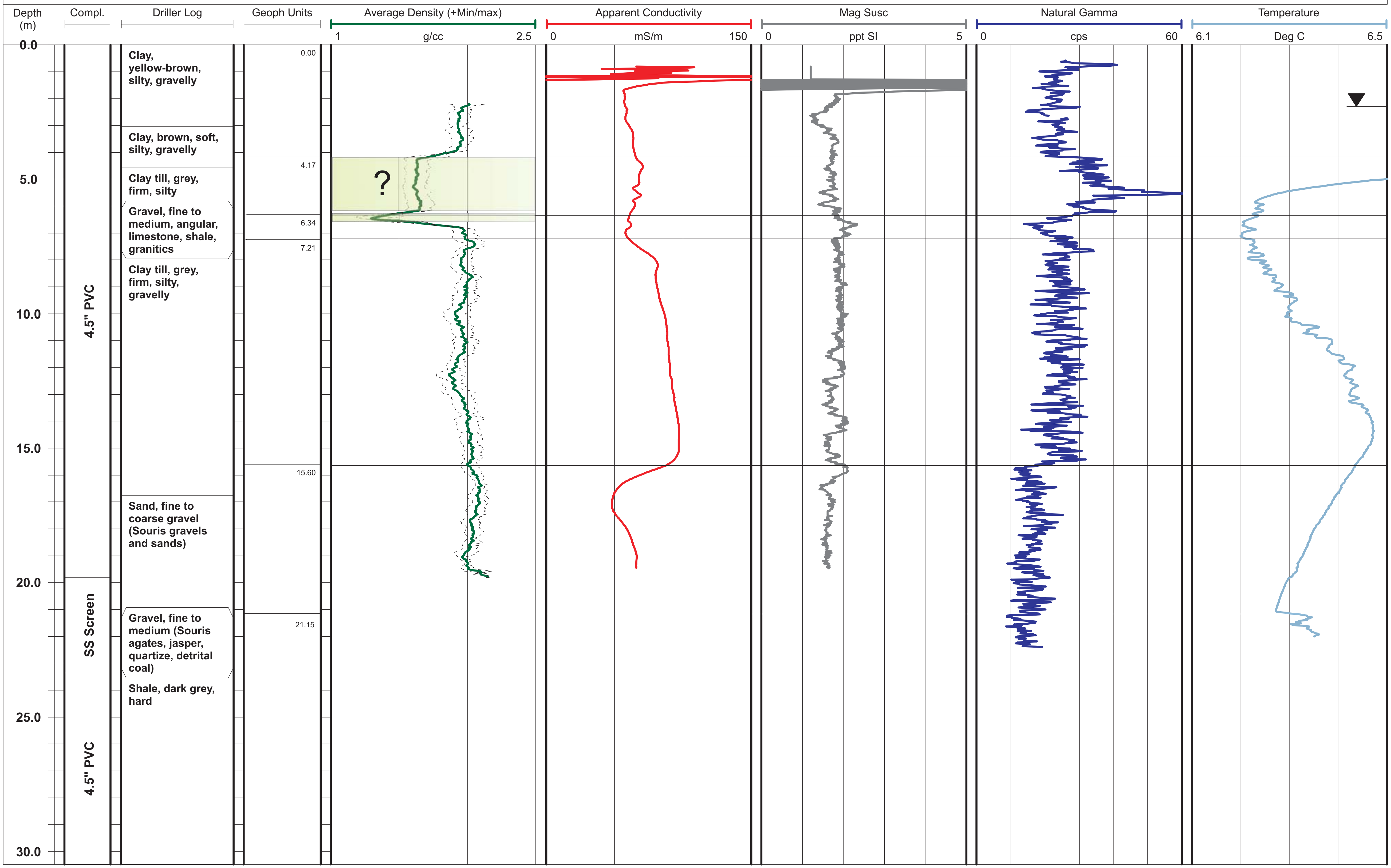


Note

Interval of interpreted enlargement in borehole wall

Figure A-4

Borehole:	DT-10-04 Kent Lake	Easting:	438 672 m	Date Drilled:	Oct 4, 2009	Date Logged:	Jul 18, 2011
Location:	Brandon, MB	Northing:	5 487 029 m	Depth Drilled:	100 ft (30.48 m)	Piezometric	
Project:	Buried Valleys	UTM Zone:	14	Method:	Mud rotary	Water Level:	2.32 m bgl
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	6.25", 4.5" PVC		



Note

Interval of interpreted enlargement in borehole wall

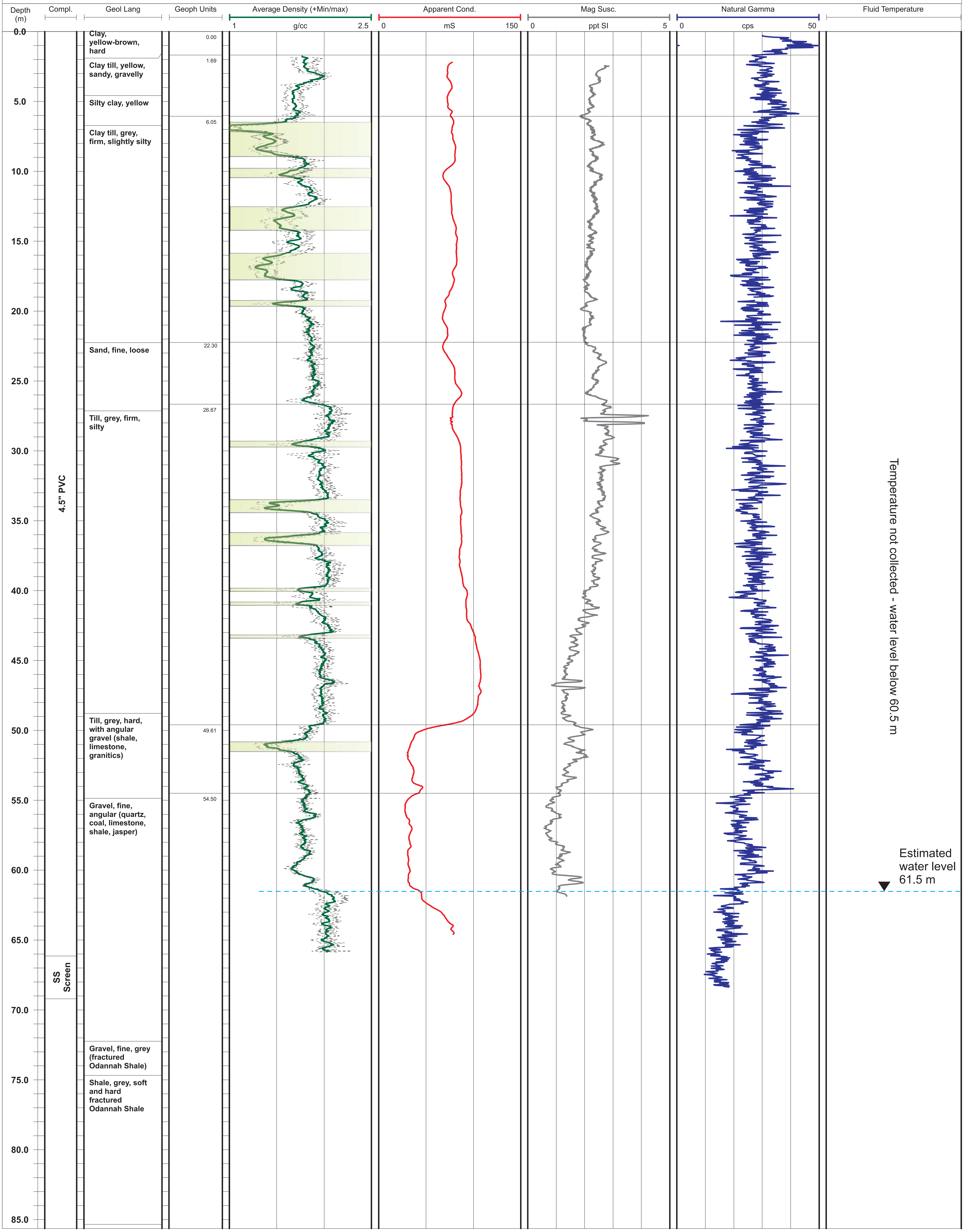
Figure A-5

Borehole: DT-10-02 Lang's Valley
Location: Brandon, MB
Project: Buried Valleys
Study Area: southwest Manitoba

Easting: 441 242 m
Northing: 5 482 037 m
UTM Zone: 14
Datum: WGS84

Date Drilled: Oct 02, 2009
Depth Drilled: 85.33 m
Method: Mud rotary
Diameter: 6.25", 4.5" PVC

Date Logged: July 20, 2011
Piezometric
Water Level: estimated 61.5 m



Note

Interval of interpreted enlargement in borehole wall

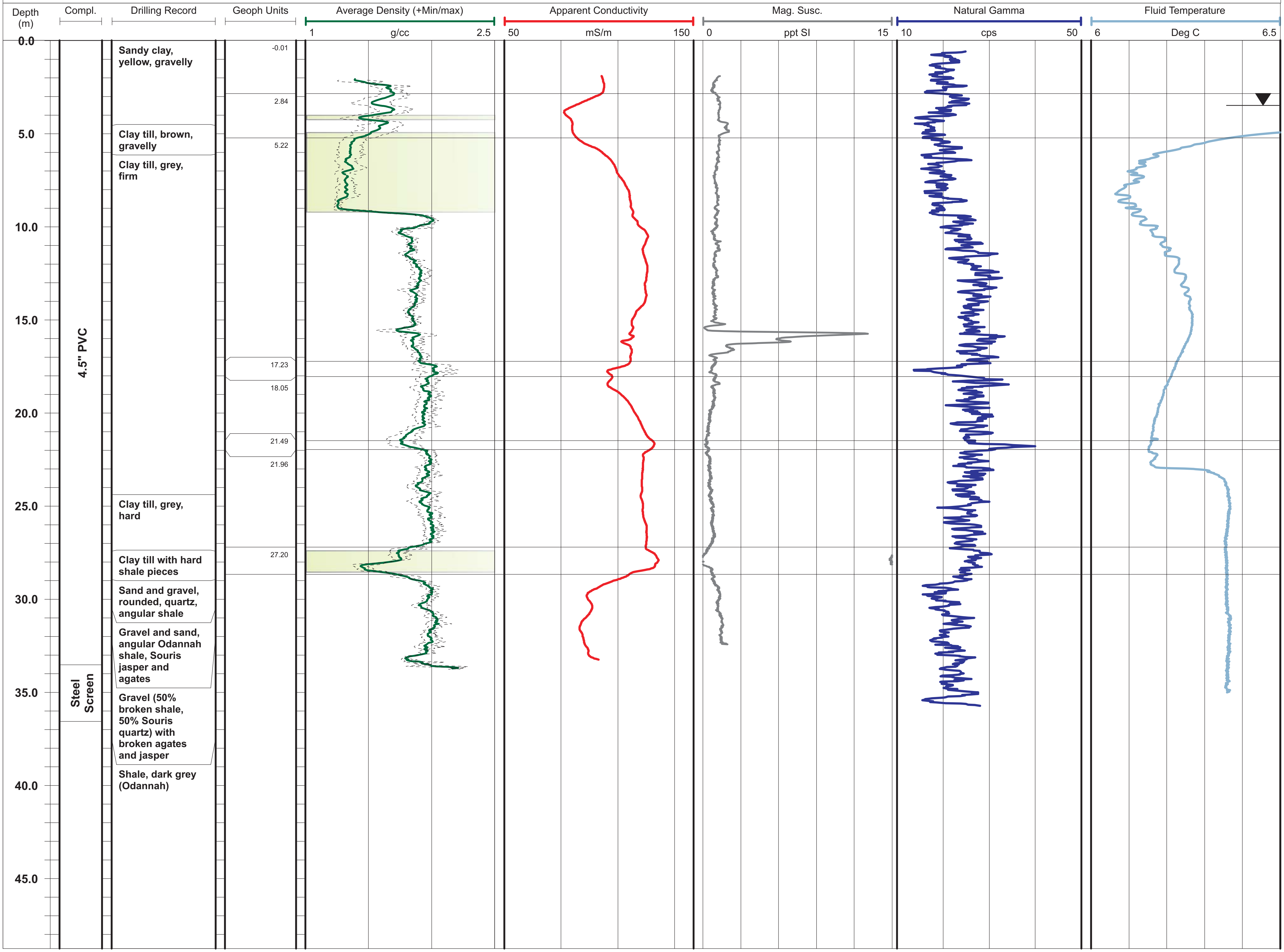
Figure A-6

Borehole: DT-10-05 Yellowbrick
Location: Brandon, MB
Project: Aquifer Assessment
Study Area: southwest Manitoba

Easting: 440 247 m
Northing: 5 488 575 m
UTM Zone: 14
Datum: WGS84

Date Drilled: Oct 5, 2009
Depth Drilled: 160 ft (48.8 m)
Method: Mud rotary
Diameter: 6.25", 4.5" PVC

Date Logged: July 18, 2011
Piezometric Water Level: 3.51 m bgl

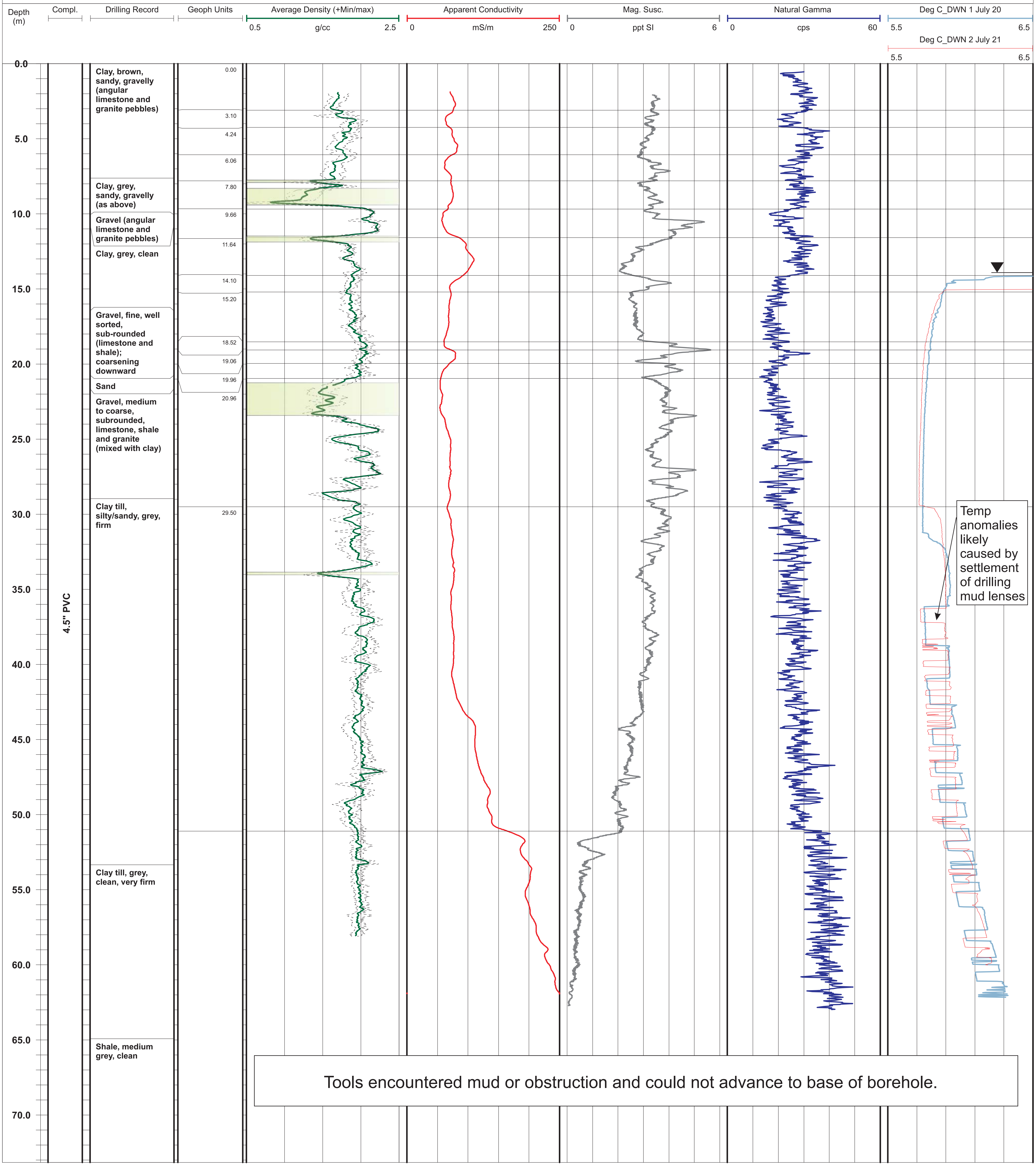


Note

Interval of interpreted enlargement in borehole wall

Figure A-7

Borehole:	DT-09-15 Brandon Hills	Easting:	434 125 m	Date Drilled:	Sept 15, 2009	Date Logged:	July 20/21, 2011
Location:	Brandon, MB	Northing:	5 508 340 m	Depth Drilled:	240 ft (73.15 m)	Water Level:	14.05 m bgl
Project:	Aquifer Assessment	UTM Zone:	14	Method:	Mud rotary		
Study Area:	southwest Manitoba	Datum:	WGS84	Diameter:	6.25", 4.5" PVC		



Note

Interval of interpreted enlargement in borehole wall

Figure A-8

Appendix B

Geophysical Logging Methods

B-1 Gamma Methods

Natural gamma logging detects the presence of naturally occurring or man-made radioactive isotopes. The most common natural 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. 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 at downhole calibration facilities.

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 soil 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 more present 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.

Gamma-gamma density logging uses an artificial gamma source (Cs^{137}) to bombard the formation with gamma rays. Two shielded detectors on the tool at near (20 cm) and far (35 cm) points from the source are used to measure formation response. Radiation from the source travels into the formation and is backscattered by a process called Compton scattering, where gamma radiation interacts with electrons in the formation. This means that electron density is measured rather than bulk density. As with the passive gamma log, the detector response is recorded in terms of counts, which are converted to 'near' and 'far' densities using a calibration procedure performed in the lab using two pure blocks of known density (1.28 and 2.60 g/cm^3).

In open boreholes where the detectors and source are ideally in contact with the formation wall, the near and far detector densities are compensated using compensation curves determined individually for the tool at the USGS downhole calibration facility in Denver Colorado. This takes into account the variability of the borehole wall and any mudcake which may be present on the borehole wall. In cased boreholes where the formation is separated from the casing wall by an annular region which is generally filled with a grouting or backfilled material, the calculation of density becomes increasingly more complicated. The compensation correction tends to overcompensate in these conditions leading to an overestimation of formation density. In these cases, the far density detector, which 'sees' farther into the formation provides a more realistic density estimate, with the difference between the near and far detector densities providing a measure of data quality. The tool is very sensitive to variation in the borehole wall (void space caused by washouts or poor grouting, etc) but these effects can be inferred by unusual drops in density values at near *and* far detectors.

B-2 Electromagnetic Induction Methods

The **apparent conductivity** logging tool uses an alternating 40 kHz AC current 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 sensitivity to the borehole fluid and improve the vertical resolution of the tool.

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 porewater is saline or otherwise conductive (e.g. leachate contamination), this will overwhelm the conductivity of the soil/rock matrix. In absence of conductive porewater, the conductivity tool provides a method of identifying litho-stratigraphhic 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 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 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, both manufactured by Geonics Ltd., but with slightly different coil configurations and temperature compensation electronics.

B-3 Fluid Logs - Temperature

The fluid temperature tool and logging system used in this survey are manufactured by IFG Corporation. The temperature probe has been calibrated by the GSC to be sensitive to ±0.005°C. Inside cased, fluid-filled, overburden boreholes, the tool detects slight variations in fluid temperature which are caused by movement of groundwater behind the casing wall, or, to a lesser degree, changes in lithology intersected by borehole.

Prior to logging, the borehole must have been allowed to sit undisturbed for at least 24-48 hours to thermally equilibrate. To measure variations of temperature on the order hundredths of a degree, the temperature probe must be the first instrument to enter the borehole fluid, the log must be recorded downward, and run slowly (~1m/min) to avoid mixing any of the fluid.

B-4 Downhole Seismic Surveys

The seismic surveys were carried out using a downhole receiver array and a source on the surface 5 m from the borehole collar. The first arrivals of the downhole seismic pulses are used to determine accurate interval velocities as a function of depth. In the case of compressional (P-) waves, data were obtained using a multi-channel hydrophone array (12 hydrophones at 1 m spacing) in the water-filled portion of the borehole and a small impulsive surface source (8-gauge shotgun shells). Shear (S-) wave logs were obtained using a clamped, 3-component downhole receiver with 15 Hz geophones, and a loaded I-beam surface plate and 16 lb sledge hammer as a source. A Geode seismograph was used and data were recorded using a laptop computer after reviewing each record on screen. The systems and procedures developed for downhole P- and S-wave logging are described in greater detail in Hunter et al. (1998).

The interval velocities were computed by dividing the receiver spacing by the time difference between two consecutive stations. This derivative method requires very accurate first break times, which were picked using software developed by Ivanov and Miller (2004). This method selects arrival times through cross correlation a using spline interpolation.