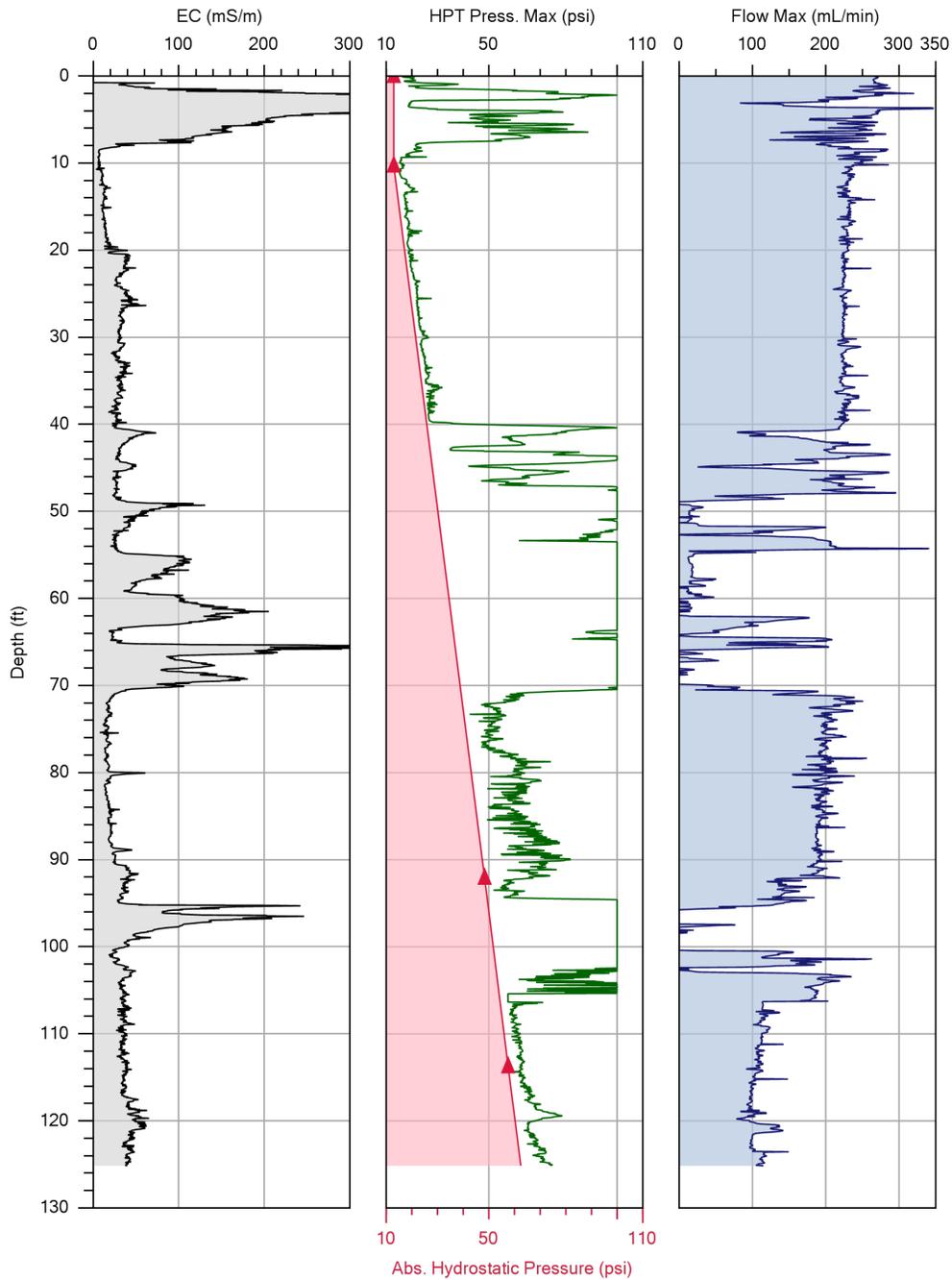


Application of the Geoprobe® HPT Logging System For Geo-Environmental Investigations

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A typical HPT log displaying absolute hydrostatic pressure (shaded) over laying the HPT pressure on center graph. Hydrostatic pressure line is based on two dissipation tests run at 92ft and 113ft below grade.

Introduction

Direct push equipment and methods for subsurface investigation have become primary tools for the geotechnical and geo-environmental site investigator. The efficiency of the direct push (DP) technique for many basic investigation activities such as soil, groundwater and soil gas sampling have made it the method of choice for many sites where work is performed in unconsolidated soils and sediments. To improve efficiency, data density and the development of more accurate conceptual site models (CSM) Geoprobe® has designed subsurface logging probes for use with DP equipment and methods. The first logging probes developed by Geoprobe® were the electrical conductivity (EC) probe and the membrane interface probe (MIP). These probes helped define subsurface lithology and volatile contaminant distribution in the subsurface, respectively. A more recent logging probe developed is the hydraulic profiling tool (HPT) that provides the field investigator with means to better understand subsurface lithology and hydrostratigraphy in a cost and time efficient manner. This document provides information about the theory of operation of the HPT probe, its use to understand relative formation permeability, and an introduction to field operation of the HPT system. Also covered is basic interpretation of the HPT log and several applications where the logs are used to better understand the subsurface and develop accurate CSMs.

What is HPT?

The hydraulic profiling tool (HPT) is a direct push probe (Figure 1) that is advanced into unconsolidated soils and sediments to assess formation permeability and hydrostratigraphy at the centimeter-scale. The HPT probe is robust and may be advanced using hydraulic push and percussion probing, commonly described as the direct push (DP) method (Figure 2). During advancement water is injected at a controlled rate into the formation through a screened port on the side of the HPT probe (Figure 3). A transducer located just above the probe measures the total pressure required to inject the water into the formation while a flow meter at the surface monitors the injection flow rate. The HPT probe also includes a Wenner-type array for measurement of soil electrical conductivity as the probe is advanced to depth. The HPT log (Figure 4) provides graphs of the electrical conductance, HPT pressure and flow rate versus depth.

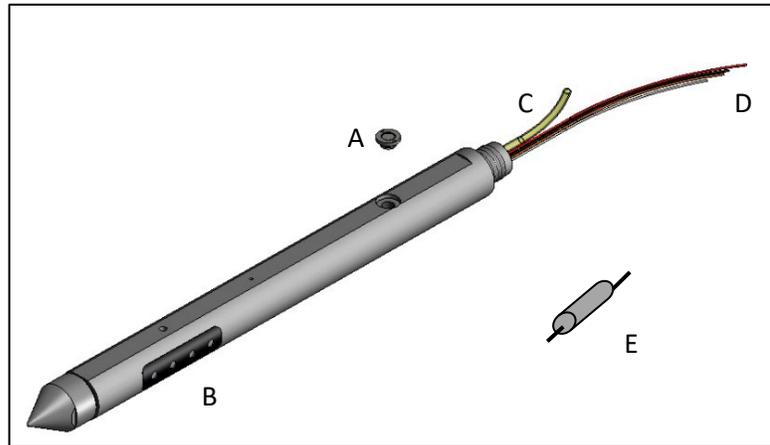
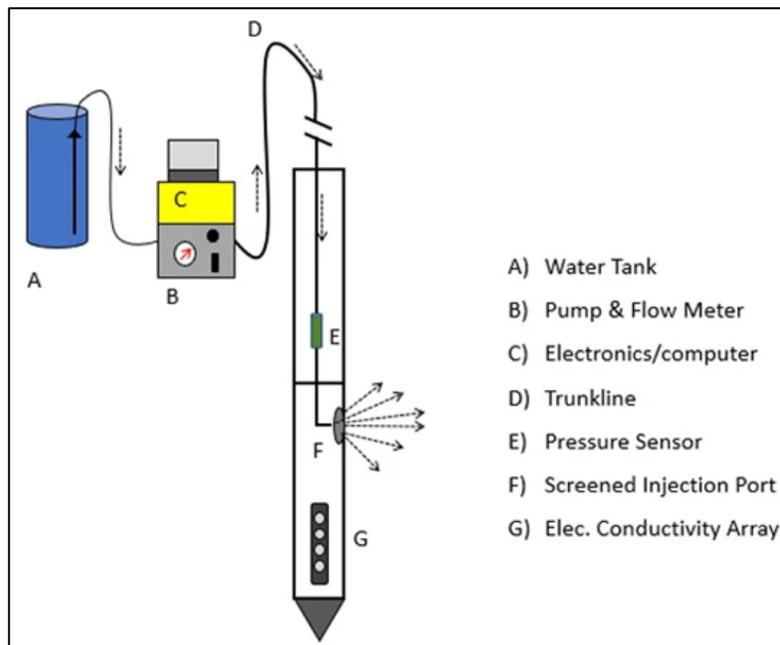


Figure 1: The HPT probe (226553) showing the removable port-screen (A) that can be replaced or cleaned in the field. The EC Wenner array electrodes (B) are located below the water injection port. The water line (C) for the port and electrical connections (D) for the Wenner array allow for connection to the trunkline and up-hole equipment. The pressure transducer (E) is installed in the connector tube above the probe for easy service access.



Figure 2: Operator setting up HPT Probe for advancement into the subsurface with a Geoprobe® 7822 machine. The HPT probe is advanced at 2cm/sec using the system hydraulics and probe hammer when required. Logs to a depth of approximately 60ft (20m) are usually completed in about one hour.

Figure 3: This image illustrates the HPT system. The water supply (A), pump (B) and Field Instrument (C) are located up-hole. Power, data & water are transmitted between the up-hole instruments and the downhole probe via the trunkline (D). The HPT pressure transducer (E) is located down-hole at the probe and is in-line with the fluid flow. Injection of water into the formation is done through the HPT screened injection port (F) on the side of the probe. Also on the HPT probe is the EC Wenner array (G).



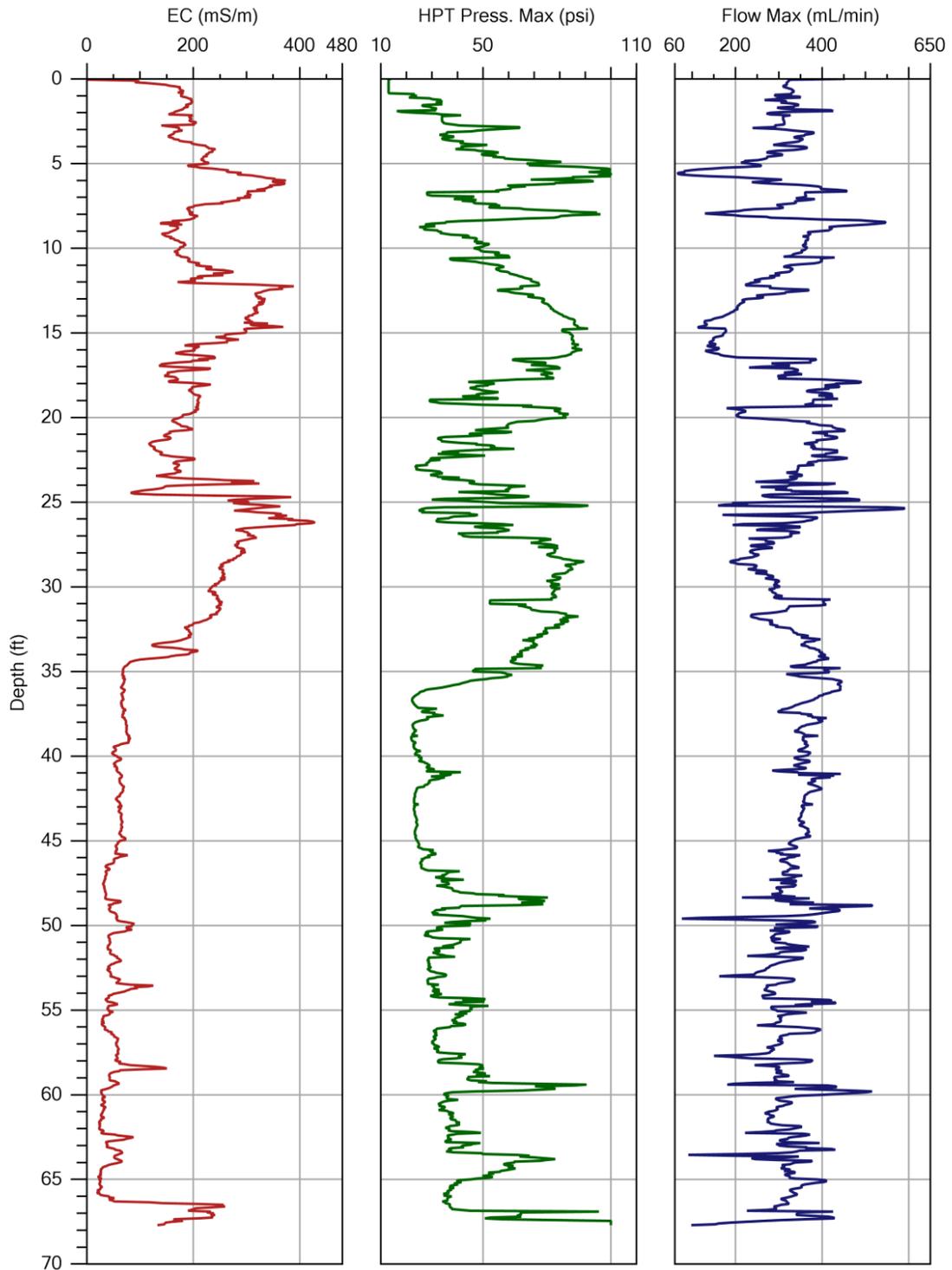


Figure 4: An HPT log as typically displayed with the electrical conductivity graph on the left followed by the HPT pressure and flow graphs. Depth is displayed along the vertical axis at left. The rate of penetration (speed) graph may also be included with the log if desired. The DI-Viewer® software is used to display and print the logs for review and reporting. The logs may be displayed with either English or metric units. This log was obtained in the alluvial deposits of the Smoky Hill River, Salina, KS.

Uses

The HPT logs may be used to support site investigation and remediation in a variety of ways. Some applications of the HPT logs include:

- Determine lithology/hydrostratigraphy.
- Qualitatively define formation permeability.
- Locate contaminant migration pathways.
- Identify optimal locations for monitoring and water supply well screens.
- Guide remedial injection programs.
- Construct Geologic cross-sections.
- Locate and define brine plumes or seawater intrusion areas (when coupled with EC).
- Estimate local formation hydraulic conductivity.
- Estimate GW Specific Conductance in applicable zones.

HPT logs also may be combined with membrane interface probe (MIP) logs to assist in determining how hydrostratigraphy influences or controls volatile contaminant distribution and migration.

Background

Several direct push (DP) logging methods have been developed for geotechnical, geological, and environmental investigations for use in unconsolidated soils and sediments. The cone penetration test (CPT) has been in use for many years to conduct geotechnical and geo-environmental investigations (Robertson et al. 1992, Lunne et al. 1997). Geoprobe Systems introduced its first DP logging tool in 1994, an electrical conductivity probe, that has been widely used to evaluate soil and sediment lithology (Christy et al. 1994, EPA 2000, Schulmeister et al. 2004, Wilson et al. 2005). This was followed by the membrane interface probe (MIP) which has been effectively applied to track and map non-aqueous phase liquids (NAPL) and plumes of fuel hydrocarbons and chlorinated volatile organic compounds (X-VOC) in unconsolidated formations (Christy 1996, Griffin and Watson 2002, ASTM D7352).

As the environmental industry matured it became evident that more detailed data about formation permeability and hydraulic conductivity (K) was necessary to accurately evaluate the potential for contaminant migration and better assess human health risks at contaminated facilities (EPA 1998, ASTM E1739, ITRC 2008). Geoprobe initially developed the pneumatic slug test system (Geoprobe 2002, 2011, ASTM D7242) and field methods (Butler et al. 2002, McCall et al. 2002) that allowed investigators to measure K over discrete intervals using temporary groundwater sampling tools, direct push installed wells or conventional wells. However, the need for higher data density and greater time efficiency eventually lead to the development of permeability logging tools such as the Cone Permeameter™ (Geoprobe 2003, Butler et al. 2007), high resolution Piezocone (Kram et al. 2008, Elsworth and Lee 2007, Lee et al. 2008), the direct push injection logger (Dietrich et al. 2008, Liu et al. 2009), the high resolution K tool (Liu et al. 2009) and the HPT system (Geoprobe 2006a, 2007, 2010b). The HPT system provides the project manager with a log of injection pressure, water flow rate and electrical conductivity for the formation penetrated (Figure 4). These logs provide information about formation lithology and permeability at the centimeter-scale. An HPT log to a depth of about 60ft (20m) can be obtained in about one hour by an experienced two-person field crew.

The HPT System and Basic Field Operation

In this section the primary components of the HPT system are introduced and described. Additional information on HPT tool configurations and system components with part numbers are provided in Appendix I. This section also outlines the basic procedures for running an HPT log and the primary quality assurance (QA) tests conducted in the field to verify that the HPT probe and system are operating properly.

HPT System Components

The primary down-hole component of the system is the HPT probe (Figure 1). Water is injected through a removable stainless steel mesh screen located on the side of the probe. The effective port diameter is approximately 0.30in. (7.6mm) and it is located above the EC Wenner array. This configuration assures that water injected from the port does not interfere with the measurement of bulk formation electrical conductivity. The pressure sensor is located in the connection tube in-line with the water supply and above the probe body for servicing access (Figure 5). The trunkline provides for electrical connections and a water supply line to the surface components of the HPT system. The trunkline is pre-strung through the probe rods which are set up in a rack for easy handling and transportation (Figure 6).

The up-hole components of the HPT system include the HPT controller, FI6000 field instrument and a laptop computer (Figure 7). The HPT pump is housed within the controller and has a maximum rated flow of 1000 ml/min. However, for logging operations flows are usually maintained in the 200ml/min to 300ml/min range. The HPT controller provides connections for water flow

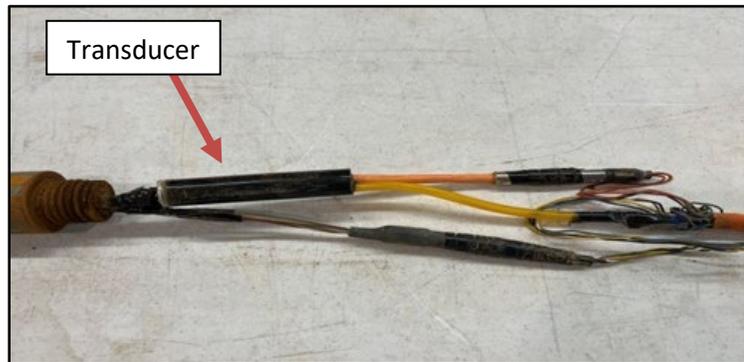


Figure 5: Checking transducer and Wenner array connections prior to logging. These connections are made in the connection tube above the probe body for easy access to service.



from the supply tank to the trunkline and monitors flow rate and line pressure. Additionally, the controller enables the field operator to stop flow when dissipation tests are performed down-hole. The field instrument receives signal input from the string pot (depth encoder), HPT controller, and

Figure 6: Probe rods are prestrung with the HPT trunkline and may be stored and transported on a Geoprobe® drop rack. In this setup the water tank, generator and instrumentation may be loaded in a vehicle for easy transportation on site.

Wenner array. This data is transferred in digital format from the field instrument to the operator's computer.

An integral part of the HPT system is the DI acquisition software. The software is installed on the computer and permits the operator to view the log (Figure 7) as the probe is advanced into the subsurface with the direct push unit. The log and associated QA data are stored on the computer for later review, interpretation, and reporting.

QA Tests

Prior to running an HPT log the operator performs quality assurance tests on the pressure sensor and Wenner array. The results of the QA tests are saved in an information file for later review and reporting (Appendix II). Initially, a test jig is placed on the Wenner Array electrodes and the test load (Figure 8) is used to verify the electrical continuity and isolation of the EC system. Next, a reference test is performed on the pressure sensor. This is accomplished by submerging the HPT probe a specified depth below the water level in a reference tube (Figure 9). A two-step test



enables the operator to verify that the pressure sensor is providing the correct measurement (0.216 psi/1.49kPa) for a defined length (6inches/15.2cm) of water column. If

Figure 9: The HPT probe is inserted in the reference tube to verify performance of the pressure transducer as a part of the pre-log QA testing protocol. The QA test provides a pass/fail report for the transducer with a known height of water column. Reference tests are saved in the information file for each log (Appendix II).



Figure 7: The HPT flow controller (bottom) draws water from the tank (upper left) and regulates flow to the probe. The FI 6000 Field Instrument (top) supplies conditioned current for the EC measurement, receives analog signal from the HPT probe and provides digital output to a lap top computer (left).



Figure 8: As part of the field QA testing the EC probe is setup in the test jig (bottom) and the EC test load (top) is used to verify the performance of the EC array before each log is run. The QA results are saved in the information file (Appendix I).

the result is more than $\pm 10\%$ out of range the transducer fails the QA test. Occasionally, the HPT screen becomes clogged or damaged and must be removed and cleaned or replaced to obtain a successful QA test.

HPT Logging

After the QA test is completed the HPT probe is placed beneath the probe hammer (Figure 2) with a slotted drive cap installed. The probe is set with the HPT port at the ground surface to start the logging process. Using the hydraulics and probe hammer the operator advances the probe at a rate of 2cm/sec (0.8in/sec) into the formation. The string pot is placed on the ground next to the foot of the rig and the cable is attached to the probe mast. This configuration accurately tracks depth as the probe is advanced. The log is visible onscreen as the probe is advanced (figure 7).

Once the probe is below the static water level the investigator may select an appropriate interval to perform a dissipation test. Dissipation tests are best run in coarser grained materials (sand \pm gravel) to assure that the local ambient hydrostatic pressure is measured quickly and accurately. The time versus pressure log (Figure 10) of a dissipation test is later used to determine the local static water level and hydrostatic pressure profile at the logged location. Dissipation tests will be covered in more detail in following sections.

After the log is advanced to the maximum desired depth the operator uses the probe hydraulics and rod grip system to extract the probe rods and HPT probe. It is important to maintain flow through the HPT port as the probe is extracted to prevent clogging and potential damage to the HPT pressure sensor. Once the probe is extracted, another QA test is performed to verify probe performance during the log and for later logging operations. The HPT log and QA tests are saved by the DI Acquisition software for later review and reporting.

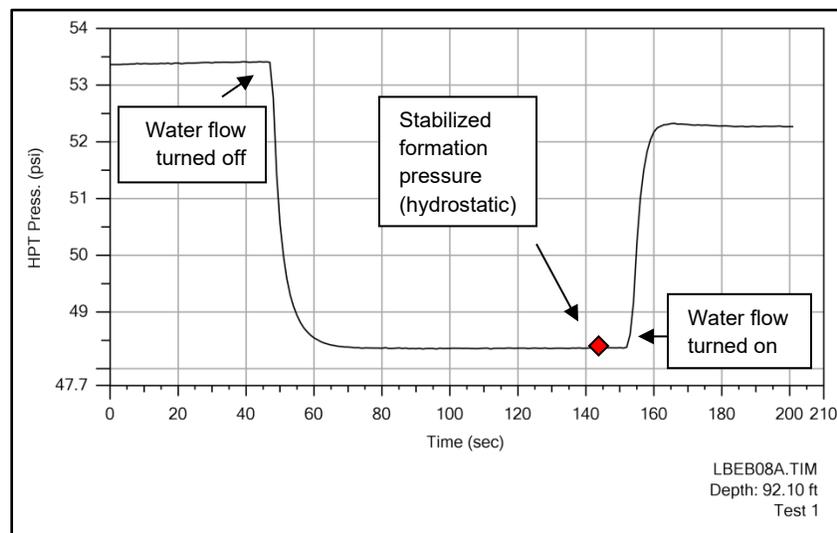


Figure10: Time log of a pressure dissipation test performed at a depth of 92.1 ft (28.1 m) below grade in Halstead, KS. The diamond label on the graph corresponds with the stabilized pressure (48.37 psi/ 333.8 kPa) for this test. This pressure is used to calculate the local water level and hydrostatic pressure profile for the tested location.

Review and Interpretation of HPT Logs

To review an HPT log after it has been completed the DI Viewer software package is used. The DI Viewer software may be downloaded at www.geoprobe-di.com. The DI Viewer software displays the three primary components of the HPT log in the default setting (Figure 4). The three components are

(left to right) electrical conductivity, HPT pressure, and flow rate. The graph for rate of penetration may be added to the log if desired. The software also provides for viewing of dissipation tests and calculation and plotting of the hydrostatic pressure trend line, corrected HPT pressure and an estimated K log (hydraulic conductivity). In addition, the software can be used to compare two or more logs in overlays and multiple pressure logs or EC logs can be plotted side-by-side to generate basic geologic cross-sections. Several of the software features will be used in the following discussion of log interpretation.

The HPT probe is advanced into the subsurface using direct push (DP) methods. Thus, the probe is in intimate contact with the formation materials being penetrated. The DP logging method simplifies log interpretation in several respects as compared to traditional open borehole or down well logging. In borehole and well logging the boring diameter, borehole fluid composition, drilling fluids, gravel packs, grouts and well casing may influence the log response (Keys 1997) and so need to be considered during interpretation. None of these factors are involved in DP log interpretation.

(The following discussion of HPT log interpretation will be based on the log in Figure 4 unless otherwise noted)

Electrical Conductivity

Geoprobe has been providing Wenner and dipole electrical conductivity (EC) logging tools for some time before the HPT probe was developed (Christy et al. 1994). Interpretation of the electrical conductivity (EC) log will be reviewed briefly here and then its use in combination with the HPT pressure log discussed in the following section. Additional information is available from several sources regarding electrical log interpretation (Christy et al. 1994, Schulmeister et al. 2003, Keys 1997, Dobrin 1976). The general rule for interpretation of EC logs in soils and sediments containing fresh water is that increasing clay content results in higher electrical conductance of the bulk formation. More detailed information on EC log interpretation follows.

The bulk electrical conductivity of unconsolidated soils and sediments is influenced by several factors. The primary factors include grain size, mineralogy, moisture content, the presence of dissolved ions within groundwater, and temperature (Keys 1997). In granular soils and sediments the clays usually exhibit higher electrical conductance than silts, sands, and gravels (Christy et al. 1994, Schulmeister et al. 2003, Wilson et al. 2005). The EC of clay rich sediments often ranges between 50 mS/m to 400 mS/m, generally increasing with higher clay content (6-8ft, 12-15ft, 25-34ft). The electrical conductance of clays is related to their mineralogy, and soils developed in humid regions (e.g. southeastern U.S.) often have clays with lower electrical conductance. Dry, clean sands and silts comprised primarily of quartz will have very low EC, often less than 1 to 2 mS/m. When clean sands are saturated with groundwater the bulk EC of the material will be largely due to the EC of the contained groundwater (35-45ft). As the dissolved solids and ions content of the groundwater increases, the EC of the bulk formation also will increase. It is recommended that targeted soil sampling be conducted to verify log interpretation, especially at a new field site where limited or no previous soil boring data is available.

The EC of pure distilled water is very low, approaching 0.005 mS/m (USGS 1992), but a small amount of dissolved ions in the water will increase its EC notably. When electrically active salts (e.g. sodium chloride/NaCl) are dissolved in water the EC of the solution will increase significantly (Keys

1997). As a reference point, the EC of ocean water is approximately 5,000 mS/m (USGS 1992). However, the EC of beach sand consisting largely of quartz and saturated with ocean water will be notably less than 5,000 mS/m due to the insulating properties of the sand matrix. Still, the presence of sea water (or brine) in a formation will generally overshadow the EC variation due to the formation solids making it difficult if not impossible to interpret formation variability (e.g. clay – silt – sand content) based solely on the EC log. However, the HPT pressure log can provide information on formation permeability and lithology even when the contained groundwater has elevated salt content.

HPT Pressure

The HPT pressure log often reveals a wide range in observed pressure (Figure 4) depending on the characteristics of the soil or sediment penetrated. From Darcy's Law we know that flow (Q) is proportional to the change in head (pressure) across a column of sediment with a given permeability (Fetter 1994). For this same sediment, as the pressure increases the flow will increase, within reasonable limits. From this relationship it is apparent that higher pressure resulting from the injection of water into a sediment at a given flow rate indicates lower permeability and conversely, that lower pressure from injection of water at a given flow rate indicates higher permeability. It is this simple relationship that allows the investigator to evaluate changes in relative permeability of soils and sediments in an HPT log by reviewing the pressure verses depth log.

Reviewing the pressure and EC logs (Figure 4) it is apparent that higher EC in general correlates with higher pressure down the log. So as increased EC generally indicates increased clay content, increased pressure generally indicates lower permeability (e.g. 13-16ft). Conversely, lower EC suggests increased sand and gravel content and lower pressure indicates higher permeability (e.g. 35-45ft). Based on this the EC and pressure log indicates that the upper 35 feet at this location consists primarily of clay rich sediments, where zones of lower EC and lower pressure indicate increasing silt and sand content. Repeated sampling at a depth of 22 to 24 feet at this site has produced wet sandy silt with clay and is the shallowest zone where groundwater can be sampled locally. This correlates nicely with the relatively lower EC in this zone as compared to the surrounding materials.

Between approximately 35-45ft at this site, the EC and pressure are relatively low and the log suggests the formation consists largely of sand ± gravel across this interval. Groundwater sampling tools installed at several locations across the site in this interval produced abundant water. Pneumatic slug tests of screened intervals in this zone provided hydraulic conductivity values ranging from about 35ft/day to 60ft/day (1.25E-2 cm/s to 2.10E-2 cm/s), consistent with sand ± gravel aquifer materials. Additionally, soil cores collected over this interval consisted primarily of saturated sand with some fine to medium gravel and minor silt ± clay.

Below approximately 45ft in this log the EC is generally low with several peaks of slightly higher EC suggesting the presence of increased clay content (e.g. clay rich lenses). The HPT log over this same interval reveals several elevated pressure peaks, roughly corresponding to the depths of the EC peaks. It is important to note that the relatively large pressure peaks across this zone indicate some significant decreases in permeability interspersed with higher permeability layers. The decreases in permeability indicated by the large pressure peaks below 45ft are greater than may have been anticipated based

solely on the small EC spikes observed. Soil sampling across this interval produced sand ± gravel interspersed with discontinuous gray colored silty-clay layers. Under some groundwater settings metals and cations may be leached from clays. This can result in fine grained layers with lower electrical conductivity than generally encountered, as seen here.

One important feature to recognize on this log occurs across the 45-50ft interval. Here the EC is consistently low, conversely the HPT pressure increases to over 75psi in this interval. This relationship is just the inverse of what is normally expected. Across this interval the speed of penetration consistently decreases and the probe hammer is run at higher frequency to penetrate this denser material. Sampling has shown that calcium carbonate cementing has occurred sporadically over this depth interval. The calcium carbonate cement would decrease the permeability locally. Other conditions may also yield low EC and relatively high HPT pressures. Some of these conditions include dilatant sands, silt layers with low clay content, and the cementing discussed here.

A drop in EC across a narrow interval corresponding with a drop in HPT pressure would clearly suggest a sandy layer bounded by finer grained materials (24-25ft, 65-67ft). Sometimes HPT pressure may be low where EC is high (e.g. 7ft). This occasionally can occur when probe advancement is stopped to add the next drive rod. Here the flow continues from the port while the probe is stationary. This can result in the applied HPT pressure exceeding the local lithostatic pressure and fracturing or channeling of the formation, resulting in anomalously low observed pressure. Fracturing of the formation could occur as the probe is being advanced when the injection pressure momentarily exceeds the local lithostatic pressure. A plot of the effective pressure verses depth over the HPT pressure log can indicate where such conditions could occur. Targeted soil sampling may be required to verify the character of formation materials over intervals where anomalous pressure and EC results occur.

HPT Log QC and Overlays

The primary method to confirm the validity of HPT logs is to collect targeted soil samples across intervals of interest. An effective way to perform the sampling would be to use DP soil sampling tools such as the MC5 system (Geoprobe 2006b, ASTM D5282). The investigator may choose intervals for sampling that are of particular importance to the purpose of the investigation. For example, is an aerially extensive layer defined by high EC and high pressure (25-30ft) actually low-permeability clay that will provide an effective barrier to downward migration of contaminants? Alternatively, is a low EC and low pressure layer across the site (35-45ft) clean sand that could behave as a preferential migration pathway for contaminants or as a productive zone for a residential water well? An option to evaluate the sand layer would be to install a temporary DP groundwater sampling device such as the SP16 or SP22 (Geoprobe 2006c, 2010a, ASTM D6001) and perform pneumatic slug tests (Geoprobe 2011, ASTM D7242).

Another approach to perform HPT log and system QC is to run a replicate log 2 to 3 ft (0.5 to 1 m) from the original log location. The DI Viewer software is used to overlay the original and replicate logs for comparison (Figure 11). While natural heterogeneity in a formation will result in some differences between the logs, the overall trends and major features will normally correspond very well as observed here. Some differences are notable below about 50ft in these two logs. However, several

samples from this depth interval found that clay layers varied locally in thickness and were discontinuous over small lateral distances.

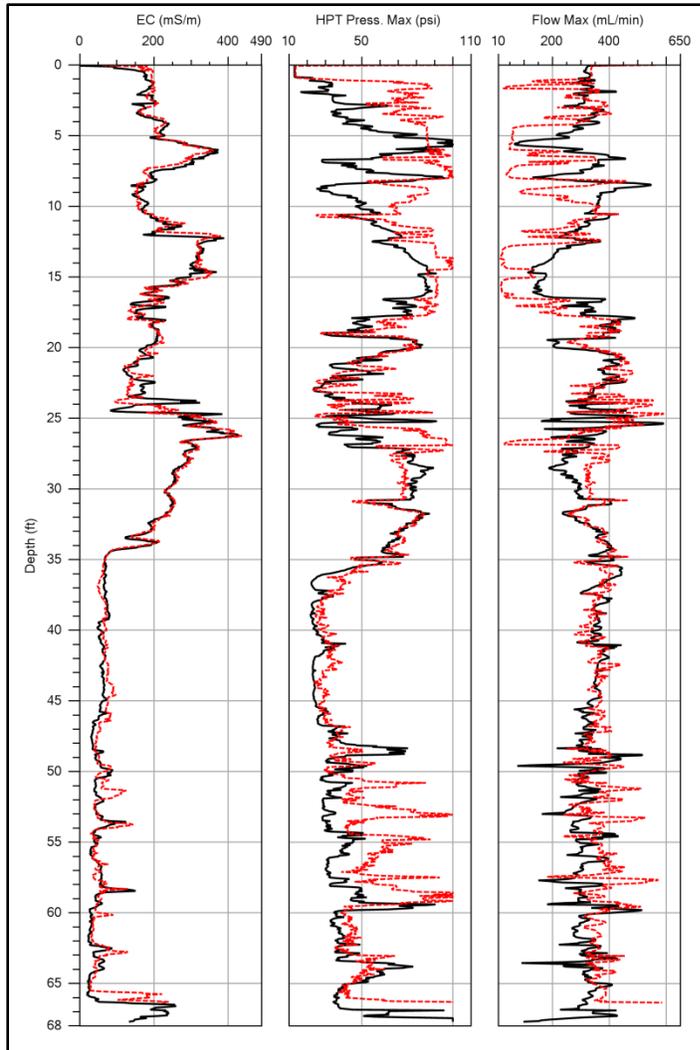


Figure 11: One method of quality control in the field is to perform a replicate log at about 2 to 3 ft (0.5 to 1 m) from the original location. The replicate logs here show good repeatability for the large-scale EC, pressure and flow features. Small scale variations are expected due to the heterogeneity that occurs in natural sediments.

Determining Local Static Water Level and Piezometric Heads

Another important feature of the HPT pressure log is the increase in hydrostatic pressure as the probe is advanced below the local water level (Figure 12). The increase in hydrostatic pressure results in a “rising baseline” on the pressure log. A simple interpretation may be used in the field to estimate the local water level by visually estimating where this “baseline” intersects atmospheric pressure, on this log at about 10ft below grade (Note: nominal atm. P =14.7psi/101.4kPa at sea level). To obtain a quantitative determination of the local static water level, a pressure dissipation test must be performed during the logging operation. As discussed above it is most efficient to perform dissipation tests in coarser grained materials, as the pressure will dissipate rapidly. To perform the dissipation test the advancement of the probe is halted and the field operator then starts a time log (Figure 10). Water flow is turned off to observe and record the dissipation of the HPT pressure verses time, until pressure stabilizes. The stabilized pressure is the absolute hydrostatic pressure at the depth of the test. Knowing the depth of the test, the absolute hydrostatic pressure, and the atmospheric pressure the static water level may be calculated (Table 1).

Hydrostatic pressure may not always increase linearly with depth. Multiple dissipation tests may be performed at different depths during a single log to evaluate variations in piezometric head with depth and local vertical gradients in the aquifer (Figure 13). This is especially important when aquitards

hydraulically isolate permeable layers in an aquifer system. A local extraction or injection well also may influence the hydrostatic pressure profile.

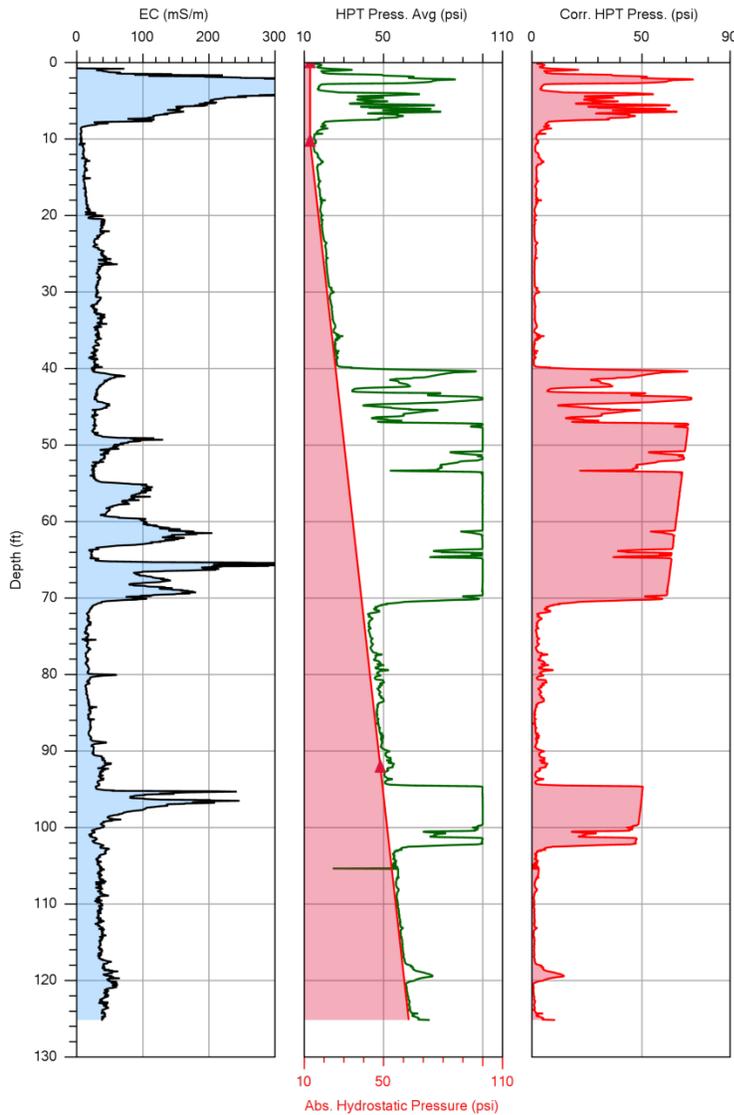


Figure 12: This log was run near Halstead, KS where brine from former oil drilling and production is starting to impact the Groundwater in the Arkansas River alluvial aquifer. The HPT average pressure along with the atmospheric and hydrostatic pressure lines are plotted on the center graph. The corrected HPT pressure (P_{inj}) is plotted on the right graph. The corrected pressure is the pressure required to inject water into the formation at the given flow rate.

The HPT pressure sensor has a maximum limit of 100 psi (690 kPa) resulting in the flat topped peaks on the HPT pressure graph (center) when the injection pressure exceeds the transducer limit.

Table 1

Calculation of Water Level from HPT Dissipation Test Data

Parameter	English		Metric	
	Value	Units	Value	Units
Measured Probe Depth (string pot data)	92.10	ft	28.07	m
Stabilized Formation Total Pressure (dissipation test data)	48.37	psi	333.8	kPa
*Transducer Meas. Atm. Press. (pre- & post-log reference tests)	12.97	psi	89.49	kPa
Calculated Hydrostatic Press. at depth of dissipation test	35.40	psi	244.3	kPa
Length of Water Column above HPT Port	81.76	ft	24.92	m
Static Water Level (below grade)	10.34	ft	3.15	m

*Average of pre- & post-log reference test results. One psi = 2.31 feet of water = 6.90 kPa (Kilopascal).

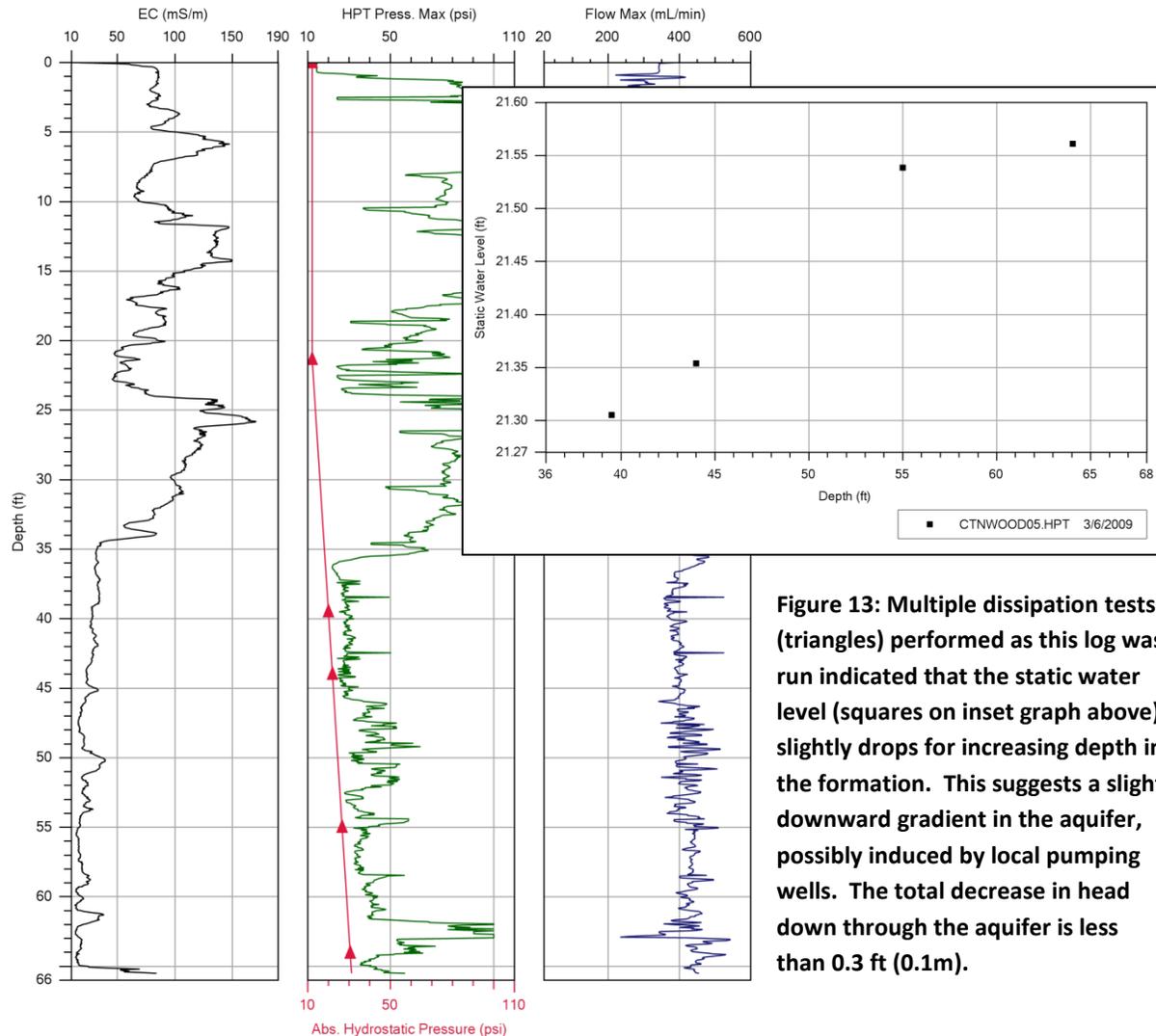


Figure 13: Multiple dissipation tests (triangles) performed as this log was run indicated that the static water level (squares on inset graph above) slightly drops for increasing depth in the formation. This suggests a slight downward gradient in the aquifer, possibly induced by local pumping wells. The total decrease in head down through the aquifer is less than 0.3 ft (0.1m).

HPT pressure dissipation tests are not used to estimate formation hydraulic conductivity (K) as done for CPTu (piezocone) dissipation tests. This is because the water in the HPT trunkline above the local water level will interfere with the early time dissipation of the observed pressure down hole (late time stabilized pressure will be accurate). However, the dissipation test data may be used in conjunction with the pressure and flow logs to estimate K for the entire log after logging is completed (See below for further discussion on K-estimation).

Note: HPT dissipation tests in fine grained materials can take up to several hours to stabilize. If hydrostatic equilibrium pressure is not reached before the test is halted this can cause determination of erroneous hydrostatic pressures and inaccurate water level determinations if the test results are used in the DI Viewer calculations.

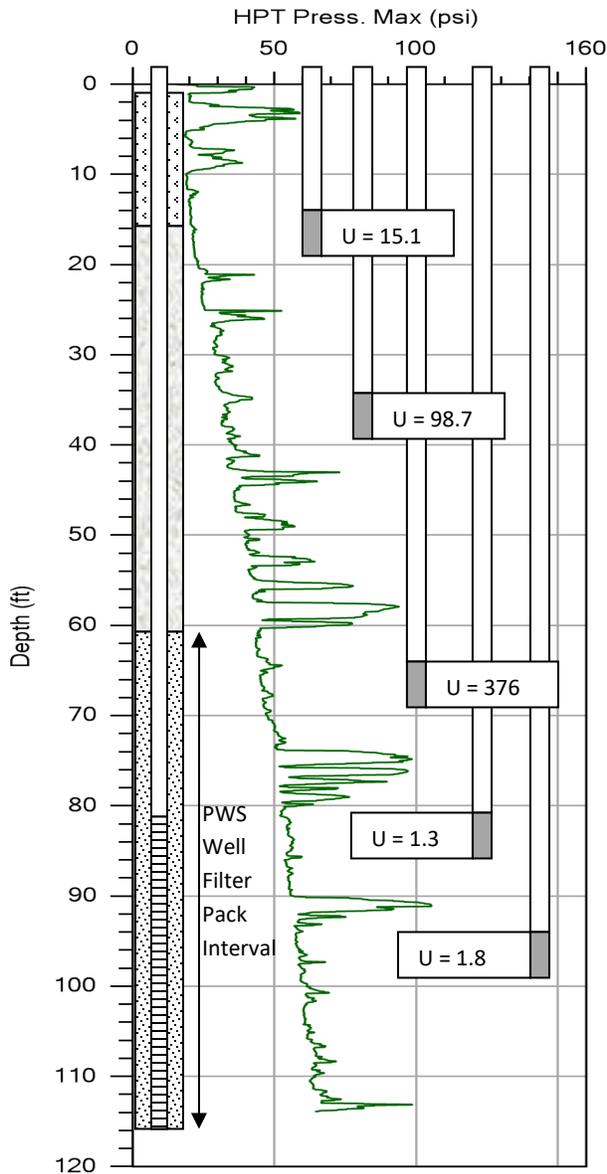


Figure 14: HPT logs were used to guide placement of DP wells at discrete intervals between clay layers (high pressure peaks) in a part of the Platte River alluvial aquifer. Uranium concentrations ($\mu\text{g/l}$) in wells higher in the aquifer exceeded the EPA MCL ($30 \mu\text{g/l}$). The extended filter pack of the 12-inch PWS well intersected the high uranium aquifer zone (After McCall et al. 2009).

monitored for basic water quality parameters and then later sampled for uranium and other analytes. Groundwater sample results for uranium posted on the log (Figure 14) allowed the local regulators to determine that water quality did vary significantly between the clay layers (aquitards) and two permeable zones were found to have uranium concentrations that significantly exceed the uranium MCL

Other Applications for HPT Logs

The above section discussed basic uses for HPT logs. The following section will introduce several additional applications for HPT logs that can be valuable in developing an accurate conceptual site model (CSM) and evaluating designs for site remediation. These applications range from simple use of the logs to guide placement of well screens, to delineation of brine plumes and even to estimation of hydraulic conductivity from HPT flow and pressure data.

Guide Placement of Well Screens

From the discussion of log interpretation above we see that zones of higher pressure indicate lower permeability materials in the aquifer which would provide poor yield to a well installed in such a zone (e.g. Figure 12: 40-72ft, 95-104ft, Figure 14: 57-60ft, 74-80ft). Conversely, lower pressure zones indicate the presence of coarser grained materials with higher permeability that should yield abundant water to wells (Figure 12: 10-40ft, 73-94ft, 106-125ft, Figure 14: 60-74ft, 80-90ft and 93-112ft). During an investigation in Clarks, NE several HPT logs were run to learn about the hydrostratigraphy of the local alluvial deposits of the Platte River (Figure 14). The investigation was being conducted to determine possible sources of elevated uranium impacting the local public water supply wells at this field site (McCall et al. 2009). Direct push wells with 5 foot screens were installed in the lower pressure zones observed on the HPT logs and between the high pressure zones. This method targeted materials that would provide abundant water for sampling and information on variations of water quality with depth. During development the wells were

of 30µg/l. While the screen (80-105ft) of the nearby supply well was set below an aerially extensive aquitard (74-80ft) the gravel pack had been extended up to 60 feet below grade to enhance well yield. Unfortunately for the local town's people the gravel pack intercepted the aquifer zone with the highest uranium concentration (376 µg/l) resulting in elevated uranium in their drinking water. If the HPT logs and groundwater sampling had been performed before the costly supply wells were constructed significant remediation/treatment costs could have been avoided.

Construction & Use of Hydrostratigraphic Cross Sections

When several HPT logs are obtained across a site the DI Viewer software may be used to construct simple geologic/hydrostratigraphic cross sections. In the DI Viewer software the "Cross Section" icon is selected and then the log parameter (e.g. pressure) to be plotted is selected. The logs are added to the cross section in sequential order (Figure 15). When displayed in this fashion, hydrostratigraphic features may be correlated across the logs. As an example, there is a relatively low pressure (higher permeability) zone apparent from approximately 21 to 26ft deep on log BWHP01 at the left (SW) side of the cross section (Figure 15). Looking to the right (NE), across the figure, you can see that the lower pressure zone across this interval persists in each log, but it slowly decreases in extent and pressures increase across this interval toward the right. Tracing this zone to the log on the far right, one sees only 2 or 3 low pressure spikes occur in the 21-26ft interval. This clearly indicates that the sand content decreases and clay and silt content increases in this part of the formation from SW to NE along this transect. So, migration to the NW of any contaminants present in the 21-26ft zone at the log BWHP01 location would be impeded by the increasing clay content in this interval. Additionally, it is apparent that the thick, high pressure (low permeability) zone below 26ft in this formation would significantly impede the downward migration of any contaminants present in the 21-26ft permeable zone.

This same HPT pressure cross section may be used to evaluate this formation for the best location to install a local water supply well. Looking over the logs one easily notes that the interval from about 43 to 60 feet on log BWHP03 is the widest low pressure (high permeability) interval in this cross section. There are only a few spikes of increased pressure across this interval in the log, indicating this is relatively clean sand and should provide good yield to a well with minimal development.

Guide Injection of Remediation Fluids

Using the cross section we discussed above (Figure 15) we can quickly develop a qualitative assessment of where it will be easy to inject remediation fluids into the formation and where it will be more difficult. Obviously the lower pressure zones identified by the HPT log from injection of water will be sections of the formation that will generally accept injected fluids at a lower pressure (e.g. log BWHP03, 43-60ft). Conversely zones of higher HPT pressure (e.g. BWHP02, 8-18ft) will require more pressure and time to inject the same fluid and volume. The viscosity of the fluid being injected and the injection pressure will have an impact on the efficiency of the injection process. Of course, if the injection pressure exceeds the local lithostatic pressure fracturing may occur. However, fracturing may occur in a random fashion and so your ability to control where injected fluids go may be poor under these conditions.

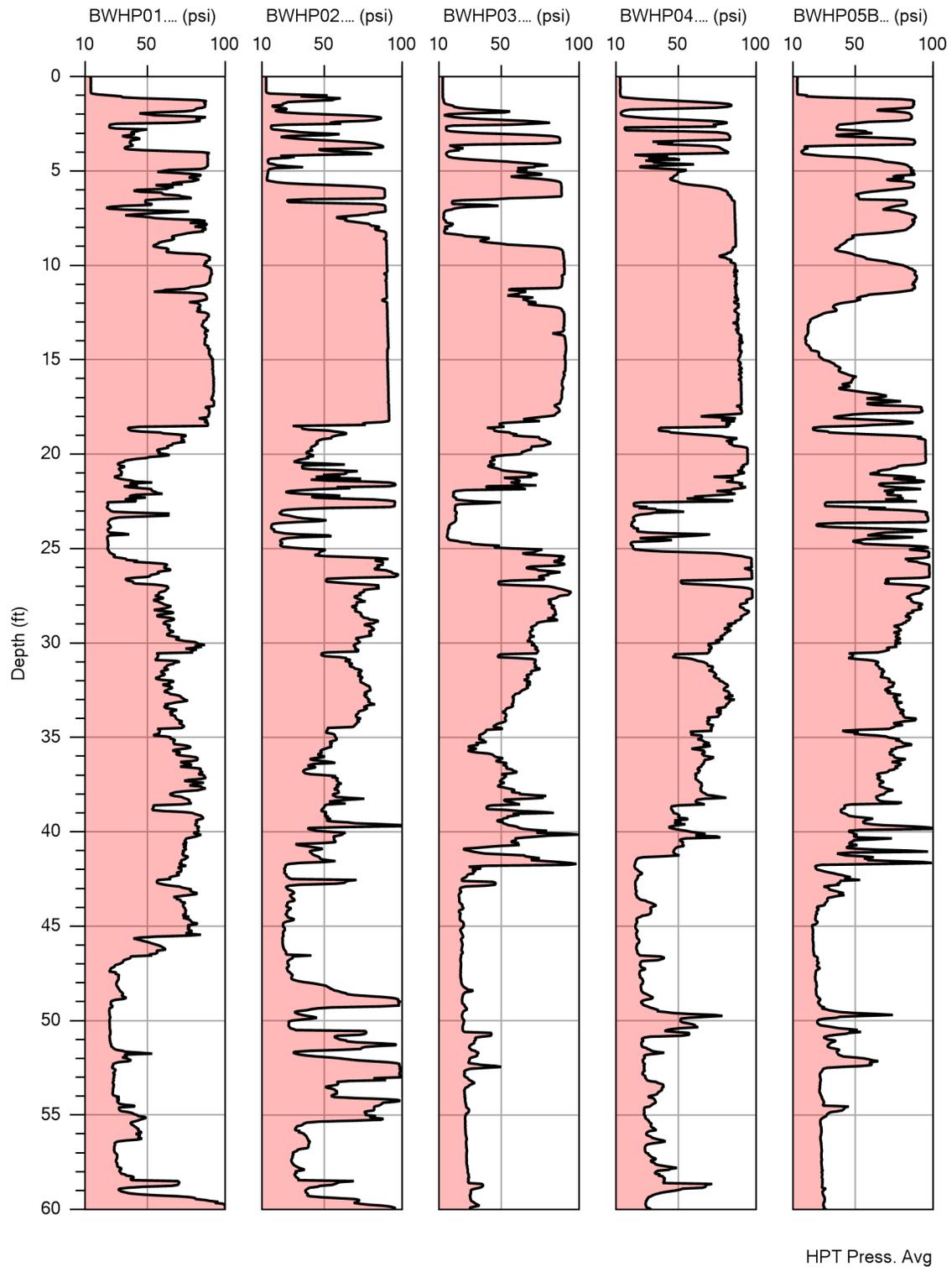


Figure 15: These five HPT pressure logs were obtained along a SW-NE transect separated by 50 ft (15 m) spacing. The DI Viewer software was used to create this cross section that provides detailed information on formation permeability and hydrostratigraphy. Lateral correlation between the logs can be used to assess migration pathways (low HPT pressure zones) and guide well placement.

Estimation of Hydraulic Conductivity

From Darcy's Law we know that hydraulic conductivity (K) is proportional to the flow rate (Q) divided by the pressure (P) required to induce that flow rate in the given sediment or soil. Simply stated this is: $K \propto Q/P$. The raw HPT pressure provided by the HPT log is the total pressure observed at the depth where the water is injected. This total pressure includes the ambient atmospheric pressure at the time of the log, the local hydrostatic pressure and the pressure required to inject the fluid into the formation. So we have:

$$P_{\text{total}} = P_{\text{atm}} + P_{\text{hydro}} + P_{\text{inj}}$$

As discussed above the atmospheric pressure is determined from the pre and post log response tests (Appendix II) and the hydrostatic pressure is defined by one or more dissipation tests (Figure 10) obtained as the log is run. Now the actual injection pressure [$P_{\text{inj}} = P_{\text{total}} - (P_{\text{hydro}} + P_{\text{atm}})$] that was required to inject the water into the formation is calculated for each depth increment of the log (Figure 12, right column). The actual injection pressure (P_{inj}) and the measured flow rate (Q) is then used to model an estimated K value for each depth increment of the HPT log (Geoprobe 2010b).

An empirical model to estimate K for HPT Q and P_{inj} data was developed by Geoprobe (McCall & Christy 2010). One field site was used to develop the basic empirical model utilizing several HPT logs and co-located slug tests (ASTM 2006) conducted in temporary groundwater sampling tools (ASTM 2005b) at targeted depths. The resulting model was found to generally fit paired HPT log and slug test data from several field sites in the central United States (Figure 16). This general model to estimate K from the HPT Q and P data is included in the DI Viewer software (Geoprobe 2010b). Once the corrected pressure for a log is determined using log specific dissipation test(s) and response test(s), the DI Viewer software can be used to calculate and plot the estimated K value verses depth (Figure 17). As this log indicates, the estimated-K value is provided at inch-scale resolution and should prove useful for risk and transport modeling as well as remediation design. To provide greater confidence in the estimated K value a site-specific model could be developed.

Under appropriate conditions, applying the general model for estimation of K (Figure 16) can provide reasonable estimates of hydraulic conductivity. Slug tests conducted in temporary groundwater samplers installed at targeted depths adjacent to one log (Figure 18) reveals that the model does provide estimates close to the slug test results under appropriate conditions. The lower K boundary for the general model is at approximately 0.1ft/day (0.03m/day) and the upper boundary is near 75ft/day (25m/day).

Delineation of Brine Plumes

In the section above explaining interpretation of HPT logs, the fact that EC logs are sensitive to salt or brine in groundwater was discussed. Conversely, HPT pressure and flow logs are relatively insensitive to salt or brine content of the groundwater. Because of these facts we can use HPT corrected pressure (P^*), EC, & Archie's Law to evaluate the potential for brine, landfill leachate, seawater, or other ionic impact to an aquifer (Figure 19). At the field area where this log was obtained, previous oil drilling and production had led to brine releases in the shallow alluvial aquifer up gradient.

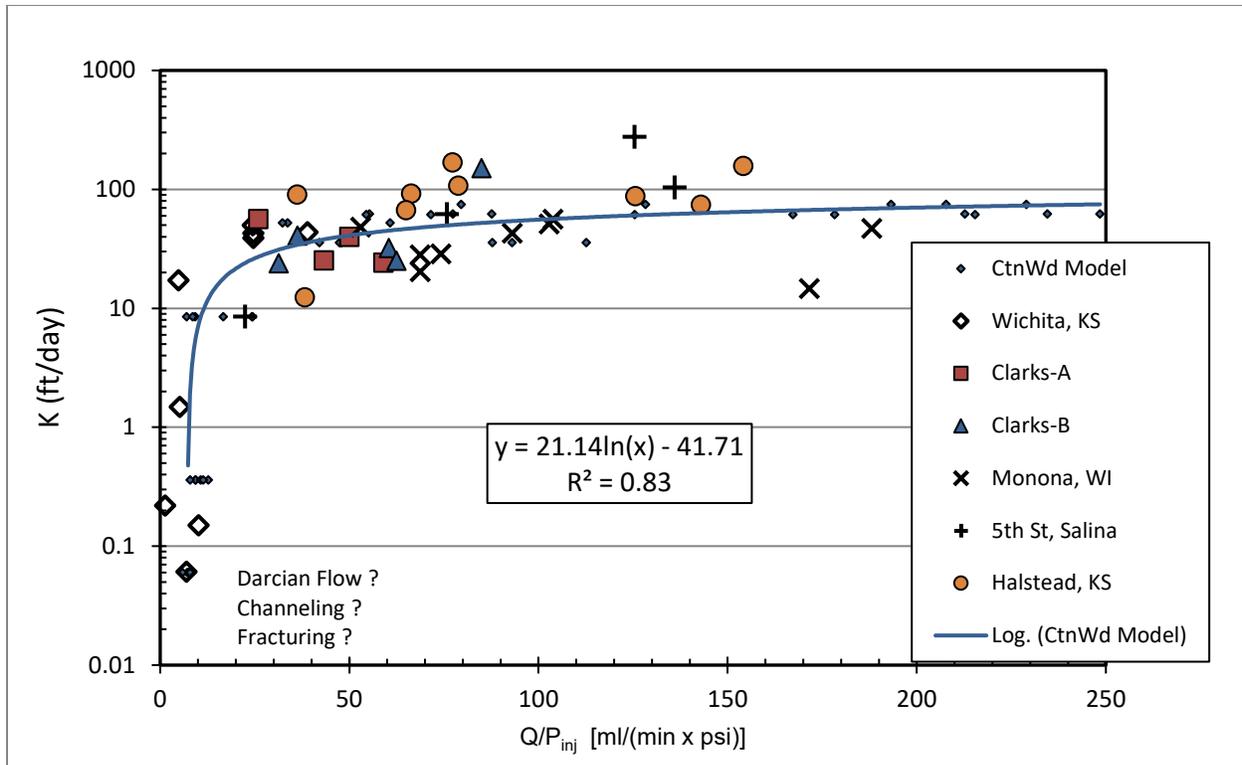


Figure 16: The general model for estimating K from HPT Q/P_{inj} was developed from logs obtained in the Smoky Hill alluvial aquifer in Salina, KS. Multiple logs were obtained at the test site and co-located slug tests were performed at selected depths with DP piezometers. Paired data for HPT Q/P_{inj} ratios and co-located slug tests from six sites from the midcontinent U.S. also are plotted with the model curve. This demonstrates the relationship of the model to multiple site data.

A detailed review of this log (Appendix III) reveals some basic relationships between EC and P^* . These are:

- When EC is relatively high and HPT pressure is low there is potential for ionic impact in the saturated aquifer.
- When both EC and pressure are relatively high this generally correlates with elevated clay content and reduced permeability.
- Low EC and low HPT pressure generally indicate coarse grained aquifer materials without ionic impact.

Targeted groundwater samples and slug tests from three zones at this location (Figure 19) confirm this general relationship. Initially, results were observed at several other locations at this site and a plot of the EC/P^* ratio versus chloride (Figure 20) shows a strong positive correlation. This relationship will be influenced by site-specific conditions. When high chloride concentrations are present this will result in elevated EC values in the EC log ($>1000\text{mS/m}$), and will be readily obvious, especially when compared to low HPT pressures over the same interval (Binder 2008).

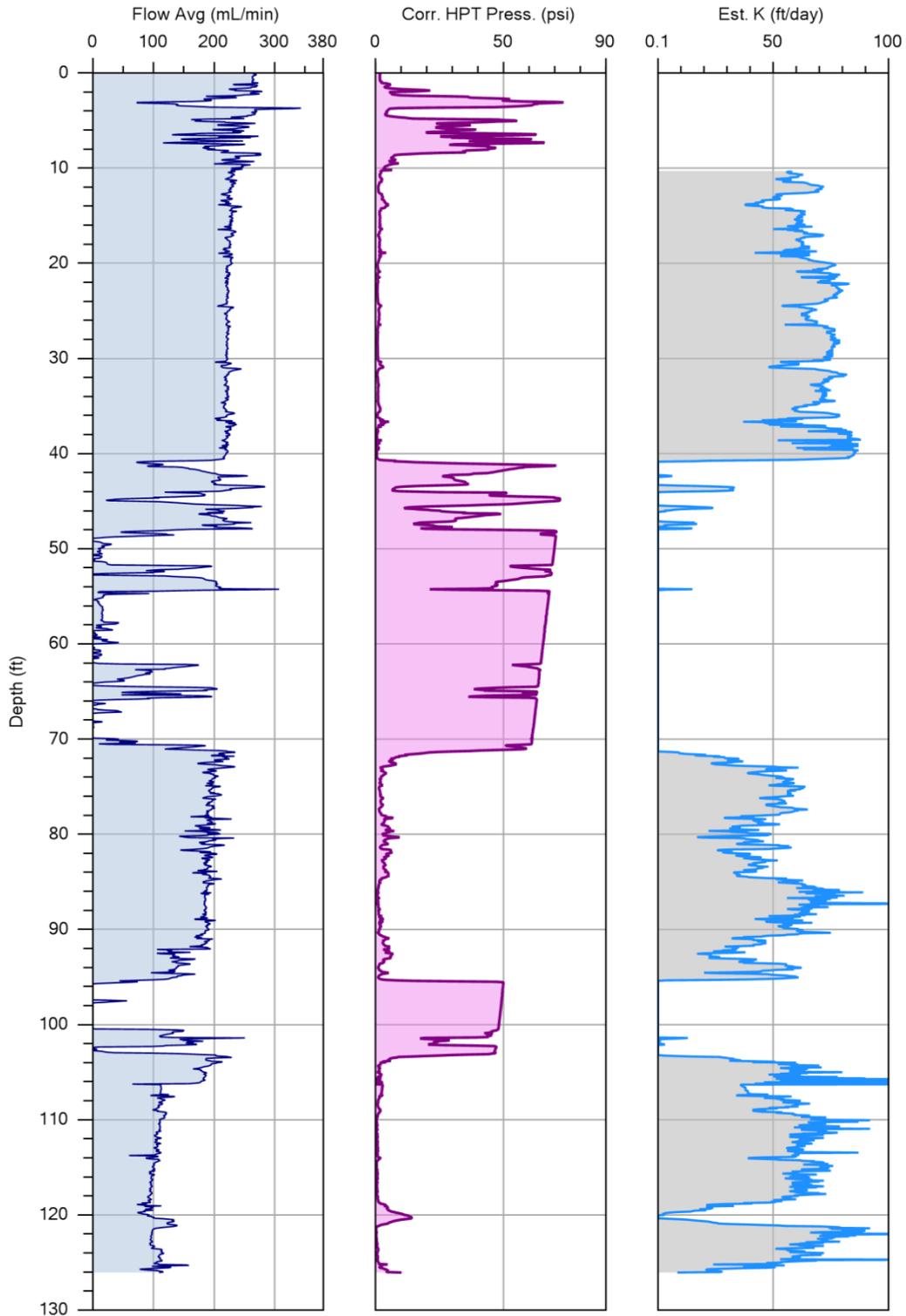


Figure 17: This log gives the average flow (Q), corrected pressure (P_{inj}) and estimated hydraulic conductivity (Est. K) for the saturated formation at a location near Halstead, KS. The Est. K is calculated based on the model in Figure 16. Note that anomalous high- K spikes occur in the estimated K where the corrected pressure approaches zero, this is an artifact of the model. The original HPT log is provided in Figure 12.

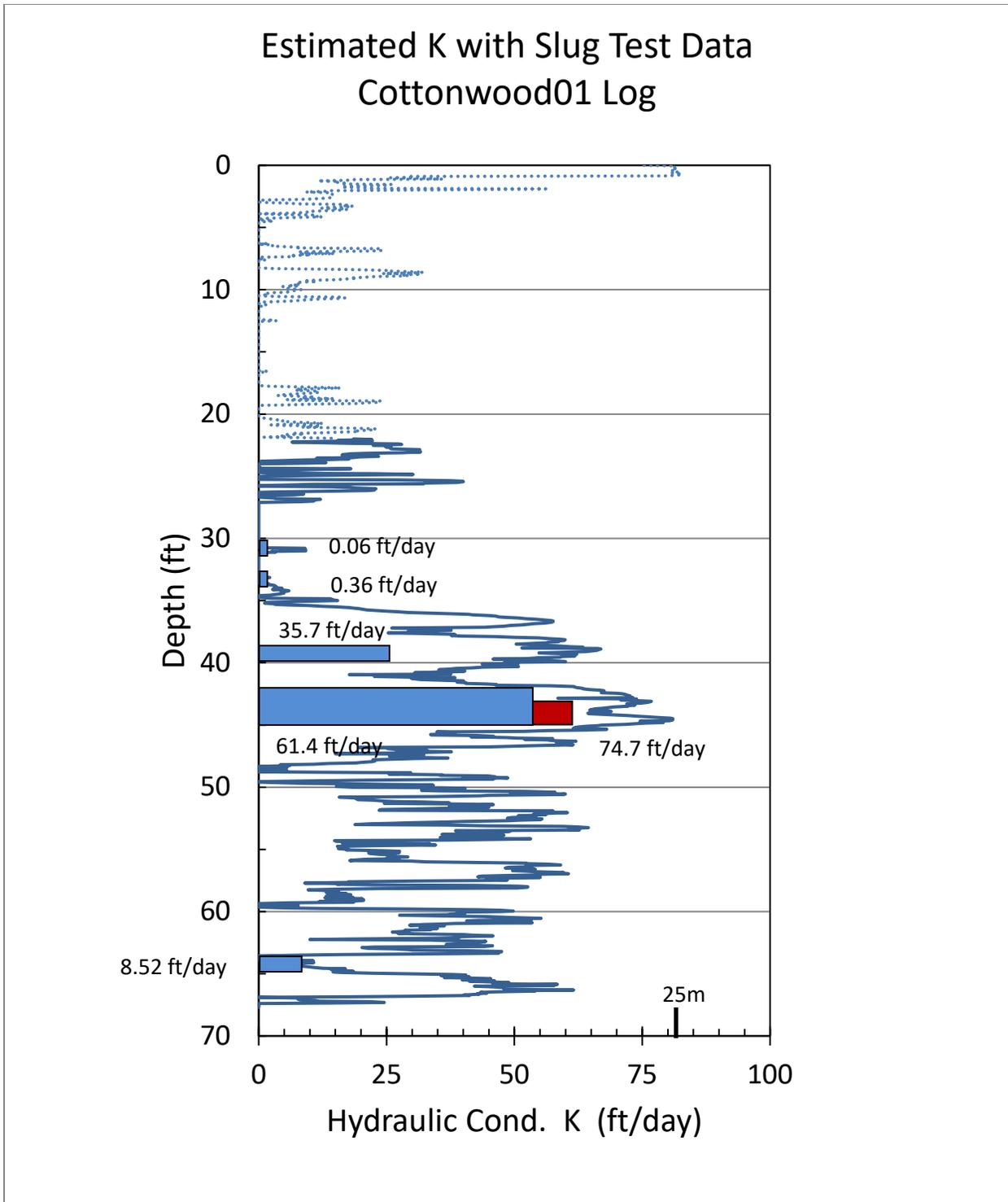


Figure 18: Log of estimated K from HPT Q/P_{inj} along with slug test results from discrete interval slug testing at this location. Slug tests were performed in SP16 groundwater samplers with a pneumatic manifold and transducer following screen development. Note: at 45ft slug tests were conducted first over a 2ft interval (43-45ft) and then over a 3ft interval (42-45ft). Estimated K shown as dashed line above the water level (After McCall and Christy, 2010).

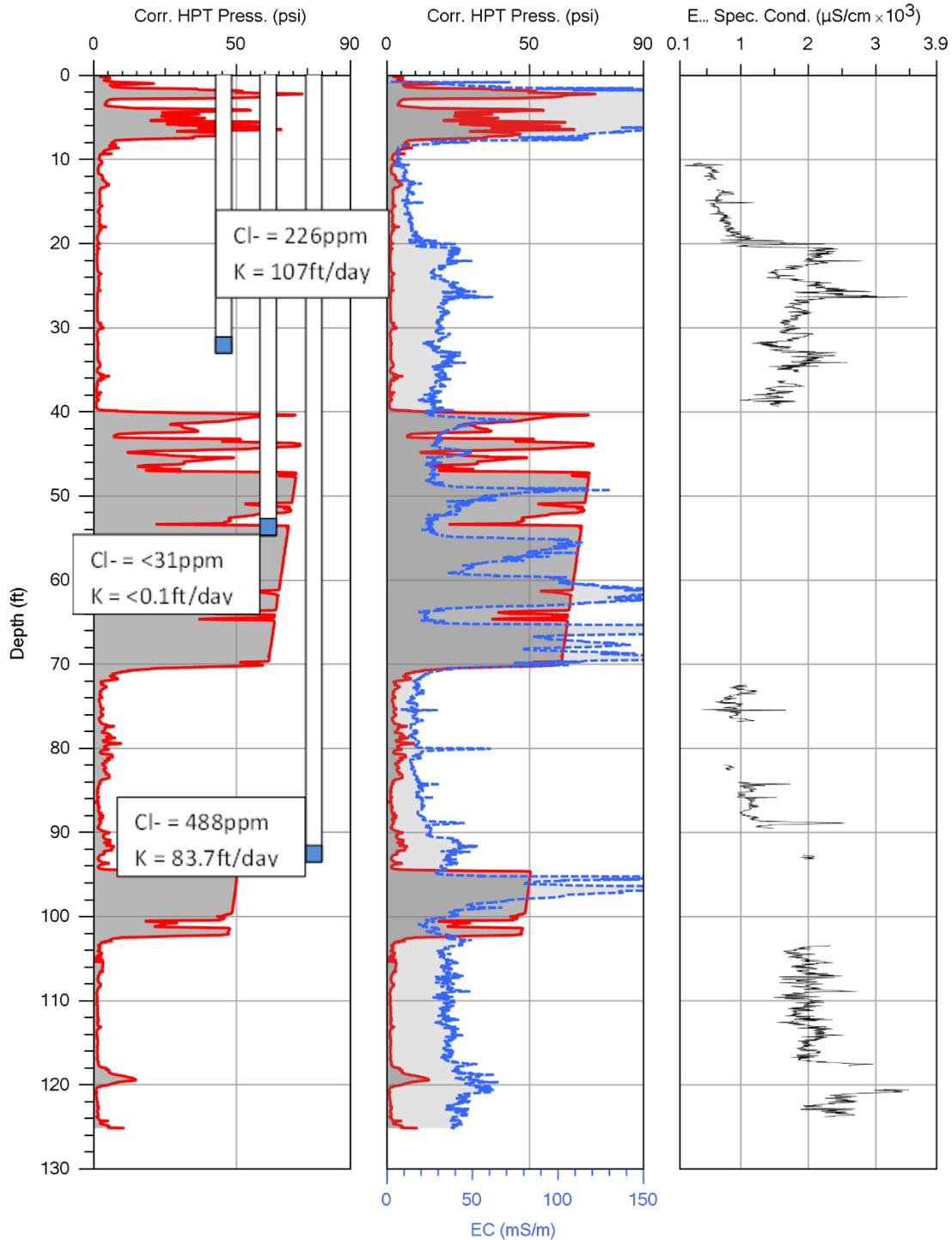


Figure 19: The left graph displays corrected HPT Pressure along with data of Chloride concentration and hydraulic conductivity measured at the indicated depth intervals with temporary piezometers. Middle is an overlay of EC and corrected HPT pressure (shaded) used to evaluate potential zones of chloride impact in this alluvial aquifer down gradient from former oil drilling and production operations. Zones where corrected HPT pressure is low (sand and gravel) but EC is elevated above a range of 10-20mS/m provides an indication of chloride impact at this site (Neshyba-Bird et al. 2009).

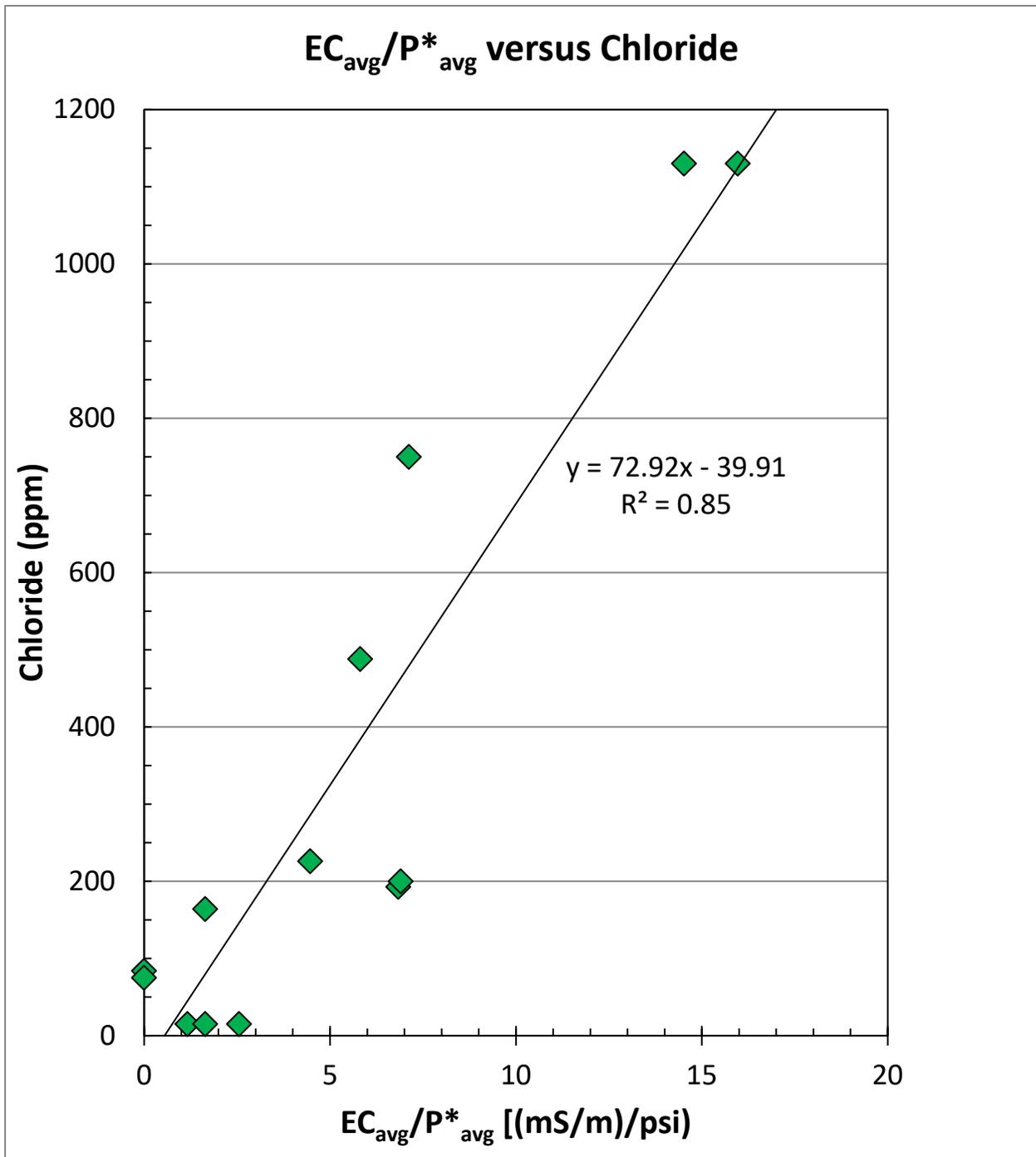


Figure 20: Data from the Halstead site was used to evaluate the relationship between chloride concentration in groundwater samples from discrete screen intervals and the ratio of the average EC to the average P_{inj} over that same depth interval. Good correlation indicates that the EC and P_{inj} data infer the presence of elevated chloride content in the groundwater at this site. Using just EC to compare to chloride will not provide a good model as EC also will be elevated where clay content of the formation is high.

Further development has enabled the calculation of Estimated Groundwater Specific Conductance (Est. GWSC) in DI Viewer (Figure 19). Archie's Law can be used, incorporating P* & EC, for appropriate unconsolidated formations to estimate the specific conductance of pore fluids that may be influencing the bulk electrical conductivity (McCall et al. 2017). For this calculation a dissipation test must have been performed and P* must be <5PSI (35kPa) (Geoprobe 2020). The model assumes that any P* <5PSI is indicative of a clean, porous formation and that the specific conductance of such a formation is negligible or zero. In such formations the pore fluid is the primary factor controlling bulk conductivity, so any discrepancy with the above assumption indicates there may be an ionic influence on groundwater. A separate study shows how Archie's Law models, with appropriate geologic parameters, trend with site data and infer groundwater quality (McCall et al. 2017) (Figure 21). At the Halstead site (Figure 19) Est. GWSC calculations correspond with zones where elevated chloride concentrations were sampled and the EC/P* ratio is greater. Hence, an Est. GWSC log can be used as an indicator of groundwater quality in permeable zones and assist in site investigations by identifying zones where targeted water sampling may be necessary. It is good practice, and is recommended, to obtain confirmation samples in contaminated zones identified by Est. GWSC values.

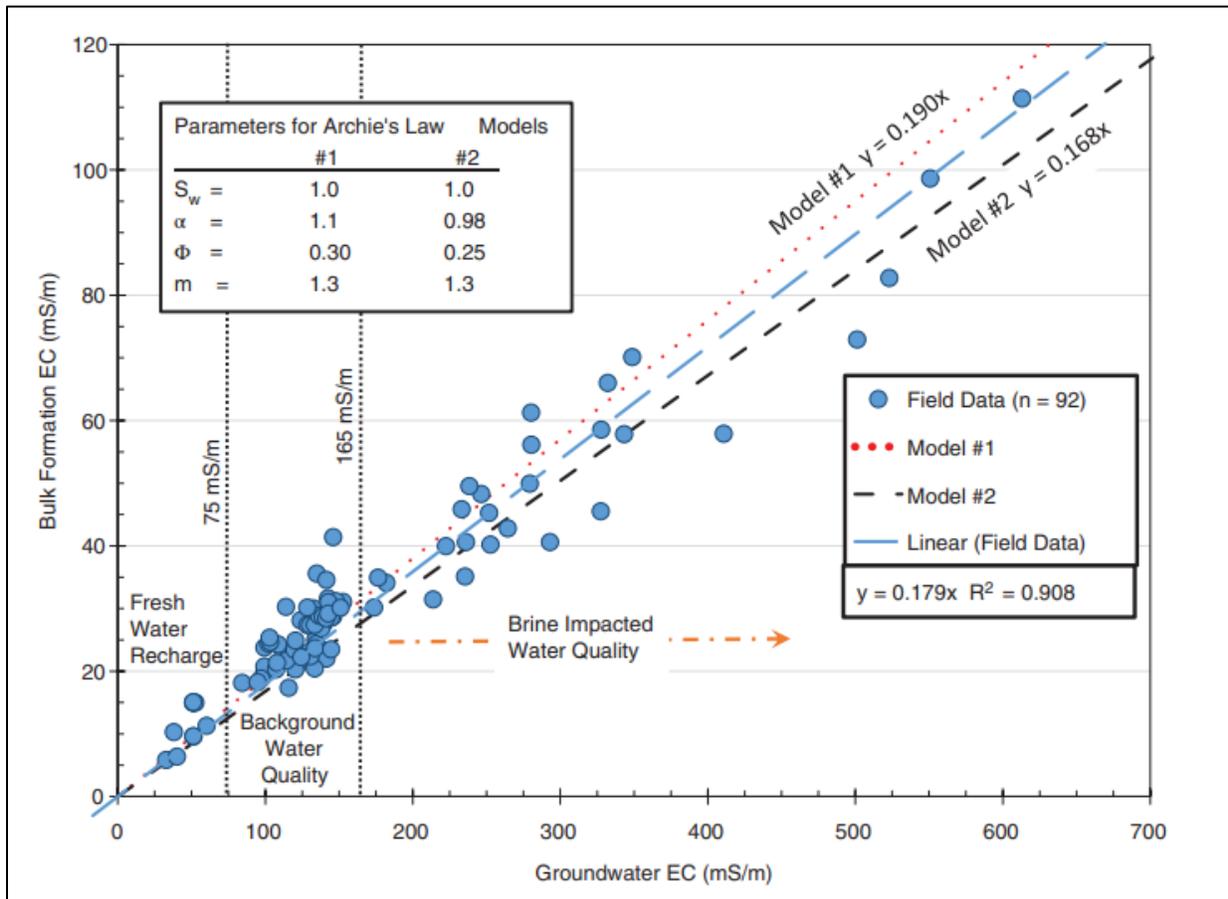


Figure 21: Data from a separate site showing the fitment of Archie's Law to field data correlating averaged bulk formation EC with measured groundwater specific conductance from multiple locations. The Archie's Law models incorporate geologically appropriate parameters and show to bracket the field data regression line. This plot shows that Archie's Law can be applied to unconsolidated sediments to estimate groundwater specific conductance.

Limitations of the HPT System

The HPT probe is designed for advancement into unconsolidated materials (clay, silt, sand±gravel) by direct push methods. It is not designed for penetration of consolidated sediments or rock. While the tool may be able to penetrate some light to moderately cemented soils (caliche) or lightly cemented sediments, the tough, indurated caliche soils or similar may be impenetrable with this tool. Very dense glacial tills and sediments with cobbles and boulders will be problematic.

In its current design and method of operation described here, the HPT system is able to resolve the permeability of soils with a hydraulic conductivity in the range of about 0.1ft/day (3.5E-5cm/sec) up to about 75ft/day (2.7E-2cm/sec), so approximately three orders of magnitude in range. Fortunately, this range is of particular value for geo-environmental investigations. At the lower end of the range the exact point where non-Darcian flow, channeling, fracturing, etc. (Figure 16) become active will vary depending on the flow rate applied, the effective pressure and the specific nature (density, grain size distribution, moisture content, cementing, etc.) of the soil or sediment being penetrated. At the upper end of the range when the formation permeability becomes high enough, the pressure required to inject fluid into the formation becomes relatively low. Under high K conditions the injection pressure may be equal to or less than the pressure resulting from the internal friction due to fluid flow in the HPT probe system. Under these conditions, the formation K is effectively above the upper limit of what the current HPT system can discern. Simply increasing flow rate to the probe will not alleviate this problem as this also increases the internal friction/pressure due to increased flow in the system. In aquifer zones where the estimated K is near the upper limit, the investigator can choose to install temporary piezometers (Geoprobe 2006c, 2010a; ASTM 2005b) across these intervals and perform slug tests (Geoprobe 2002, 2011; ASTM 2006) to more precisely define higher K zones.

The HPT probe is currently designed with a 100psi (~700kPa) pressure transducer. This is equivalent to approximately 230 feet (70m) of water pressure. In order to provide some room for resolution of high permeability materials from lower permeability materials, this gives an effective upper operating limit in the range of 80psi (550kPa), or about 180ft (~55m) below the water table in an unconfined aquifer.

The HPT pressure and flow logs give us information on the relative permeability of the materials being penetrated. We can make inferences regarding sediment type and dominant grain size, especially when the EC log is used with the HPT pressure and flow logs. However, this is just an inference without at least some sampling of the soils and sediments being logged. A fine-grained soil with abundant fractures may have permeability similar to a sandy soil. Conversely, a cemented sand and gravel sediment may have permeability similar to fine, silty clay. Log and sample wisely.

Specifications for Procuring HPT Logging Services

The experience, training and competency of the field operator for the HPT system and Geoprobe® unit will have an impact on the quality of HPT data you obtain for any project. Providing adequate specifications to your contractor or subcontractor can help assure the type and quality of data you obtain is what is required to meet your project data quality objectives. The attached outline

(Appendix IV) will provide guidance on setting up procurement specifications for HPT logging services and reporting. For further details on required equipment and tooling review the HPT operating procedure (Geoprobe 2021) and visit the Geoprobe® Direct Image website (Geoprobe-DI.com).

For quality assurance purposes it is recommended that both pre-log and post-log response tests be performed for each HPT log using the HPT Reference Tube (MN 212689 or MN211762). If the response test gives results outside of the control limit range (0.22psi ±10%: 1.5kPa ±10%) for the pressure sensor corrective measures should be taken. Often, simply removing and cleaning or replacing the HPT screen will correct the problem. If this is not successful, the pressure sensor should be replaced before proceeding with the next log. Purge all air from the trunkline and probe prior to response testing.

In order to get full benefit of the HPT log data it is necessary to run at least one dissipation test during each log. As discussed earlier, the system operator stops probe advancement, stops flow to the probe and acquires a time data file for each dissipation test. The dissipation is allowed to run until the stable, total pressure is obtained. This will allow the investigator to calculate water levels from the HPT data as well as determine corrected pressure profiles and estimate hydraulic conductivity if desired. If the formation is stratified and sand layers are interlayered with silty-clay low permeability layers dissipation tests may be needed in each sand layer to assess changes in piezometric pressure with depth in the different sand zones. This will be valuable data to assess the existence of vertical gradients in the formation or aquifer system. Run HPT dissipation tests in sandy zones for best results and efficiency.

The procurement officer also will want to assure that adequate data and information is supplied to the project manager after the logs are obtained. All HPT data files, including information files, response test data and dissipation test data for each log should be provided to the project manager in digital format for use on Geoprobe's DI Viewer® software (free software download at www.geoprobe-di.com) . Filenames should be set up to meet proposal specifications. Field/onsite reporting may be desired to assist the project manager with making onsite decisions to achieve Triad/Accelerated site characterization goals. Include any onsite reporting requirements in the project specifications.

Summary and Discussion

The hydraulic profiling tool is a powerful system that can be used to understand the subsurface geology and hydrostratigraphy in unconsolidated soils and sediments. The HPT log can be used to evaluate the presence and location of preferential migration pathways and potential aquitards. The HPT provides the investigator with logs of injection pressure and flow rate versus depth, as well as electrical conductance of the bulk formation. These logs are independent of human interpretation, unlike a soil boring log, and so are not prone to human bias. Field quality assurance/quality control tests provide confirmation of system performance and reliability.

Interpretation of the HPT pressure log is relatively simple, with higher injection pressure indicating lower permeability and lower injection pressure indicating higher permeability. Additionally, the EC log provides a measure of independent confirmation for the HPT log. Furthermore, the HPT logging system is an effective tool to accomplish one of the primary goals of a geo-environmental

investigation; that is to establish an accurate site conceptual model (CSM) of the subsurface and provide data to substantiate the model.

As reviewed above the HPT logs can be applied for many site assessment needs. These applications range from simple interpretation of local lithology/hydrostratigraphy, construction of geologic cross sections, and guiding well screen placement to more complicated applications such as guiding remedial fluids injection, delineation of brine plumes/sea water intrusion and estimation of hydraulic conductivity with inch-scale resolution. The HPT system is a useful tool for the site investigator that can save time and cost to obtain an accurate CSM and help achieve remediation objectives.

References

- American Society for Testing and Materials (ASTM), 1995. E1739 Standard Guide for Risk-Based Corrective Action at Petroleum Release Sites. ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA. www.astm.org
- ASTM, 2005. D6282-98 Standard Guide for Direct Push Soil Sampling for Environmental Site Characterization. ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA. www.astm.org
- ASTM, 2005b. D6001-05 Standard Guide for Direct-Push Ground Water Sampling for Environmental Site Characterization. ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA. www.astm.org
- ASTM, 2006. D7242 Standard Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Ground Water Samplers. ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA. www.astm.org
- ASTM, 2007. D7352 Standard Practice for Direct Push Technology for Volatile Contaminant Logging with the Membrane Interface Probe (MIP). ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA. www.astm.org
- Binder, Jeffrey L., 2008. Use of Hydraulic Profiling Tool to Identify Preferential Pathways for Chloride-Impacted Groundwater Migration. Proceedings of the Sixth International Conference on Remediation of Chlorinated and Recalcitrant Compounds: Paper F-011. Battelle, Columbus, OH. www.battelle.org/chlorcon
- Butler, James J., Jr., John M. Healey, G. Wesley McCall, Elizabeth J. Garnett and Steven P. Loheide, 2002. Hydraulic Tests with Direct-Push Equipment. Ground Water Vol. 40, No. 1. January-February. Pages 25-36.
- Butler, James J., Jr., P. Dietrich, V. Wittig and T. Christy, 2007. Characterizing Hydraulic Conductivity with the Direct-Push Permeameter. Ground Water, Vol. 45, No. 4. Pages 409-419.
- Christy, Colin D., Thomas M. Christy and Volker Wittig, 1994. A Percussion Probing Tool for the Direct Sensing of Soil Conductivity. Geoprobe Systems, Salina, KS. 15 pages.
- Christy, Thomas M., 1996. A Permeable Membrane Sensor for the Detection of Volatile Compounds in Soil. In Proceedings of the NGWA Outdoor Action Conference, Las Vegas, NV. NGWA Westerville, Ohio. May.

Dietrich, Peter, James J. Butler and Klaus Faiß, 2008. A Rapid Method for Hydraulic Profiling in Unconsolidated Formations. *Ground Water*, Vol. 46, No. 2. March-April. Pages 323-328.

Dobrin, Milton B., 1976. *Introduction to Geophysical Prospecting*. McGraw-Hill, New York, NY.

Elsworth, D., and D.S. Lee, 2007. Limits in Determining Permeability from on-the-Fly μ CPT Sounding. *Geotechnique* Vol. 57, No. 8. Pages 679-685.

Fetter, Charles W., 1994. *Applied Hydrogeology*, 3rd Edition. Prentice-Hall, Upper Saddle River, NJ.

Geoprobe 2002, Geoprobe® Pneumatic Slug Test Kit: Standard Operating Procedure, Tech. Bul. 19344. Revised December 2005. Replaced, January 2011. Kejr Inc., Salina, KS. www.geoprobe.com

Geoprobe, 2003. *Geoprobe® Systems Tools Catalog*, V.6. Kejr Inc., Salina, KS. www.geoprobe.com

Geoprobe, 2006a. Hydrostratigraphic Characterization Using the Hydraulic Profiling Tool (HPT). Tech. Bul. No. MK3099. Kejr Inc. Salina, KS. April. www.geoprobe.com

Geoprobe, 2006b. Geoprobe® Macro-Core® MC5 : 1.25-inch Light-Weight Center Rod Soil Sampling System, Standard Operating Procedure. Tech. Bul. No. MK3139. Kejr Inc. Salina, KS. November. www.geoprobe.com

Geoprobe, 2006c. Geoprobe® Screen Point 16 Groundwater Sampler, Standard Operating Procedure. Tech. Bul. No. MK3142. Kejr Inc., Salina, KS. www.geoprobe.com

Geoprobe, 2010a. Geoprobe® SP22 Groundwater Sampler, Standard Operating Procedure. Tech. Bull. No. MK3173. Kejr Inc. Salina, KS. April. www.geoprobe.com

Geoprobe, 2010b. Tech Guide for Calculation of Estimated Hydraulic Conductivity (Est. K) Log from HPT Data. Kejr Inc. Salina, KS. November. www.geoprobe.com

Geoprobe, 2011. Geoprobe® Pneumatic Slug Test Kit (GW1600):Installation and Operation Instructions, Instructional Bul. #MK3181. Kejr Inc., Salina, KS. January. www.geoprobe.com

Geoprobe, 2020. Direct Image® Viewer User Guide. Kejr Inc., Salina, KS. [DIVIEWERUserGuide.pdf](http://www.geoprobe.com/DIVIEWERUserGuide.pdf)

Geoprobe, 2021. Geoprobe® Hydraulic Profiling Tool (HPT) System, Standard Operating Procedure. Tech. Bull. No. MK3137. Kejr Inc. Salina, KS. March. www.geoprobe.com

Griffin, Terry W., and Kenneth W. Watson, 2002. A Comparison of Field Techniques for Confirming Dense Nonaqueous Phase Liquids. *Ground Water Monitoring & Remediation*, Vol. 22, No.2. Spring. Pages 48-58.

Interstate Technology & Regulatory Council (ITRC), 2008. *Use of Risk Assessment in Management of Contaminated Sites: RISK-2*. ITRC 444 North Capitol Street, NW, Suite 445, Washington, DC. August. www.itrc.org

Keys, W. Scott, 1997. *A Practical Guide to Borehole Geophysics in Environmental Investigations*. CRC/Lewis Publishers, Boca Raton, FL. 176 pages.

Kram, Mark, Gary Robbins, Jessica Chau, Amvrossios Bagtzoglou, Daniel Eng, and Norm Jones, 2008. Detailed Hydraulic Assessment Using a High-Resolution Piezocone Coupled to the GeoVIS. NAVFAC Technical Report TR-2291-ENV, ESTCP Project CU-0421. Engineering Service Center, Port Hueneme, CA. April.

Lee, Dae Sung, Derek Elsworth and Roman Hryciw, 2008. Hydraulic Conductivity Measurement from On-the-Fly μ CPT Sounding and from VisCPT. *Journal of Geotech. And Geoenviron. Eng.*, Vol. 134, No. 12. Pages 1720-1729. December.

Liu, Gaisheng, James J. Butler Jr., Geoffrey C. Bohling, Edward Reboulet, Steve Knobbe and David W. Hyndman, 2009. A New Method for High-Resolution Characterization of Hydraulic Conductivity. *American Geophysical Union: Water Res. Research*, Vol. 45. W08202. 6 pages.

McCall, Welsey, Christy, Thomas M. and Ewald, Mateus K, 2017. Applying the HPT-GWS for Hydrostratigraphy, Water Quality and Aquifer Recharge Investigations. *Groundwater Monit R*, 37: 78-91. <https://doi.org/10.1111/gwmmr.12193>

McCall, Wesley, James J. Butler Jr., John M. Healey, Alyssa A. Lanier, Stephen M. Sellwood and Elizabeth J. Garnett, 2002. A Dual-Tube Direct-Push Method for Vertical Profiling of Hydraulic Conductivity in Unconsolidated Formations. *Environ. & Eng. Geoscience*, Vol. VIII, No. 2. May. Pages 75-84.

McCall, Wesley and Thomas M. Christy, 2010. Development of a Hydraulic Conductivity Estimate for the Hydraulic Profiling Tool (HPT). The 2010 North American Environmental Field Conference & Exposition: Conference Program with Abstracts: Session VII. January. www.envirofieldschool.com

Neshyba-Bird, Dolores, Marcia K. Schulmeister, G. Wesley McCall, and Thomas M. Christy. Direct-Push Electrical Conductivity Assessment of an Historic Brine Plume in the Equus Beds Aquifer, KS. Geological Society of America. http://gsa.confex.com/gsa/2010NC/finalprogram/abstract_171297.htm

Robertson, P.K., J.P. Sully, D.J. Woeller, T. Lunne, J.J.M. Powell and D.G. Gillespie, 1992. Estimating Coefficient of Consolidation from Piezocone Tests. *Can. Geotech. J.* Vol. 29. Pages 539-550.

Schulmeister, M.K., J.J. Butler, Jr., J.M. Healey, L. Zheng, D.A. Wysocki and G.W. McCall, 2003. Direct-Push Electrical Conductivity Logging for High-Resolution Hydrostratigraphic Characterization. *Ground Water Mon. & Rem.* Vol. 23, No. 3. Summer. Pages 52-62.

U.S. Environmental Protection Agency (EPA), 1998. *Seminars: Monitored Natural Attenuation for Ground Water*. Office of Research and Development, Washington, D.C. EPA/625/K-98/001. September.

U.S. EPA, 2000. Innovations in Site Characterization: Geophysical Investigation at Hazardous Waste Sites. OSWER (5102G), Washington, D.C. EPA 542-R-00-003. August. www.epa.gov/tio

U.S. Geological Survey (USGS), 1992. Water Supply Paper 2254: Study and Interpretation of the Chemical Characteristics of Natural Water, 3rd Edition. U.S. Dept. of the Interior. U.S. Government Printing Office, Washington, D.C. 263 pages with attachments.

Wilson, John T., Randall R. Ross and Steven Acree, 2005. Using Direct-Push Tools to Map Hydrostratigraphy and Predict MTBE Plume Diving. *Ground Water Mon. & Rem.* Vol. 25, No. 3. Summer. Pages 93-102.

List of Appendices

I. HPT System Tool Configuration and System Components

II. The HPT Information File

III. Detailed Log Review Regarding the Assessment of Brine or Seawater Impact

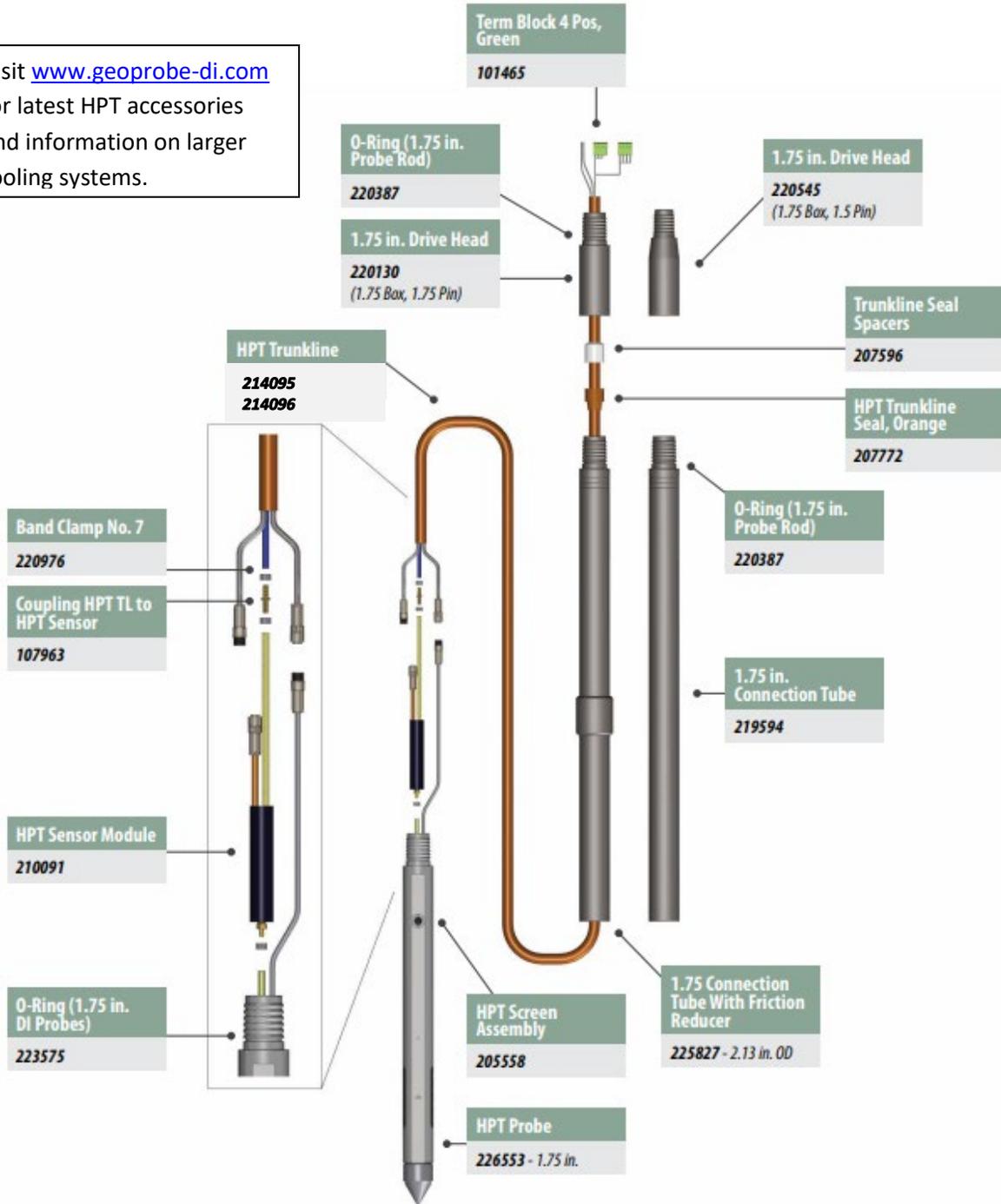
IV. Outline of Specifications for Procuring HPT Logging Services

Appendix I

HPT Tool Configurations and System Components

HPT Probe, Connection Tube and Trunkline Assembly for 1.5 or 1.75-inch Rod System

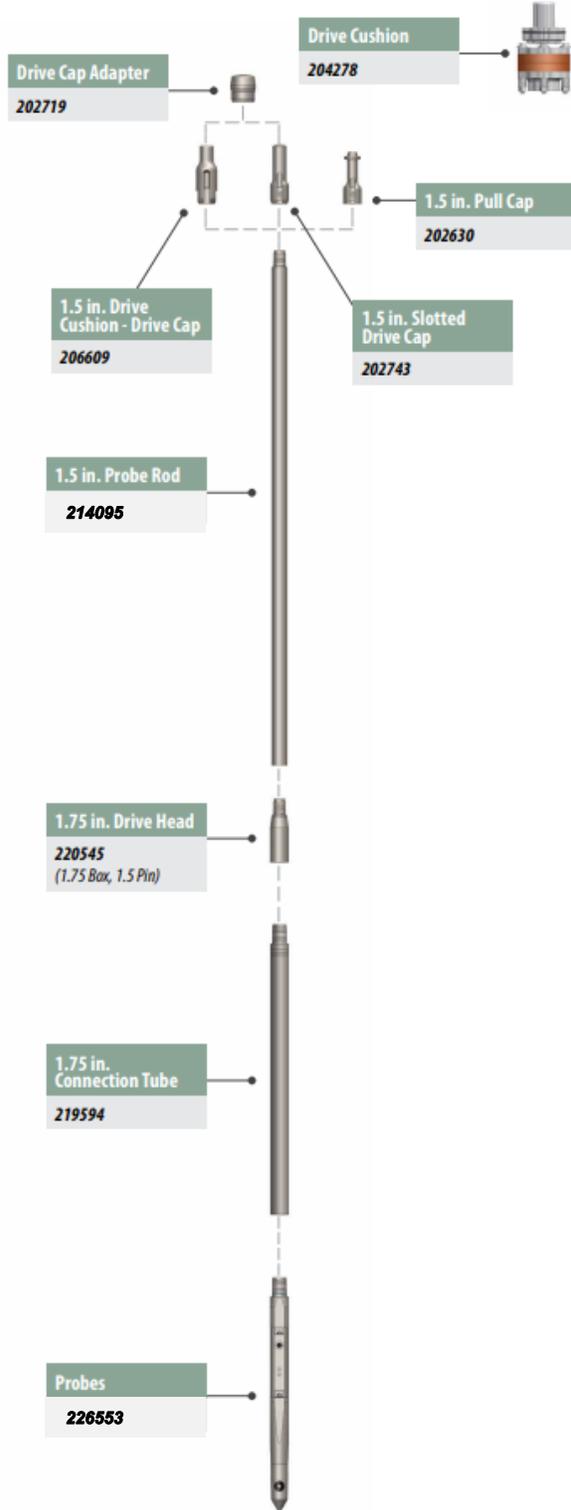
Visit www.geoprobe-di.com for latest HPT accessories and information on larger tooling systems.



HPT Tool Configurations and System Components

(continued)

1.5-inch Drive Rods and Accessories for HPT Logging



Components	Part	MN	Notes
	Drive Cap Adapter	202719	GH40 to GH60 Series
	1.5 in. Drive Cushion	206609	Slotted, Threadless
	1.5 in. Slotted Drive Cap	202743	GH40, Threaded
	1.5 in. Pull Cap	202630	Slotted
		201682	60 in.
		202248	48 in.
		207261	36 in.
		202715	24 in.
		203193	1 m
	1.75 in. Drive Head	220545	1.75 Box x 1.5 Pin
	1.75 in. Connection Tube	219594	
	Connection Tube LB Pin and Box	206304	
	LB Box x 1.5 Pin	203794	3.73 in. S-S
	Rod Wiper Weldment	204387	
	Rod Wiper Donut	600341	1.25 in. / 1.5 in. / 1.75 in.
	RG Handle Assembly	202724	1.25 in. / 1.5 in., GH60
	RG Jaw	202660	1.25 in. / 1.5 in., GH60
	Drive Cushion	204278	Use with GH40 Drive Cap

Probes

Components	Part	MN	Notes
	MIHPT Probe Square	226720	1.75 in.
	OIHPT-UV Probe	227466	UV275
	OIHPT-G Probe	231346	GL525
	HPT Probe	226553	1.75 in.

Visit www.geoprobe-di.com for latest HPT accessories and information on larger tooling systems.

Appendix II

The HPT Information File

shop test 1.zip

SITE INFORMATION -- DIRECT IMAGE HPT PROBE

Geoprobe DI Acquisition Software for Windows
Version: 3.6 Build: 22041

Pre-Log EC Load Tests

Test	Target (mS/m)	Actual (mS/m)	% Diff	P/F
Test 1	195.0	197.3	1.2	PASS
Test 2	97.0	98.3	1.3	PASS
Test 3	24.0	23.7	1.2	PASS

COMPANY: Geoprobe
OPERATOR: NB
PROJECT ID: test
CLIENT: Engineers
UNITS: ENGLISH
PROBE AND ARRAY: K6050 HPT Probe with Wenner
LOCATION: shop
100 INCH STRING POT USED
ROD LENGTH: 5 feet

PRE-LOG HPT REFERENCE TEST VALUES

PRE TEST TIME: Wed May 24 2023 13:50:45

TEST	HPT PRESSURE (psi)	FLOW (mL/min)	HPT PRESSURE (kPa)
TOP with FLOW=0	15.481	0.0	106.740
TOP with FLOW>0	16.928	284.7	116.720
BOTTOM with FLOW=0	15.256	0.0	105.190
BOTTOM with FLOW>0	16.630	289.4	114.660

EXPECTED FLOW=0 HPT DIFF.: 0.22 psi (1.5 kPa) +/- 10%
ACTUAL FLOW=0 HPT DIFF.: 0.22 psi (1.5 kPa)

TRANSDUCER TEST PASSED

HPT IDEAL COEFFS: 2.2696e1, -2.2356
HPT SENSOR CAL NUMBERS: XD31679A, 0.0000, 0.0000, 0.0000, 0.0000, 9.9530e-1, -1.4320
LOG START TIME: Wed May 24 2023 13:55:00

The HPT Information File

(Continued)

LOG END DEPTH: 38.80 ft (11.826 m)
LOG END TIME: Wed May 24 2023 15:30:05

LATITUDE: 0.00000000
LONGITUDE: 0.00000000
ELEVATION: 0.000 METERS 0.00 FEET
GPS Quality: None

POST-LOG HPT REFERENCE TEST VALUES

POST TEST TIME: Wed May 24 2023 15:47:05

TEST	HPT PRESSURE (psi)	FLOW (mL/min)	HPT PRESSURE (kPa)
TOP with FLOW=0	15.404	0.0	106.210
TOP with FLOW>0	15.695	291.1	108.210
BOTTOM with FLOW=0	15.176	0.0	104.640
BOTTOM with FLOW>0	15.474	290.4	106.690

EXPECTED FLOW=0 HPT DIFF.: 0.22 psi (1.5 kPa) +/- 10%
ACTUAL FLOW=0 HPT DIFF.: 0.23 psi (1.6 kPa)

TRANSDUCER TEST PASSED

Post-Log EC Load Tests

Test	Target (mS/m)	Actual (mS/m)	% Diff	P/F
Test 1	195.0	198.2	1.6	PASS
Test 2	97.0	98.4	1.4	PASS
Test 3	24.0	24.3	1.1	PASS

***** USER NOTES *****

HPT log Hadensville, VA. No issues reported during acquisition of log.

Appendix III

Detailed Log Review Regarding the Assessment of Brine or Seawater Impact

(Notes for the HPT Log in Figures 12 and 19)

Some details to note about this log:

- 8-10 ft: low EC, correlates with dry sand above water level.
- 10-20ft: EC slowly rises while pressure slowly drops & Est. GWSC also begins to increase.
 - Suggests increasing EC not due to fines.
- 20-40ft: EC goes up and stays around 40mS/m while pressure stays low.
 - Est. GWSC is elevated to an approximate average of 2,000 $\mu\text{S}/\text{cm}$.
 - Suggests elevated ionic content in this zone.
 - Groundwater sample at 30-32 ft = 226ppm chloride.
- 40-70ft: Spikes/peaks in EC correlate with increased pressure over this zone.
 - Indicates elevated EC and pressure due to lower permeability and increased clay content across this interval.
 - No Est. GWSC calculation since $P^* > 5$ PSI.
 - Groundwater sample at 52-54 ft = <31ppm chloride.
- 70-94ft: Slowly rising EC and some variability in low pressure across this interval.
 - Intervals of slightly higher pressure suggest some clay may be present in those intervals.
 - Slowly increasing EC & Est. GWSC indicate ionic content may slowly increase.
 - Groundwater sample at 90-92ft = 488ppm chloride.
- 94-104: Higher EC and increased pressure.
 - Indicates lower permeability and increased clay content.
- 104-125: EC at about 40mS/m and low pressure except at about 120ft.
 - Increased Est. GWSC to approximately 2,000 $\mu\text{S}/\text{cm}$.
 - Indicates some ionic content in sandy saturated formation.
 - Increase EC and P around 120ft indicates increased clay (clay lens).
 - No water samples collected in this zone.

To summarize, the basic relationships between EC and P^* are:

- When EC is relatively high, HPT pressure is low & Est. GWSC is elevated then there is potential for ionic impact in the saturated aquifer.
- When both EC and pressure are relatively high this generally correlates with elevated clay content and reduced permeability.
- Low EC and low HPT pressure generally indicate coarse grained aquifer materials without ionic impact.

Targeted groundwater samples and slug tests from three zones at this location (Figure 19) confirm this general relationship.

Appendix IV

Specifications for Procuring HPT Logging Services

The experience, training, and competency of the field operator for the HPT system and Geoprobe® unit will have a significant impact on the quality of HPT data you obtain for any project. Providing adequate specifications to your contractor or subcontractor can help assure the type and quality of data you obtain is what is required for your project data quality objectives. The following outline will provide guidance on setting up procurement specifications for HPT logging services and reporting. For further details on required equipment and tooling review the HPT operating procedure (Geoprobe Technical Bulletin # MK3137).

HPT System Specifications

- Data Acquisition rate 5Hz
- Recommended Probe Advancement Rate 2cm/sec
- Electrical Conductivity Array Wenner Array, 4-pole electrode
 - Optional dipole electrode array
- Working Depth Maximum (100 psi) 180ft (55m) below water table
- Depth Tracking : String Pot MN 214227 – 100” or 80” options
- HPT controller/pump (MN 214091) 0-1000 ml/min: 500psig max

HPT Probe & Trunkline Specifications

- HPT Probe : 1.5 or 1.75-inch rod system MN 226553
- HPT Probe : 2.25-inch rod system MN 214097
- HPT Screen, stainless steel, replaceable MN 205558
- Pressure Sensor, 0-100 psi (0-690kPa) MN 210091
(± 2.5% full scale: max over pressure 400psi/2500kPa)
- Trunkline, 150ft length/120ft depth MN 214095

Computer Software & Hardware Specifications

(The field instrument FI6000 and a portable computer will be required.)

- FI6000 Field Instrument MN 213940
- DI Acquisition Software Most recent version
- DI Viewer Software Most recent version

HPT System Power Requirements

- The HPT system, including all electronics, computer, and pump, may be operated from a single 15amp, 120V circuit. This is easily supplied by an inverter style portable generator.

Geoprobe Unit specifications

- To advance 1.5 or 1.75-inch rod system HPT 5400, 6600 and 7000 Series Machines
(e.g. 6620DT, 7822DT etc.)
- To advance 2.25-inch rod system HPT 7000, 3100, 3230, & 8000 Series Machines
(e.g. 3100GT, 3230DT, 7822DT, 7730DT, 8040DT etc.)

Data & Reporting Specifications (in field/final)

- In Field: print of log and/or digital copy with ID and location information
- Final reporting:
 - Digital files complete with all field QA test results.
 - Summary table of log filenames, total depths, locations, and description of any deviations from protocol or work plan.

Field Quality Assurance/Quality Control Specifications

HPT Reference Tube	MN 212689 or MN 211762
EC Test Load	MN 208075
EC Test Jig	MN 214237
Pre-log pressure transducer response test and EC Array test load results.	
Post log pressure transducer response test and EC Array test load results.	
Dissipation tests (minimum 1 per log)	

Tool String Specifications for 1.5 & 1.75-inch Rod System

(See Appendix I or www.geoprobe-di.com)

Tool String Specifications for 2.25" Rod System

(See Appendix I or www.geoprobe-di.com)

Equipment and tool specifications, including weights, dimensions, materials, and operating specifications included in this document are subject to change without notice. Where specifications are critical to your application, please contact Geoprobe® Systems.

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