FINAL REPORT

Determining Source Attenuation History to Support Closure by Natural Attenuation

ESTCP Project ER-201032

September 2013

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14. ABSTRACT

An innovative approach for reconstructing the contaminant concentration vs. time trend—i.e., the "source history"—for a site using high-resolution soil data from low permeability (low-k) zones was tested during this project. Essentially, soil cores in these zones serve a similar role as tree rings, in that the cores store information about historic environmental conditions. For the case of contaminants that have migrated into low permeability zones via diffusion and slow advection, the concentration vs. depth profile can be used to determine if attenuation of the contaminant source in the overlying transmissive zones has occurred. This can be an important line of evidence for evaluating the viability of monitored natural attenuation for evaluating the viability of monitored natural attenuation for site management. The project demonstrated high-resolution sampling methods.

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ACRONYMS

CPT	Cone Penetration Testing
CSU	Colorado State University
CVOC	Chlorinated Volatile Organic Compound
D	Dimensional
DCA	Dichloroethane
DCE	Dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved oxygen
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
ft bgs	Feet below ground surface
GSI	GSI Environmental Inc.
GW	Groundwater
HASP	Health and Safety Plan
HPT	Hydraulic Profiling Tool
I_k	Index of hydraulic conductivity
LIF	Laser-induced fluorescence
MAROS	Monitoring and Remediation Optimization Systems
MIP	Membrane Interface Probe
MNA	Monitored Natural Attenuation
MTBE	Methyl tert-butyl ether
MW	Monitoring Well
NAS	Naval Air Station
OD	Outer diameter
ORP	Oxidation-reduction potential
OU	Operable Unit
PCE	Tetrachloroethene
PVC	Polyvinyl chloride
RI/FS	Remedial Investigation/Feasibility Study
RMS	Relative Mean Square
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
SC	Specific conductance
SERDP	Strategic Environmental Research and Development Program
SVE	Soil Vapor Extraction
TCA	Trichloroethane
TCE	Trichloroethene
UG	University of Guelph
VC	Vinyl Chloride
VOC	Volatile Organic Compound

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This report presents the results and conclusion from a collaborative project between researchers at GSI Environmental, Inc. (GSI) and the University of Guelph (UG) This demonstration project was funded by the Environmental Security Technology Certification Program (ESTCP), with the main goal of demonstrating the utility of source history modeling of contaminant distributions in lower permeability zones as a line of evidence to assess concentration history in higher permeability zones at the interfaces with the lower permeability zone, and hence support natural attenuation assessment at contaminated sites since such datasets can support inferences that concentrations are stable or declining.

Investigators for this project included Dr. Charles Newell (Principal Investigator, GSI), Dr. David Adamson (GSI), Dr. Beth Parker (UG), and Steven Chapman, M.Sc. (UG). Field work was completed by Mr. Chapman, Adam Gilmore (UG), Dr. Adamson, Nicholas Mahler (GSI), and Poonam Kulkarni (GSI). Several personnel at Stone Environmental Inc., including Seth Pitkin and Mike Rossi, were instrumental in helping design and implement the field programs. We gratefully acknowledge Michael Singletary (NAVFAC) for his help in identifying and coordinating the work at Naval Air Station Jacksonville. Other site personnel that provided valuable support include Tim Curtain and Bill Respet. Geoprobe drilling was conducted by James Laymon of Probe Domain. Laboratory extractions and analyses of soil samples for VOCs was conducted by Maria Gorecka (UG).

The modeling tool that was generated as part of this project was developed by Shala Farhat and Phil DeBlanc (GSI Environmental) with additional technical support and testing by Mr. Mahler and Dr. Adamson. Numerical modeling was completed by Mr. Chapman.

Additional technical support was provided by Dr. Thomas Sale (Colorado State University) and Doug Mackay (University of California, Davis).

Finally, the project team wishes to thank Dr. Andrea Leeson, Dr. Jeff Marqusee, and the support staff from the ESTCP program office for their help and guidance throughout the demonstration.

EXECUTIVE SUMMARY

Key Points

- Like tree rings, high resolution soil sampling of low-k zones can be used to evaluate the *style* of source history that unfolded at contaminated groundwater sites. By "style" we mean the general historical pattern of concentration and composition vs. time over the span of decades at the location where the soil core was collected (see **Exhibit 1** next page, and **Figure ES.2**).
- Source histories were successfully reconstructed by the GSI Environmental and University of Guelph project team at two sites at Naval Air Station Jacksonville (see **Figure ES.1** below) using a simple and free software model developed as part of this project.
- The arrival time and historical composition of the plumes were reconstructed from the period 1962 onward at one site and 1971 at the second site. At the first site (Building 106), the source reconstructions showed relatively constant source concentrations since 1961, but significant attenuation over time in the transmissive zone plume downgradient of the source. At the second site (Building 780), source concentrations showed approximately a one order of magnitude reduction since 1971, attenuation in the source transmissive zone but apparently less attenuation in the downgradient transmissive zone plume.
- The source reconstruction method appeared to reflect site remediation efforts (excavation and SVE) that were implemented at the second site in the 1990s. In addition, the potential transition from TCE to 1,1,1-TCA seemed to be reflected in the data.
- Finally, a detailed analysis using molecular biological tools, isotopes, patterns of degradation products, and other lines of evidence suggested that majority of the degradation activity at both these particular sites is associated with the high-k zones compared to low-k zones.

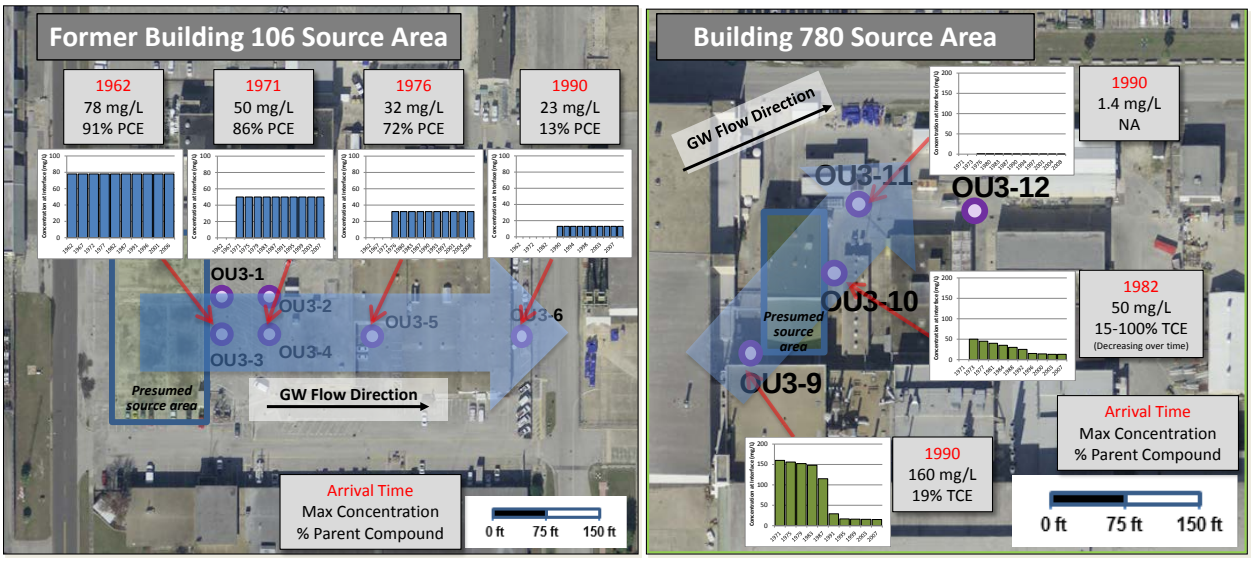
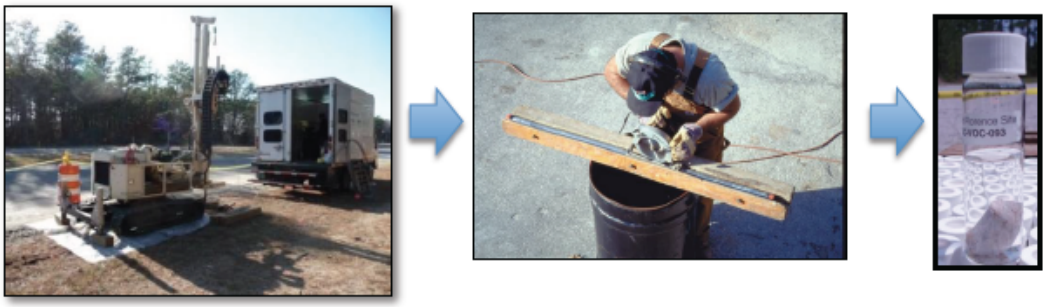
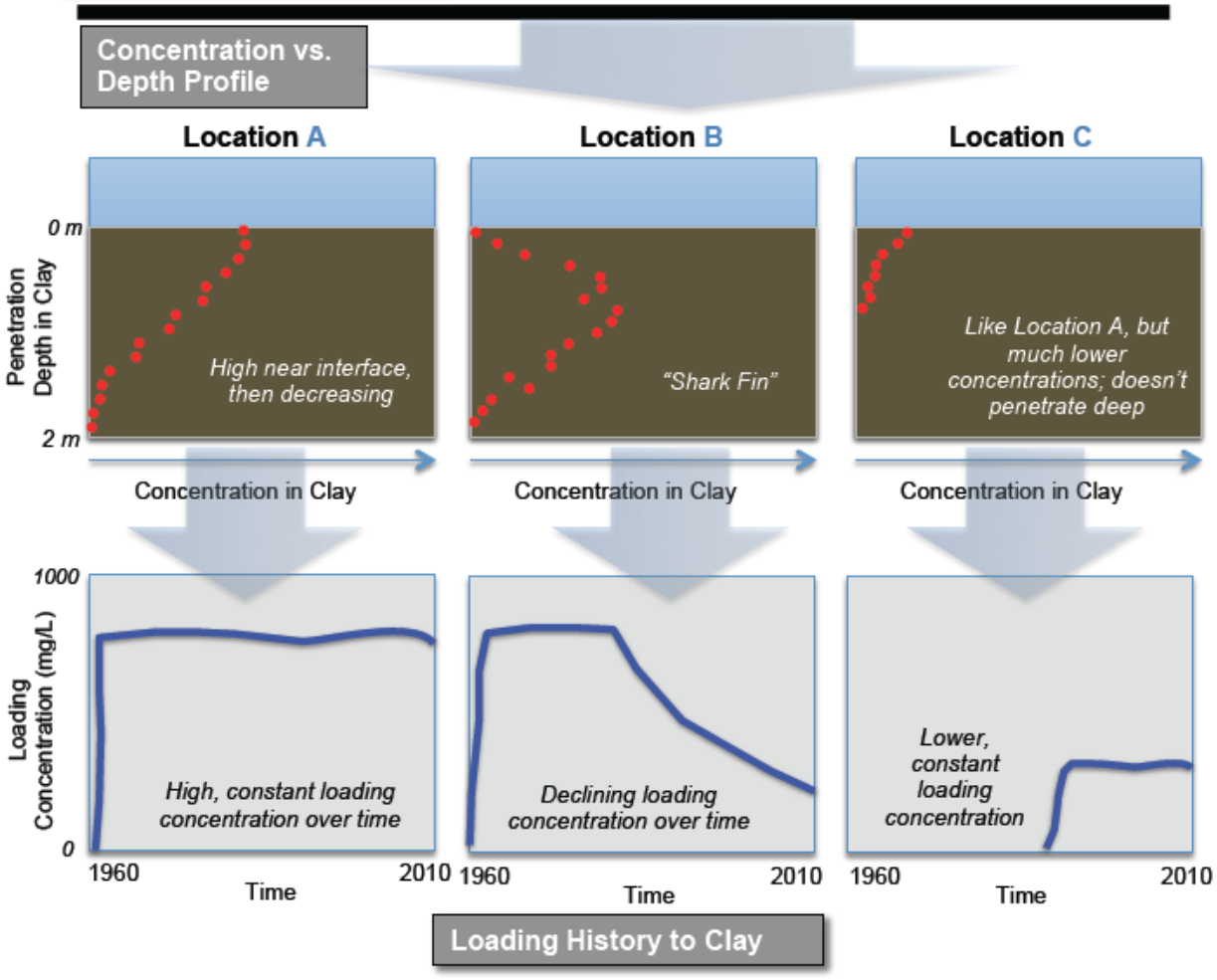


Figure ES.1. Plume Arrival Times Based on Source History Modeling Results at Former Building 106 Source Area and Building 780 Source Area. Dates reflect plumes arrival, concentrations reflect total chlorinated ethenes in the transmissive zone starting at that date, and percentages reflect contribution of parent compound (PCE or TCE) to total chlorinated ethene concentration.

EXHIBIT 1
Reconstructing Source Histories from High-Resolution Sampling of Low-k Zones: Conceptual Example

1. First collect high-resolution data to find the interfaces between contaminated transmissive zones and underlying/overlying low-k zones (typically clays or silts).
2. Then find the concentration vs. penetration depth profile in the low-k zone.
3. With this data, the general style of the long-term source history in the transmissive zone at the location the core was collected can be estimated.





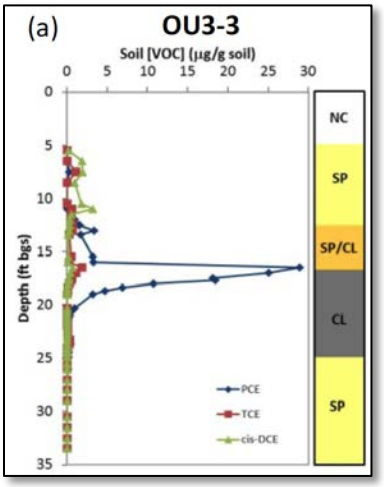
Overview

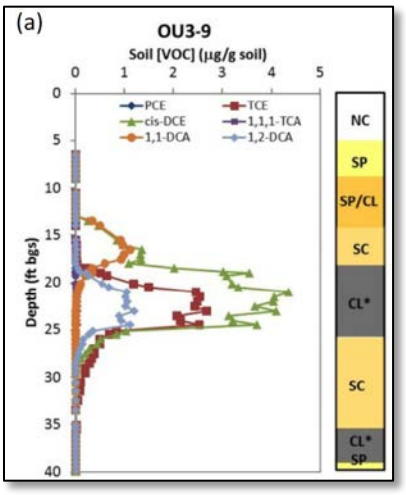
An innovative approach for reconstructing the contaminant concentration vs. time trend—i.e., the "source history"—for a site using high-resolution soil data from low permeability (low-k) zones was tested during this project. Essentially, soil cores in these zones serve a similar role as tree rings, in that the cores store information about historic environmental conditions. For the case of contaminants that have migrated into low permeability zones via diffusion and slow advection, the concentration vs. depth profile can be used to determine if attenuation of the contaminant source in the overlying transmissive zones has occurred. This can be an important line of evidence for evaluating the viability of monitored natural attenuation for site management. The project demonstrated high-resolution sampling methods and developed a simple transport-based spreadsheet tool for generating source history estimates from high-resolution data. To validate the tool, data was collected from two different source areas located at the Naval Air Station Jacksonville, and soil core data from other sites was used to supplement the evaluation.

Based on the results and an evaluation of the project performance objectives, the key conclusions from the project include the following:

- The overall concept of using high-resolution data from low-k zones to reconstruct source histories was successfully verified in the field (see **Figure ES.1** and **Exhibit 1**, next page). The arrival time and historical composition of the plumes were reconstructed from the period 1962 onward at one site and 1971 at the second site. The method appeared to capture site remediation efforts (excavation and SVE) that were implemented at one site in the 1990s. The transition from TCE to 1,1,1-TCA was also reflected in the data. Finally, the analysis suggested that the majority of the degradation activity at these particular sites is associated with the high-k zones compared to low-k zones.

- A constant chlorinated ethene source concentration was reconstructed over the period 1962 onward at one of two NAS Jacksonville source areas (Building 106). This was consistent with the measured soil concentration profiles where the maximum concentrations were encountered at the transmissive/low-k interface and then decreased moving into the low-k clay. The release date predicted for the near-source location, as well as the subsequent arrival dates at downgradient locations, were consistent with site characteristics. While the concentrations at each location were predicted to be relatively constant over time, historical attenuation in the transmissive zone along the plume flowpath was detected by sampling data from the low-k unit.





- A declining chlorinated ethenes source concentration over time was reconstructed over the period 1971 onward at the second source area investigated at NAS Jacksonville (Building 780). This was consistent with a peak soil concentration that was encountered below the transmissive/low-k interface several feet into the low-k clay. This result provided a line of evidence for a reduction in source strength in the transmissive zone over time. With the exception of one constituent (1,2-DCA), no evidence for decay of chlorinated ethane sources was obtained from co-located soil core data at this site. Again, the release and arrival dates that were predicted by the model were consistent with available site information.
- The modeling software developed for this project—***the ESTCP Source History Tool***—is easy to use for estimating source histories from soil core data. It was successful at modeling data from the source areas that were part of this project, and, using data from other sites, it was able to generate source history estimates that were similar to existing estimates and/or site information. Consequently, it enhances our understanding of the style of source history that is likely for a site.
- Understanding the potential impact of degradation is an important component of the source history approach. The modeling tool incorporates a degradation option within the low-k zone by including a constituent half-life as an input parameter. While the default assumption is that degradation is minimal in low-k zones, a focused sampling and analysis program to assess biodegradation in the low-k zones at one of the NAS Jacksonville source areas was completed. This included the use of molecular biological tools, compound-specific isotope analysis, geochemical parameters, as well as the relative distribution of parent compounds vs. degradation by-products.
- The majority of degradation was occurring in the high-k zone and not the low-k zone at these two sites.
- Soil sampling indicated that the fraction of organic carbon (f_{oc}) levels for the clay (median 0.0018 g/g) were approximately three times higher than the sands in the transmissive zone (median 0.0005 g/g). These data from this site supports the use of higher retardation factors for low-k zones when modeling matrix diffusion processes.
- Using one or more screening-level characterization tools to identify suitable locations for subsequent coil coring was a valuable step. Methods tested as part of this project included MIP, Waterloo$^{APS\ TM}$, and Geoprobe HPT. These methods are well-suited for determining a relative permeability distribution and locating interfaces between low-k and high-k zones.
- The uncertainty analysis that is part of the Tool is helpful in understanding the relative sensitivity of various input parameters and can be used to simulate alternative scenarios. For the sites investigated during this project, the results were most sensitive to porosity and tortuosity. The constituent half-life has little impact until values fall below ~10 years.
- Commercially available sampling and laboratory techniques can be used to reconstruct source histories; no special research lab techniques are required.

- The importance of proper sample handing, preparation and analysis methods were demonstrated through a thorough evaluation of various procedures on data quality. These results confirmed that the project-specific methods, particularly prompt methanol preservation of soil samples in the field, generate high-quality data and should be adopted to the extent possible.
- For a site where source history method was applied at a scale similar to that used for this project, the standalone costs were approximately $161K, or $1.15K per vertical foot (cored); $35.8K of this was related to project-specific reporting. For a full-scale application of this approach where it leads to the selection of MNA, it is estimated that it would cost 23% less than enhanced in situ bioremediation (which may or may not be effective in low-k zones) and 75% less than pump-and-treat over the project lifetime. Regardless of whether or not the results are used to support MNA as a remedy, the information can prove valuable for developing and/or refining the conceptual site model.

Background and Technology Description

The overall objective of this project is to provide a method for reducing the uncertainty associated with assessing long-term concentration trends for use in remedy selection at sites with chlorinated solvent contamination in soil and groundwater. There is increasing evidence that source strength *does* decrease over time as natural processes deplete mass from the source zone, a process that would support the selection of MNA as a long-term remedy. We have proposed a new approach that allows for a reconstruction of *long-term source histories* that extend back to the beginning of the original source release. Methods developed by Parker et al. (2004, 2008)—specifically the collection of closely spaced soil concentration measurements at discrete depths in low permeability zones within and downgradient of source zones to provide insight into historic concentration trends at interfaces with the low permeability zones—offer a focused way to reconstruct long-term source histories that extend back to the beginning of the original source release (see **Figure ES.2**). Evaluation of such datasets from this technology using modeling tools developed as part of this demonstration places us in a far better position to make informed and cost-effective decisions about managing and closing these sites.

The subsurface environments where chlorinated solvents are released are often quite heterogeneous, and abrupt contacts between highly transmissive and less transmissive zones are common in these settings. Consequently, high concentrations of aqueous-phase contaminants in transmissive sediments come into contact with lower permeability sediments, such as clays, silts, and rock matrices. Over time, contaminants migrate from the plumes in the transmissive zones these lower permeability zones via vertical advection and slow diffusion. These transport processes are predictable and controlled by concentrations at the interface as well as characteristics of the lower permeability zone which can be measured on core samples or estimated with good certainty.

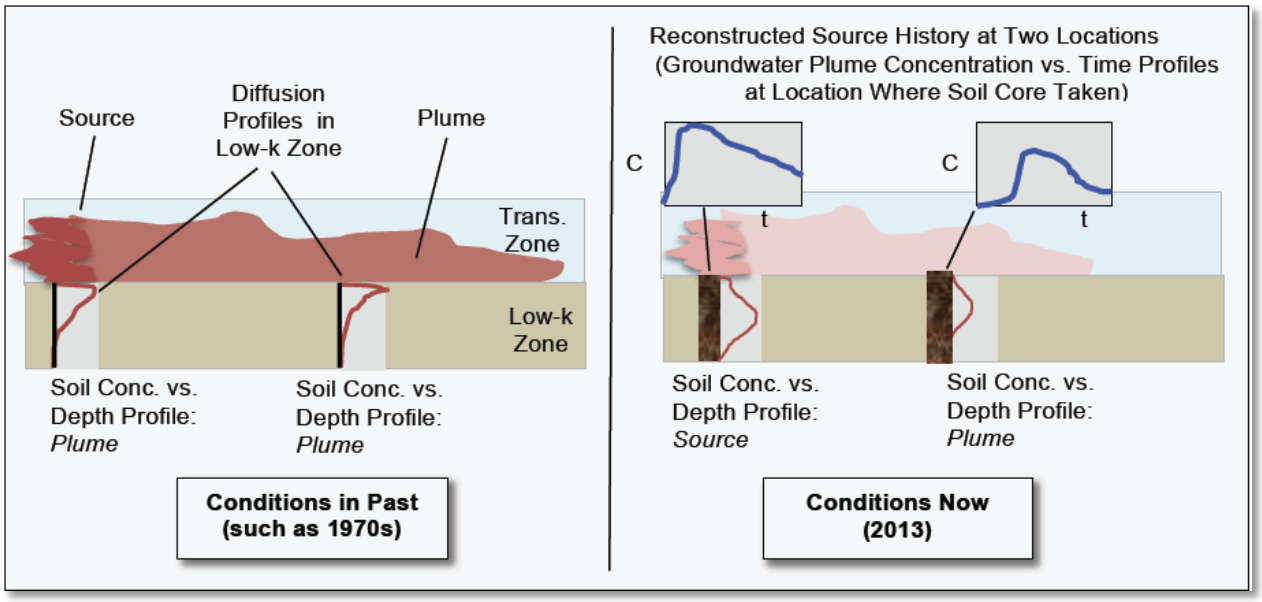
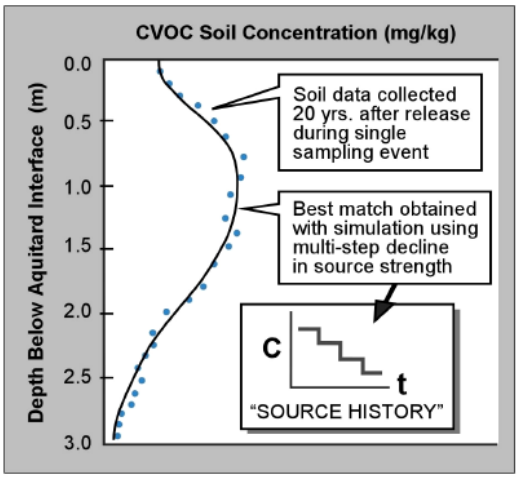


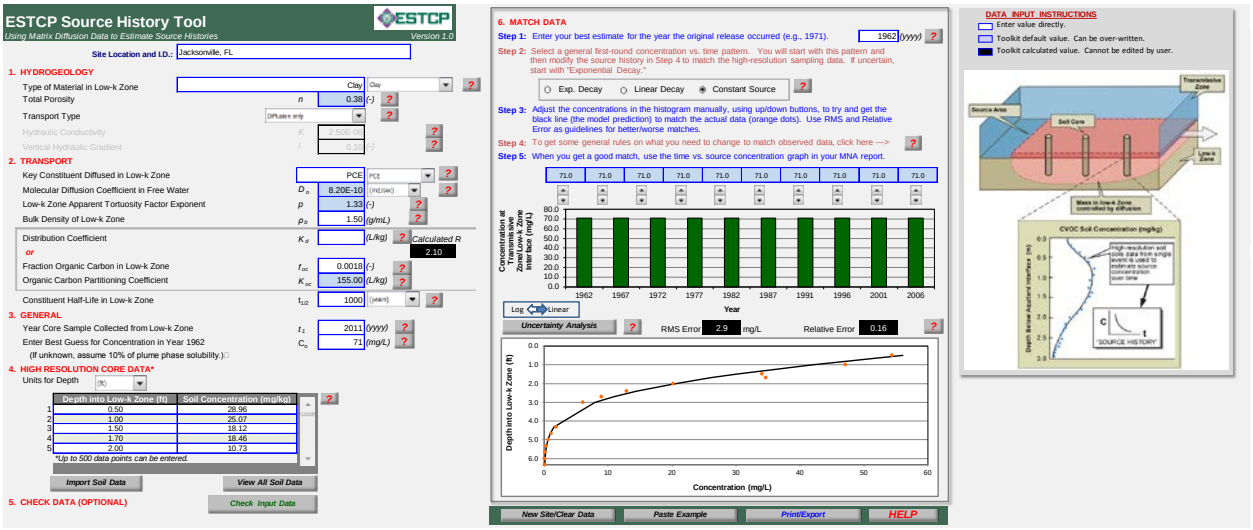
Figure ES.2. Example of how source reconstruction using soil core data works. High-resolution analysis of soil cores collected in 2013 show the style of the source history of the groundwater point at the location the core was collected.

This "source loading" process can result in the long-term storage of substantial contaminant mass as dissolved and sorbed-phase within the low permeability zones. The contaminant storage capacity in these lower permeability zones is generally greatly enhanced by sorption; given these zones typically contain higher organic carbon content. At a later time, even if no DNAPL remains, plumes can be sustained by the slow release ("back diffusion") of mass from the low permeability zones into the higher permeability zones (Liu and Ball; 1998a, 1998b, 2002; Parker et al., 2004; Chapman and Parker, 2005; Seyedabbassi et al., 2012).

The basis for the modeling approach for this project was the one-dimensional (1-D) diffusion equation (e.g. Freeze and Cherry, 1979) using Fick's second law. This law defines the diffusion of a chemical in solution in response to a concentration gradient. The analytical solution allows for the concentration at any depth to be determined based on the concentration at the interface. The goal of the approach being tested as part of this project is to use the vertical concentration profile within the low permeability zone to establish the interface concentration vs. time pattern that would best represent this profile. This is done by systematically adjusting the interface concentration (C_o) at various time intervals (t) until a representative "best" fit is obtained.



The Source History Tool generated by this project (see below for screenshot example) is a simple spreadsheet-based model that follows this approach to obtain a source history estimate that best represents the soil concentration profile. It also uses a vertical advection term and a first-order decay term to understand the potential impacts of these processes on contaminant fate and transport in addition to diffusion and sorption.



Project Results and Performance Objectives

The objectives of this project were to: 1) Conduct a field demonstration to collect data for model validation and protocols for sampling and analysis; and 2) Develop a simple, user-friendly modeling tool (and associated guidance) for site managers to apply this methodology and to aid in interpretation of results.

The field demonstration collected data at two different source areas at NAS Jacksonville for the purposes of source history modeling. Multiple locations were characterized at each site to allow for a more comprehensive assessment of spatial differences in historical source loading, as well as location-specific influences related to advection, sorption, degradation, and other processes. At each location, the following sequence was implemented:

1. Detailed vertical stratigraphic profiling and groundwater sampling to locate key interfaces;
2. High resolution vertical soil sub-sampling of the low-k units in contact with the interface; and
3. Use of the ESTCP Source Attenuation Tool to reconstruct the style of the source history from the soil data from Step 2.

Screening-level characterizations were completed at a minimum of 4 locations per site, with full characterization (i.e., continuous soil coring and high-resolution subsampling) completed at 3 or more of these locations per site. The various characterization methods generated data that was consistent with those obtained by subsequent soil coring and classification. They successfully

identified the critical low permeability zones for further characterization efforts using soil and groundwater sampling. CVOC trends (in terms of magnitude and distribution of contaminants) were largely similar regardless of the sampling matrix or approach. Note that while the focus was on source areas, downgradient locations were also included at each site, in part to provide a more detailed picture of attenuation processes during transport.

Building 106 Source Area: The first source area, the former Building 106 at OU3, was a dry cleaner that started operating in the early 1960s, with PCE as the primary contaminant that was released. MIP survey results suggested that the majority of contaminant mass was present within and immediately above a 5 to 15-ft thick lower permeability layer first identified (using the EC signals from MIP/HPT and the permeability (I_k) estimates from Waterloo$^{APS\ TM}$/HPT, later verified with inspection of soil cores) at a depth of 15 to 20 ft bgs.

CVOC concentration data collected at these locations confirmed that the majority of contaminant mass was present within the low permeability clays and in the transition zone immediately above the clay layer. At the near source location, OU3-3, the CVOC profile is dominated by PCE and TCE, with maximum total CVOC concentrations of approximately 30 mg/kg at 16 ft bgs. At least 80% of the total mass at this location was present between 15 and 21 ft bgs within the clay layer, with little indication of penetration through this layer and the shape of the profile indicative of diffusion-controlled transport. Moving downgradient, the maximum total CVOC concentrations gradually decreased but the relative contribution of cis-1,2-DCE was significantly higher. At these locations, the majority of the total CVOC mass (at least 80%) was encountered in these sand and transitional intervals above the clay layer. The furthest downgradient location, OU3-6, saw a significant shift to cis-1,2-DCE (~90% of the observed mass), and the maximum CVOC concentration (~15 mg/kg) was in the shallow sands at 13 ft bgs.

Multiple potential lines of evidence for contaminant degradation were evaluated in an effort to determine if degradation in the low-k zone impacted the current soil concentrations, and as a consequence, the source history estimates. These included the presence/absence of parent compounds, the presence/absence of degradation products, the relative distribution of parent and compounds in the high-k vs. low-k zones, concentration vs. distance trends, geochemical conditions, biomarker data, and carbon isotope data.

Collectively, these data supported a hypothesis that the majority of the degradation activity (which contributed the formation of significant amounts of by-products at downgradient locations) was occurring **in the high-k zones and not the low-k zones at these particular sites**. The carbon isotope data were particularly illustrative. At each location, the $\delta^{13}C$ values for a particular constituent were generally higher (indicative of degradation) within the high-k zones than the values associated with the low k zone. This is true regardless of whether the shallow high-k zone (above the clay ldiayer) or the deeper low-k zone (below the clay layer) is considered. The pattern also holds true for each of the constituents (PCE, TCE, cis-1,2-DCE, and VC). Because this means that the majority of the degradation products originated in the high k zones before diffusing into the low-k zones, the consequence is that source history modeling can neglect low-k zone degradation for this site.

Source histories were generated for both PCE separately and PCE plus its degradation products at four distinct coring locations (plus a duplicate) using the Source History Tool. The modeling demonstrated that the locations at this source area were characterized by relatively constant source histories. This was consistent with soil profiles that exhibited decreasing concentration with depth into the low k zone, which is a distinguishing characteristic of continued loading over these low k zones by a source strength at the interface that remains high relative to historical values. This constant source history trend held regardless of whether the parent compound (PCE) or parent compound plus degradation products were modeled.

The location-specific arrival dates for PCE loading (i.e., time zero for the source history estimate) matched expectations regarding plume arrival for this site (reported groundwater seepage velocity of 2 to 70 ft/yr at this location):

Location	*Distance from Source (feet)*	*Reconstructed Plume Arrival Year*	*Reconstructed Arrival Conc. (mg/L)*	*% Parent Compound*
OU3-3	0 - 20	1962	78	91% PCE
OU3-4	75	1971	50	86% PCE
OU3-5	230	1976	32	72% PCE
OU3-6	430	1992	13	23% PCE

Year	*Reconstructed Source History (Near Source OU3-3) (mg/L)*	*Reconstructed Source History (Downgradient Plume OU3-6) (mg/L)*
1962	71	3.1
1972	71	3.1
1982	71	3.1
1992	71	3.1
2002	71	3.1

The predicted source concentrations were also consistent with the limited groundwater data that were available from the site, which exhibit some fluctuation but demonstrate no clear temporal trends. The median concentration values from these monitoring locations were within a factor of 2 of the (constant) values predicted using the project Tool.

The modeling confirmed that while the source strength was constant at individual locations, the PCE concentration and the total CVOC concentration declined moving downgradient as a result contaminant degradation within the plume. This caused a stronger decline in concentrations than would be expected from physical processes (e.g., dispersion) only, as evidenced by the decreasing percentage of mass represented by the parent compound. The pattern is consistent with the increased contribution of degradation products to the total CVOC concentration moving away from the source. These results suggest that while an appreciable decline in the source strength cannot be verified, significant attenuation along the plume flowpath has occurred. Consequently, MNA may not an appropriate site remedy if source control is a requirement, but attenuation processes are clearly helping to maintain plume stability and reduce risk.

Building 780 Source Area: The second source area, Building 780 at OU3, housed a paint stripping and solvent recycling facility that reportedly operated in the 1970s and 1980s. Both chlorinated ethenes (primarily TCE) and chlorinated ethanes (1,1,1-TCA) were known to be have been used there. The only screening-level tool that was employed at this source area was Waterloo$^{APS\ TM}$, such that the data generated during the initial stage was limited to an index of hydraulic conductivity (I_k) profile from four locations. Typical results are shown in **Figure 5.12**. The profiles suggested that a relatively distinct lower permeability interval was present starting at ~20 ft bgs at most locations, and extended to approximately 27 ft bgs. Below this interval, additional low k zones of varying thickness were evident. The I_k data suggest that the Building 780 soils were generally more heterogeneous than those of the former Building 106 source area.

Similar to the other OU3 source area, CVOC concentration data collected at these locations confirmed that the majority of contaminant mass was present within the low permeability clays and in the transition zone immediately above. The primary differences at this source area are: (1) the presence of chlorinated ethanes in addition to chlorinated ethenes; (2) the maximum total CVOC concentrations are generally lower (10 mg/kg or less); and (3) peak concentrations of TCE and other compounds are frequently encountered within the low-k layer and not at the interface (consistent with source decay and back diffusion). At the farthest upgradient location, OU3-9, the concentration profile is characterized by significant levels of TCE, DCE, and 1,2-DCA in the lower permeability zones. The overlying sandy layers contain much lower levels of DCE and negligible DCE and 1,2-DCA, but 1,1-DCA is present at a peak concentration of approximately 1 mg/kg. No 1,1,1-TCA was found. At the next location, OU3-10, 1,2-DCA is absent, but the vast majority of contaminant mass (primarily TCE with lower levels of DCE) is associated with the low permeability clay. 1,2-DCA is mostly confined to narrow clay-rich subintervals at 13 ft bgs and 21 ft bgs. The farthest downgradient location, OU3-11, is characterized by much lower concentrations (maximum total CVOC concentration of less than 0.3 mg/kg) and a lack of chlorinated ethanes. TCE is the primary contaminant and the peak concentration coincides with a depth below that of the primary clay unit, where a thin sand layer (3 ft) was encountered. Again, 1,1,1-TCA was not encountered at these downgradient locations.

A comprehensive sampling and analysis program to evaluate low-k zone degradation was not completed at this site. However, based on the available lines of evidence (primarily the contaminant distribution and the lack of low-k degradation activity at the nearby Building 106 source area), it was assumed that degradation in the low-k zone at Building 780 was relatively negligible for the purposes of source history modeling.

The modeling demonstrated that the locations at this source area were characterized by declining source histories for TCE, i.e., source loading that changed gradually over time. At the near source location, OU3-9, a declining source history was also observed for 1,2-DCA, while a relatively constant source history was observed for 1,1-DCA. No 1,1,1-TCA (the parent compound for 1,1-DCA) was observed at OU3-9. Further, none of the chlorinated ethanes (1,1,1-TCA, 1,1-DCA, or 1,2-DCA) were observed at the other coring locations at this source area. Reasonable fits between simulated and measured soil concentration data were obtained at all locations, though there was a generally higher level of uncertainty when compared to the source history estimates from the other source area due to site heterogeneity.

With the exception of 1,1-DCA at OU3-9, soil profiles generally exhibited a maximum concentration at some distance (between 1 to 4 ft) into the low-k clay unit, with lower concentrations measured near the interface. This pattern is a distinguishing characteristic of a declining source strength over time, such that concentrations near the near the low-k interface have declined, changing the concentration gradient and causing diffusion out of the low-k zone, with higher remnant concentrations occurring deeper into the low-k zone and lower concentrations at the interface. These source history trends held regardless of whether the parent compound or parent compound plus degradation products were modeled.

For TCE, the starting dates for contaminant loading at each location (i.e., time zero for the source history estimate) were again consistent with expectations regarding plume arrival. The date of arrival increased moving downgradient, from 1971 at the near source location OU3-9 to 1976 at the far downgradient location OU3-11. The date for OU3-9 (1971) falls at the beginning of the presumed release period based on the solvent use at this site (1970's through 1980's).

The location-specific arrival dates for contaminant loading (i.e., time zero for the source history estimate) matched expectations regarding plume arrival for this site (representative groundwater seepage velocity of 2-70 ft/yr):

Location	*Distance from Source (feet)*	*Reconstructed Plume Arrival Year*	*Reconstructed Arrival Conc. (mg/L)*	*% Parent Compound*
OU3-9	Adjacent	1971	160	18% TCE
OU3-10	120	1973	58	15-100% TCE
OU3-11	180	1976	1.4	-

Year	*Reconstructed Source History (Near Source OU3-9) (mg/L)*	*Reconstructed Source History (Downgradient Plume OU3-11) (mg/L)*
1973	30	Not arrived
1983	25	0.7
1993	3	0.3
2003	1	0.2

Collectively, the results obtained at this source area suggest that significant source strength attenuation has occurred over time for TCE and 1,2-DCA. Potential contributing factors to this decline are active degradation process (particularly at the upgradient location) and interim remedial measures that were implemented at this site. 1,1,-DCA did not show a similar decline in source strength, but the lack of detection of the parent compound (1,1,1-TCA), combined with the lack of detection of any chlorinated ethanes at downgradient locations, confirm that significant chlorinated ethane attenuation is occurring. Consequently, monitored natural attenuation may be an appropriate for remedy for this site because the source history estimates provide evidence that these attenuation processes are controlling the source(s).

Performance objectives were developed for this demonstration, primary related to the quality of the data generated by the field methods and by the modeling software. The pre-test success criteria and outcomes are summarized below with additional explanation provided after the table.

Performance Objective	Success Criteria	Success Criteria Achieved?
1. Reconstruct Source History - Accuracy	Source history captures the style of measured field data: RPD ≤ ±30% for majority of paired depth-discrete data (e.g., measured soil concentration vs. modeled soil concentration at same depths	***NO*** • Only 7 of 17 source histories met criterion • Criterion overly stringent and not very representative • Passes "eyeball test" for style
	Source history captures the style of measured field data: Ratio of RMS error to maximum measured concentration for 75% source history estimates ≤ 0.3 (30%)	***YES*** • 17 of 17 source histories met criterion • More representative metric
2. Reconstruct Source History – Precision	Similar source history generated from duplicate datasets from same location at same site: i) RPD ≤ 30% at majority of time points; or ii) same temporal concentration trend using non-parametric statistical test	***YES*** • Same source history trend (constant) observed using data from duplicates – confirmed using Mann-Kendall • RPD < 30% for 10 of 10 datapoints
3. Reconstruct Source History - Sensitivity	Quantify sensitivity of source history to individual input parameters: i) same temporal concentration change trend following ±10% change in each input parameter; ii) same style in soil VOC vs. depth profile following ±50% change in each input parameter	***YES*** • No changes to temporal concentration trends • No changes to style of soil VOC vs. depth profiles
4. Comparison of Modified Data Collection Method with Standard Data Collection Methods	Identify consistent trends between field extracts analyzed using UG methods vs. Encore samplers analyzed at commercial lab: $R^2 \geq 0.9$ using regression analysis for paired data	***NO*** • $R^2 = 0.83$ Significant low bias in unpreserved Encores contributed excessive variability
	Identify consistent trends between soil extracts analyzed at Guelph vs. soil extracts analyzed at commercial lab: RPD ≤ ±30% for majority of paired data	***YES*** • RPD < 30% for 37 of 39 analytes Pattern relatively consistent for all analytes
	Median RSD of duplicates analyzed at Guelph < ±10% (i.e., similar to acceptable RSD for duplicates analyzed at commercial lab)	***YES*** Median RSD = 7%
Ease of Use	Single mobilization required per site to collect adequate level of data	***PARTIAL*** • Second mobilization required to accommodate expanded scope of work • Methods were easy to implement
Selection of Appropriate Locations	Assess what previous historical data was used to select locations and how this improved the results.	***YES*** • Existing data were sufficient to select areas • Multiple coring locations per site proved valuable

The quantitative performance objectives related to precision and sensitivity were easily met. Precision was demonstrated by showing that duplicate cores collected at location OU3-5 (1-m apart) resulted in very similar source histories that both exhibited the same constant concentration trend over time. Sensitivity was evaluated using the Monte Carlo-based uncertainty analysis component of the Tool, and demonstrated that small changes to the input parameters did necessitate any changes to the source concentration trends to fit the data (i.e., the same trend was able to fit the data before and after the parameter value was adjusted).

Accuracy was assessed by demonstrating goodness of fit of predicted soil data (generated by the project Tool) to actual soil data. The majority of cases easily passed the "eyeball test", in that the predicted and actual soil data appeared very similar in style throughout the entire low permeability interval. However, only 7 of 17 sources histories met the original criterion (RPD $\leq$ 30% for the majority of depths). Based on the inadequacy of this criterion, and alternative metric was developed using the ratio of the relative mean square error (an optimization metric generated by the Tool) to the maximum concentration. This metric was less subject to biases and is more representative of the fit across the entire depth interval being modeled. For 17 of 17 source histories, this ratio was $\leq$ 30%, meaning that the new success criterion was achieved.

The final quantitative performance objective used a series of evaluations to demonstrate that the project-specific data collection methods generated similar or higher data quality than standard methods. All success criteria were met with the exception of the correlation between data collected using field-preserved soil samples analyzed at the UG lab and unpreserved Encore-sampled soils analyzed at a commercial lab. The latter data were negatively impacted by contaminant losses due to the lack of preservation and incomplete extraction, resulting in significant variability in the data. While this ultimately prevented the success criterion from being achieved, it more importantly highlighted that standard sample collection, handling, and analysis methods can lead to lower quality data.

Implementation Issues

Implementation issues for this technology are relatively limited. The methods for collecting data are already familiar to environmental professionals and are unlikely to be subject to additional regulatory oversight.

The primary end-user concerns are associated with understanding how to collect site data and apply the source history model in an appropriate way, as well as understanding how to use results. To aid in this process, a User's Manual is provided for the Source History Tool that has been developed as part of this project. The results should be considered a "line of evidence" for supporting MNA decision-making. The results are likely to be unfamiliar to a regulator, so a certain level of educating by the end-user may be necessary, as is the case with any line of evidence for MNA. Again, the User's Manual is valuable educational aid. The model is relatively transparent and can be used for additional iterations using alternative scenarios, if desired. The sensitivity analysis performed as part of this project demonstrated how various input parameters impacted the results, and it is easy for end-users to do similar evaluations using the built-in sensitivity module for the Tool.

It should be understood that the source history results from the model are not "unique", meaning that they are aimed at capturing the ***style*** of the source history. While not necessarily providing a unique solution, it can be equally valuable to use the model to understand what are ***not*** reasonable estimates of the source history for a particular location. This can be useful for building a proper conceptual site model, as well as for evaluating whether certain pre-conceived notions about a site are technically sound based on the model output.

Implementation Costs

Costs associated with this technology demonstration were tracked in order to provide a basis for estimating costs of a full-scale implementation of the technology. An outcome-based cost comparison was made, using the project data to determine the viability of MNA vs. more aggressive remedial options, and then determining the net cost difference between the various outcomes. Cost elements that were tracked as part of the cost model were primarily those that are unique to this technology. These included: 1) review of existing data and preliminary selection of locations; 2) screening-level characterization; 3) soil sampling and analysis; 4) data review and source history reconstruction (modeling); and 4) long-term monitoring.

The cost elements described above then were included in several scenarios for comparing the costs associated with the source history approach (at a similar scale to that used for this project).

- ***Scenario 1: Implementation of Source History approach as a standalone characterization method***. In this case, it was assumed that the source history method was used to improve the conceptual site model but was not necessarily included as part of remedy selection process. The standalone costs were approximately $161K, or $1150 per vertical foot (cored). Essentially, this represents the approximate costs that were associated with implementing the method at former Building 106 source area in a standard manner (i.e., if the costs of extra project-specific analyses and personnel were excluded). Note that this method includes $35.8K related to the project-specific report, a cost that could likely be reduced from a generic application (to approximately $950 per vertical foot). Regardless of whether or not the results are used to support MNA as a remedy, the information can prove valuable for developing and/or refining the conceptual site model.
- ***Scenario 2: Source History Leading to MNA vs. Source Treatment.*** For a case where the source history method was implemented and resulted in a strong line of evidence for source attenuation over time, such that MNA was approved as a site remedy moving forward, the total life-cycle cost was $651K (or $59/cy). Approximately 26% of this was associated with the supplemental source history characterization method, while the remaining cost was associated with long-term monitoring and reporting. The alternative outcome was that source treatment was required as an initial step, specifically in situ bioremediation followed by MNA as a long-term management strategy. The total life-cycle cost associated with the alternative source treatment option was estimated to be $849K (or $76/cy), with approximately 50% of this cost related to the treatment itself and the remaining cost

attributable to long-term monitoring and reporting. Therefore, the source history approach resulted in a total cost that was 23% lower than the source treatment option.

- ***Scenario 3: Source History Leading to MNA vs. Pump-and-Treat.*** This case also involves the use of the source history method as a strong line of evidence that ultimately supports the selection of MNA as a long-term management strategy to ultimately achieve site closure. For this case, the total life-cycle cost was again $651K (or $59/cy), with approximately 26% related to the supplemental source history characterization method. The alternative outcome was that pump-and-treat was required as part of the long-term management strategy for the site. The total life-cycle cost associated with the alternative pump-and-treat option was estimated to be $2,570 K (or $232/cy), with approximately 50% of this cost related to long-term (30 year) operations and maintenance of the system. Therefore, the source history approach resulted in a total cost that was 75% less than the pump-and-treat option.

Sensitivity analysis was also completed using the number of locations core per site and the soil sampling frequency (i.e., number of samples collection from each core) as cost drivers. These were selected because they are important considerations in the level of characterization data acquired for a particular site. When the number of locations is increased from 3 to 12, the cost per foot decreases from approximately $1.25K to $0.80K. When the soil sampling frequency is increased from 0.2 ft per sample to 2 ft per sample, the cost per foot decreases from approximately $1750 to $950.

1.0 INTRODUCTION

This document serves as the final report for ESTCP Project Number ER-201032, "Determining Source Attenuation History to Support Closure by Natural Attenuation". It was prepared in accordance with ESTCP program guidance by the Principal Investigators for this project, GSI Environmental Inc. (GSI) and the University of Guelph (UG)

1.1 Background

One of the key constraints on our ability to select remedies for closing sites contaminated by chlorinated solvents is that there is typically only a short time interval where monitoring data are available to assess trends. This problem is exacerbated in situations where source material is expected to be present because of uncertainty about plume stability versus source stability. In particular, this hinders an evaluation of monitored natural attenuation (MNA) as a remedy, despite the fact that recent historical surveys of MNA have determined that it was a feasible remedy in over 75% of the sites where it was included in the evaluation, either alone or in conjunction with an active treatment technology (McGuire et al., 2004; Newell, 2006). Often concentration trends are difficult to discern, even with the use of advanced statistical tools such as AFCEE's MAROS tool, such that insufficient evidence is available to demonstrate that natural attenuation is viable. This can delay the decision-making process until more data can be collected and evaluated, and any supplemental data is gathered to support a "lines of evidence" approach that is not necessarily definitive or reflective of long-term trends.

Furthermore, regulators frequently adhere to a conceptual model of an unchanging, non-attenuating source zone, and insist on source remediation projects to replace or augment natural attenuation. As a result, site managers often are faced with implementing a costly technology and demonstrate performance in terms of mass removal efficiency, even though estimates of the mass present or remaining in a source zone are typically difficult to make and are subject to significant uncertainty given the limitations in monitoring data and investigation resolution, especially as subsurface releases age over time.

To aid in the selection of MNA as a long-term remedy, we propose a new approach that allows for a reconstruction of *long-term source histories* that extend back to the beginning of the original source release. Methods developed by Parker et al. (2004, 2005, 2008)—specifically the collection of closely spaced soil concentration measurements at discrete depths in low permeability zones within and downgradient of source zones to provide insight into historic concentration trends at interfaces with the low permeability zones—provide a focused way to reconstruct long-term source histories that extend back to the beginning of the original source release.

1.2 Objective of the Demonstration

The overall objective of this ESTCP project is to reduce the uncertainty associated with assessing long-term concentration trends for use in remedy selection at sites with chlorinated solvent

contamination in soil and groundwater. This is based on the hypothesis that diffusion of contaminant mass into and out of low permeability geologic strata within a source zone provides a method of reconstructing the source history by obtaining detailed soil concentration profiles within these less transmissive layers, along with measurement of relevant transport parameters controlling the advective - diffusive development of the profile. Specific objectives include:

1. Determine if existing 1-D can be used to determine source histories from high resolution low-k soil sampling data.
2. Conduct a field demonstration to collect data for model validation and protocols for sampling and analysis.
3. Develop a simple, user-friendly modeling tool (and associated guidance) for site managers to apply this methodology and to aid in interpretation of results.

These objectives were examined at several sites by completing high resolution soil and groundwater sampling within high and low permeability zone interfaces in source zone(s) and also the downgradient plume(s). The sampling program was aimed at defining the mass distribution in low permeability zones. These high-resolution characterization data can then be used as input data for the diffusion model. The result is a historical reconstruction of the source concentration history at the interface over time. In cases where the characteristic back diffusion profile from locations within the source and in the downgradient plume are encountered in the low permeability zones, they can be used to demonstrate a declining concentration trend resulting from source depletion that has occurred in the time elapsed following initial contaminant releases. This is done by back-calculating possible scenarios for the source loading (i.e., concentration history at the low permeability interface) that would have resulted in the measured soil concentration profile in the low permeability layers as the result of diffusion-dominated transport in these layers.

1.3 Regulatory Drivers

A key outcome of this project is developing a methodology that can be used to help break the logjam of sites where natural attenuation has been proposed but not accepted by regulators due to concerns that the source is not being treated fast enough, or where routing monitoring data do not show definitive trends. A long-term source history from the beginning of releases at a site to present time would help confirm a site conceptual model that shows attenuation is a significant process for both the source and the plume, and it generates data that are well-suited for use in predicting future concentration and attenuation trends. This approach has the potential to eliminate source removal as a necessary step at some sites prior to adopting natural attenuation as a long-term remedy, which reduces the complexity of remedy selection and accelerates implementation. The key requirement is the presence of low permeability strata within or downgradient of the source zone. Given the increased understanding of the role of small-scale permeability contrasts in enhancing transport, as well as the potential long-term storage of mass within fine-grained intervals, the potential exists for low permeability zones to serve as a contributor to source and plume behavior at even moderately heterogeneous sites. Consequently, the methods proposed in this project have wide applicability to many DoD sites.

2.0 TECHNOLOGY

2.1 Technology Description

2.1.1 Theory and Approach

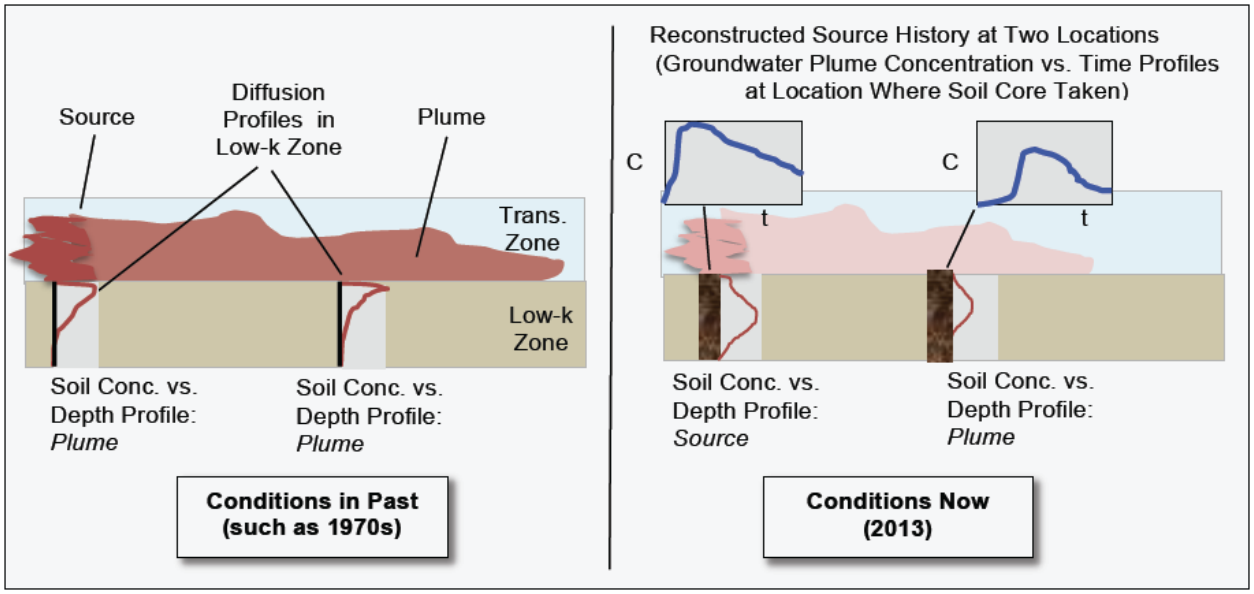
Most sites impacted with chlorinated solvents initially released as dense non-aqueous phase liquids (DNAPLs) have only limited long-term temporal information about source strength via downgradient concentration trends in monitoring wells. As described in Section 1.1, this makes it more difficult for site managers to make a data-driven argument for MNA as a suitable long-term remedy, especially given that conventional conceptual models often neglect or dismiss source attenuation that can occur over the decades that have generally elapsed at most sites since initial DNAPL releases occurred.

This line-of-thinking does not take into account increasing evidence that source strength *does* decrease over time as natural processes deplete mass from the source zone. Recent research has shown that many sources—and perhaps most—do show significant attenuation over the relatively long time periods since releases occurred, i.e., 20 to 50 years, the age of many of the sources the DoD now has to manage. Research performed as part of SERDP ER-1292 showed that over two-thirds of small TCE source zones decayed over a 5 to 15 year period (Newell et al., 2006) and several other studies have demonstrated the impact between changes in source mass and source strength, with the implicit understanding that source decay over time leads to decreases in the groundwater contaminant mass flux from the source (which contributes to plume development) (Zhu and Sykes, 2004; Parker and Park, 2004; Falta et al., 2005; Falta, 2008; Basu et al., 2008; Newell et al., 2011). Source decay may have resulted in significant depletion of the mass that was originally released and, more importantly, in the source zone mass discharge to the downgradient plume. Therefore such decay should continue to contribute to attenuation and prevent future expansion (and even cause contraction) of a plume that is currently stable.

We propose a new approach that allows for a reconstruction of *long-term source histories* that extend back to the beginning of the original source release. Methods developed by Parker et al. (2004, 2005, 2008)—specifically the collection of closely spaced soil concentration measurements at discrete depths in low permeability zones within and downgradient of source zones to determine source loadings—provide a focused way to reconstruct long-term source histories that extend back to the beginning of the original source release. Evaluation of such datasets from this technology using modeling tools developed as part of this demonstration places us in a far better position to make informed and cost-effective decisions about managing and closing these sites.

This approach attempts to provide quantitative information on the source history, i.e., the time of release and the attenuation of that source during this period. The behavior of source material (i.e., DNAPL) following release is strongly influenced by heterogeneities in subsurface environments, which contribute to the complexity of site characterization and remediation strategies. In particular, abrupt contacts between highly transmissive and less transmissive zones

are common in most geologic settings. Any DNAPL that is released is preferentially transported within the zones with the highest permeability, and generally accumulate at interfaces with lower permeability zones which act as capillary barriers. Subsequent dissolution of the DNAPL mass into groundwater flowing in the transmissive zones leads to plume formation, which contributes to source decay and attenuation over time. However, the presence of different geologic intervals in a source zone and in the downgradient plume zone also means that a portion of the contaminant mass is subject to diffusion into and storage within the less transmissive layers. This occurs as high concentrations of aqueous-phase contaminants in transmissive zones come into contact with lower permeability zones. Over time, contaminants migrate into the lower permeability zones (e.g., silts, clays, fractured bedrock) via vertical advection and slow diffusion.



In particular, the diffusion process is predictable and controlled by concentrations at the interface as well as characteristics of the lower permeability zone which can be measured on core samples or estimated with good certainty. This "source loading" process can result in the long-term storage of substantial contaminant mass as dissolved and sorbed phase within the low permeability zones. The contaminant storage capacity in these lower permeability zones is generally greatly enhanced by sorption; given these zones typically contain higher organic carbon content. At a later time, even if no DNAPL remains, plumes can be sustained by the slow release ("back diffusion") of mass from the low permeability zones into the higher permeability zones (Liu and Ball; 1998a, 1998b, 2002; Parker et al., 2004; Chapman and Parker, 2005; Seyedabbassi et al., 2012).

The nature of the contaminant profiles in the low permeability zone can be used to infer the concentration history at the interface. For example, **Figure 2.1** shows temporal concentration profiles for three different interface concentration histories: constant source, finite source with interface concentrations becoming negligible after 20 years (e.g. representing a scenario with complete source removal or isolation), and constant source for 10 years followed by linear declining interface concentrations (e.g. representing a scenario with a source being naturally

depleted). **Figure 2.2** shows the same profiles together at a time period of 40 years, which may be the present day age of many sites where DNAPL releases occurred decades ago. This shows how the present-day profiles can be used to provide insight into the "style" of the past concentration history at the interface.

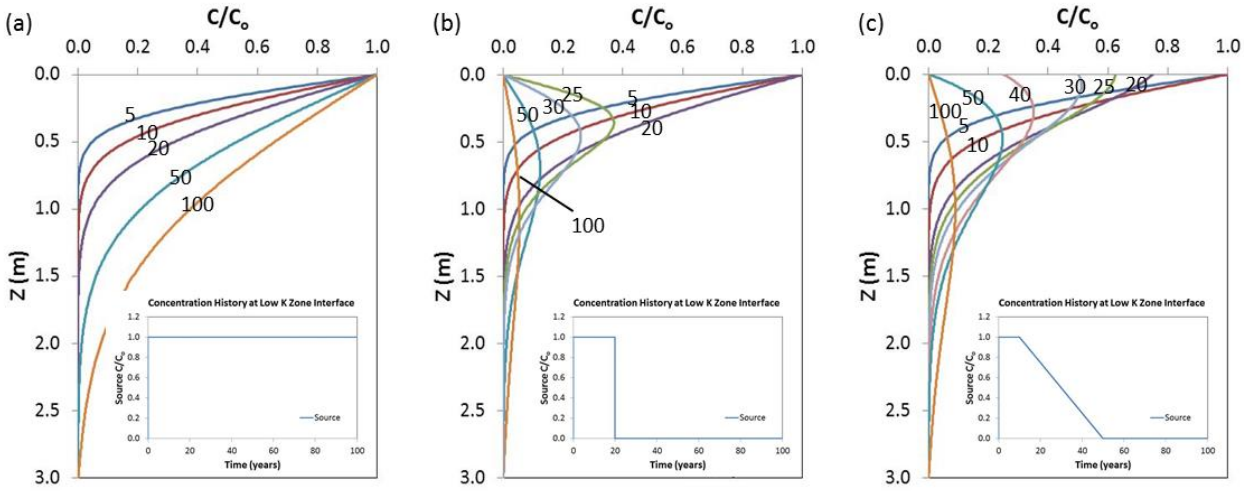


Figure 2.1. Low-k zone profiles for different historical interface concentration conditions: (a) constant concentrations, (b) constant concentrations for 20 years followed by complete removal of source, and (c) constant concentrations for 10 years followed by linearly declining concentrations with source depleted by 50 years.

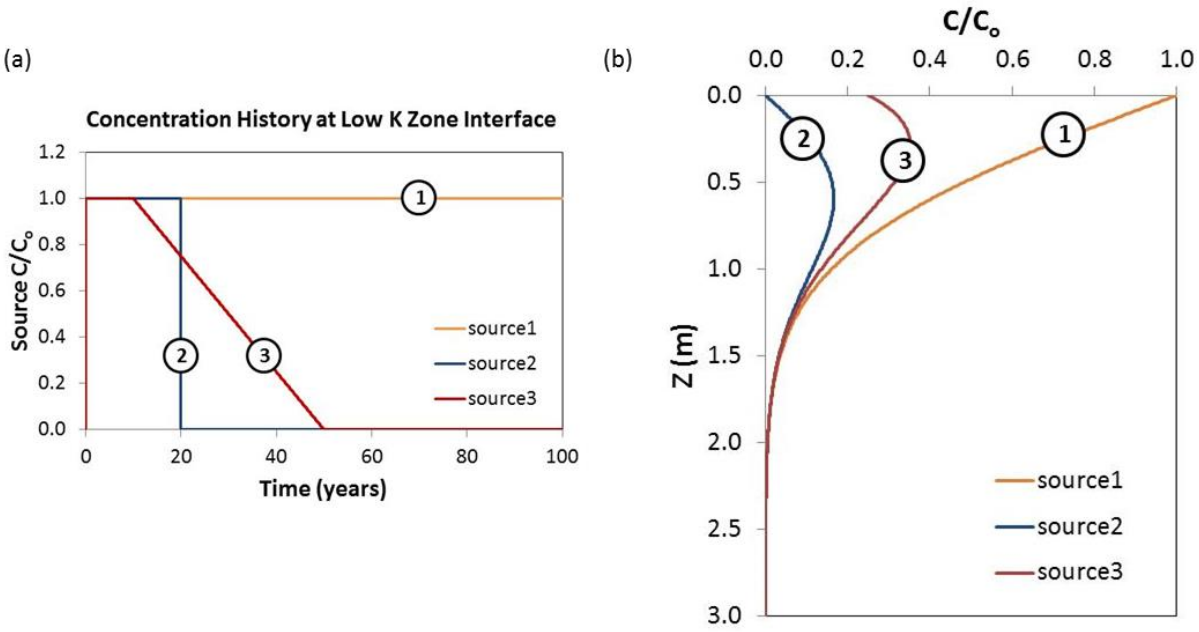


Figure 2.2. Example of: (a) three different interface concentration histories, and (b) resulting low K zone profiles at 40 years.

The technical approach focuses on the collection of high-resolution depth-discrete data from low permeability zones and then using a diffusion-based transport model to "reconstruct" the historical source loading. A schematic of the technology and its benefits are shown in **Figure 2.3** and **Figure 2.4**. The specific sampling methodology used during this project will involve the collection of depth-discrete soil samples near geologic interfaces and into the low permeability zone for subsequent laboratory extraction and analysis to generate a detailed contaminant profile with depth. Supporting measurements of parameters such as porosity and organic carbon content are also made on samples to be used in assessment and modeling. In cases where the characteristic back diffusion profile from locations within the source and in the downgradient plume are encountered, they can be used to demonstrate a decreasing concentration trend resulting from source decay and/or active remedial measures that has occurred in the time elapsed following release (assuming a reasonable estimation of the time of release can be made) (**Figure 2.3**). This is done by back-calculating the source loading (i.e., concentration history at the low permeability interface) that would have resulted in the measured soil concentrations in the low-permeability layers as the result of diffusion-dominated transport in these layers.

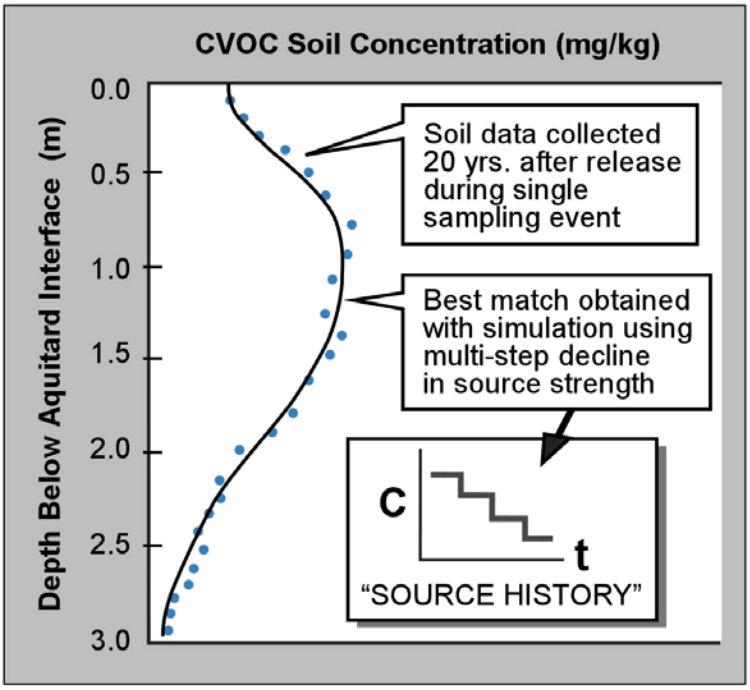


Figure 2.3. Conceptual Model of the Source History Approach

The utility of this method is outlined in the right-hand panels in **Figure 2.4**. The concentration "signature" within the low permeability zones can be used to estimate the source strength behavior over time, with the potential to quantitatively establish that significant attenuation has occurred since the time of initial DNAPL releases. Compare this to the typical case where only a limited temporal record is available from monitoring of groundwater concentrations in wells generally positioned in the higher permeability zones (left-hand panels of **Figure 2.4**), such that

the true extent of source attenuation cannot be adequately appreciated because the majority of source decay occurred prior to the collection of the groundwater monitoring data. This hampers an evaluation of the attenuation potential at a site, both in terms of what has already occurred and what can be expected to occur in the future.

As a consequence, an important additional component of this technique is its potential for predicting future concentration trends. This can be done with a higher degree of certainty than typical trend analyses because the method expands the historical record to provide a more complete basis for establishing the expected trend. This projection can be done in cases where no DNAPL remains and back diffusion from low permeability zones serves as the primary mechanism for aquifer loading. Detailed evaluations and modeling incorporating back diffusion from low permeability zones and resulting concentrations in higher permeability zones is beyond the scope of this demonstration, but forms a major component of SERDP project ER-1740 "Management of Contaminants Stored in Low Permeability Zones". The trend analysis can be particularly useful in estimating source lifetime in the absence of additional source control measures. Finally, if sufficient information about the spatial extent of the release is known, coupled with assessment of the current contaminant mass discharge from the source zone (for example determined using detailed depth-discrete groundwater concentration and volumetric discharge data from a transect installed perpendicular to flow immediately downgradient of the source zone and/or from other methods such as passive flux meters demonstrated in SERDP project ER-200114 "Demonstration and Validation of a Water and Solute Flux Measuring Device"), estimates of the total mass removed due to historical source decay can be estimated with much more certainty. When coupled to trend analysis tools that are already in widespread use, such as MAROS, these data provide a clearer picture of the expected source history and a strong foundation for informed decision-making on site management issues.

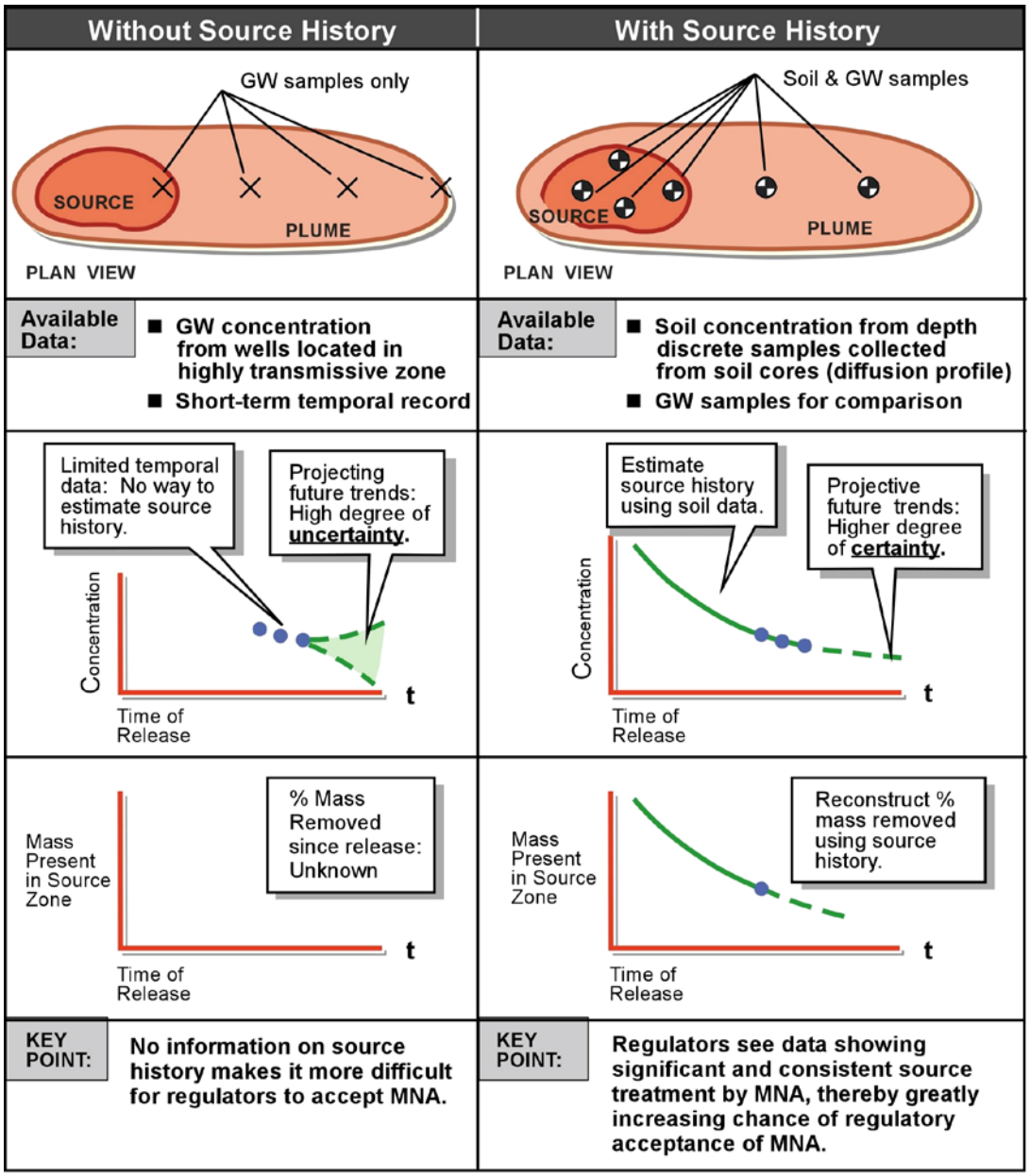


Figure 2.4. Example of Benefits of Reconstructing Source History for MNA Decision-Making

2.1.2 Expected Technology Applications

A key objective of this project is to help break the logjam of sites where natural attenuation has been proposed, but not accepted by the regulators due to concerns that the source is not being treated fast enough. Consequently, the methods proposed in this project have wide applicability to most or all DoD sites. A long-term source history from the time when contaminant releases first occurred at a site to present time would help confirm the site conceptual model that shows

attenuation is a significant process for both the source and the plume at the majority of sites, and it generates data that are well-suited for use in predicting future attenuation trends. At some sites, this approach has the potential to reduce the need for further source treatment because it would show that significant mass has already been removed from the source zone over time via natural processes and that the source strength and input to the plume is also declining over time. This can serve to accelerate the selection and implementation of less costly approaches like monitored natural attenuation at many sites, allowing more focused application of scarce funds to sites where more active remedial measures can have more impact on reducing risk. The key requirement is the presence of low permeability strata within or downgradient of the source zone in which contaminant transport is largely diffusion-controlled. Small-scale permeability contrasts are increasingly understood to play a significant role in the evolution of source zones and contaminant plumes (Payne et al., 2008), with the finer-grained materials serving as mass reservoirs or sinks to enhance long-term contaminant storage but also as long-term sources once the primary source (i.e. DNAPL) becomes depleted due to natural processes or if active remedial measures (source zone isolation and/or treatment) cause reduction in source strength. It is now an expectation that low permeability zones will serve as a major contributor to source and plume behavior at all but the most homogeneous of sites.

This demonstration project specifically addresses sites where chlorinated solvents have impacted soil and groundwater, but it also has potential applicability at other DoD sites where other COCs are present, such as fuels, MTBE, perchlorate, and explosives.

With respect to cost benefits, the proposed approach provides valuable information to base decisions on whether or not to implement or continue an active source treatment or control remedy vs. natural attenuation. These decisions necessarily rely on a quantitative assessment of contaminant mass both in terms of the percentage of mass remaining, the contaminant loading to the downgradient plume, and the rate of attenuation that has occurred since the time of release and expected future rates of attenuation. As a consequence, these data allow stakeholders to better evaluate whether remediation goals will be achieved within a reasonable time frame without the implementation of aggressive source treatment technologies. For those sites where source treatment is eliminated, the potential cost savings is significant, given that unit costs for typically source treatment technologies range from $30 to over $300 per cubic yard (McDade et al., 2005). For a typical site, source history data using the method outlined in this proposal can likely be obtained in a short period of time at a cost in the range of $100,000 to $300,000. Therefore, the expected return on investment is net positive on all but the smallest sites (i.e., < 1000 cubic yards), and the time for payback on this investment is immediate.

For all sites, including those where this type of evaluation of the source attenuation history validates the use of source treatment, there is a significant benefit in improving the input data for life cycle cost assessments. Since the data provide a basis for determining source lifetime, the costs associated with long-term monitoring can be more accurately represented. Furthermore, sustainability assessments (e.g. carbon, energy) rely an understanding of project lifetimes so that decisions about prospective short-term investments can be balanced against long-term implications.

Information from the demonstration has been incorporated into a user-friendly spreadsheet-based modeling tool (i.e., similar to BIOSCREEN and the Matrix Diffusion Tool Kit). The User's Guide also provides guidance for collecting the high-resolution data necessary for the evaluation and on applying the tool for informed management decisions.

2.2 Technology Development

The source history reconstruction approach based on using diffusion profiles in low permeability zones that has been used as part of this project is an extension of a methodology that has been previously applied by members of the project team. Use of diffusion profiles of natural constituents in low permeability clayey aquitards has been applied as a means to assess processes on geologic time scales (e.g. Husain and Parker, 1997). The use of contaminant profiles in low permeability zones as a means to age-date source zones was first proposed in 1995 by Parker and Cherry in a study entitled *"Age-Dating DNAPL Source Zones from Diffusion Profiles in Low Permeability Layers"* (1995). More directly related to estimating source history at contaminated sites, Parker et al. (2004; 2008) and Chapman et al. (2005) collected high resolution profiles into low permeability zones within source zones and downgradient plumes at sites in Connecticut and Florida and used these profiles combined with numerical modeling to assess the concentration history at the low permeability interface. Previous work related to estimating source loading over time was also presented in a series of papers by Liu and Ball (1998a, 19998b, 1999, 2002) that summarized field and modeling work performed at Dover Air Force Base.

Parker et al. (2004, 2008; Chapman and Parker, 2005) completed extensive field characterization and modeling studies showing that contaminant mass that has diffused into low permeability zones provides a means for determining the source history at a site. One of these studies was conducted at a site in Connecticut, originally to determine the integrity of a silt / clay aquitard underlying a sand aquifer contaminated with TCE DNAPL. Groundwater monitoring data starting in the early 1990s was available, but no data existed from the longer term period that had elapsed since the majority of the DNAPL was released (estimated 1950s to 1960s). To investigate the extent of diffusion into the low permeability aquitard following the installation of a source isolation measure, soil samples were collected at discrete depths from within the aquitard below the source zone and also below the downgradient plume. At some locations within the source zone where DNAPL was still present, diffusion into the clayey aquitard had resulted in relatively smooth profiles, consistent with diffusion processes from a constant source, where the maximum soil concentration occurred at the interface and then decreased with depth into the aquitard. However, at other locations, the maximum soil concentration was encountered deeper within the aquitard, with lower concentrations measured at the interface. This was presumed to be due to historically high concentrations at the interface due to DNAPL presence, which was then depleted in the intervening years, such that concentrations at the interface declined, and subsequent back diffusion from the intervals nearest to the interface had decreased the concentration relative to those deeper in the aquitard.

A modeling approach was developed to quantify these effects, using a solution of the advection-dispersion equation where advection within the aquitard was considered negligible. Using this approach, it was found that a stepped declining source (i.e., non-continuous or decaying source)

was suitable for describing the characteristic back diffusion profiles encountered during soil sampling at a location downgradient of the source zone at a site in Connecticut where the DNAPL source zone was isolated years earlier (**Figure 2.3**). Using these techniques provided evidence that the source, which was heavily impacted by DNAPL, had decayed significantly over time (Chapman and Parker, 2005) prior to source isolation. Importantly, the model was capable of correlating the measured soil concentrations (following an initial conversion to porewater concentrations) in the aquitard at the interface to groundwater concentrations in the overlying aquifer. These calculations determined that the measured soil concentrations in the aquitard at this downgradient location were explained by an original source area concentration in the aquifer at the interface at or near TCE solubility levels (~1100 mg/L) in ~1957 that declined to less than 100 mg/L in the 1990s when the monitoring data became available.

Note that the reconstructed "source histories" were not the focus of the site characterization activities described above but established the potential efficacy of this approach at other sites. Similar, the modeling completed during the studies described above largely relied on numerical groundwater flow and solute transport models (e.g., HydroGeoSphere) that, while commercially-available and very powerful, require considerable expertise to learn and apply at a specific site. The current ESTCP demonstration project is intended to build on the potential that was established by these earlier studies. This is accomplished by systematically characterizing contaminant profiles at several sites and using this data to develop and calibrate a readily-accessible tool for evaluating the profiles and aiding stakeholders in decision making.

Analytical modeling approaches for better understanding the impacts of matrix diffusion on site management are summarized within an AFCEE-funded research document (AFCEE, 2007) that was jointed prepared by Colorado State University and the Colorado School of Mines (partly using work originally performed by Drs. Beth Parker and John Cherry). Recently, an ESTCP-funded project (ESTCP ER-201127) has integrated these approaches into free software called the Matrix Diffusion Toolkit. Based on the Microsoft Excel® platform, the Matrix Diffusion Toolkit is an easy-to-use, comprehensive, free software tool that is designed to assist site personnel in estimating what effects matrix diffusion will have at their site, and transfer the results to stakeholders. The toolkit contains two models (one simple and one more complex) that can be used to provide planning-level estimates of:

- mass discharge (sometimes called mass flux, in grams per day) and/or concentrations in the transmissive zone caused by matrix diffusion; and
- mass of contaminants and concentrations in the low-k zone.

Both models assume a simplified two-layer configuration, where a plume in a transmissive zone is in contact with a low-k zone. The loading period (where contaminants diffuse from the transmissive zone to the low-k zone) has to be estimated, followed by a release period (where contaminants diffuse from the low-k zone to the transmissive zone). One of the key challenges for running the Toolkit is coming up with reasonable estimates for the year the loading period started (i.e., when DNAPL was first released and plume formation started) and year the release period starts (when DNAPL becomes depleted or is isolated / removed).

The output generated by source history modeling can be used to support further understanding of the impacts matrix diffusion at the site—specifically by providing a better representation of the loading period over time. Because the Matrix Diffusion Toolkit was developed by several of the same PIs as the current project, incorporating the source history spreadsheet tool as a module into the Matrix Diffusion Toolkit in the future is an easily-implementable option.

Table 2.1. Chronological Summary of the Development of the Technology

Time Period	Description of Technology Development
1980s	• Experimental results demonstrate influence of diffusion within heterogeneous media (particularly fractured media) on DNAPL fate and transport (e.g., Sudicky et al., 1985; Sudicky, 1986; Schwille, 1988) • Initial implementation of field methods for drive-point based depth-discrete subsurface characterization (e.g., CPT, GeoProbe, HydroPunch)
1990s	• Increased recognition that diffusion of DNAPL into fractured porous media and other low permeability matrices can influence contaminant transport long after initial release (e.g., Parker et al., 1994, 1996, 1997; Liu and Ball, 1998a, 1998b, 1999) • Further development and commercialization of field methods that are aimed at high-resolution subsurface characterization of chlorinated solvents (e.g., Waterloo Profiler, MIP, LIF)
2000-present	• Further improvement and industry acceptance of field characterization methods that are suitable for investigating low permeability media (e.g., EPA Triad Approach) • Detailed source characterization at several sites coupled with analytical and numerical modeling efforts to estimate source loading and back diffusion effects (Parker et al., 2004, 2008; Chapman et al., 2005; Liu and Ball, 2002) • Release of several technical guidance documents that highlight influence of matrix storage and release on contaminant transport and remediation (AFCEE, 2007; Sale et al., 2008) • Development of the Matrix Diffusion Toolkit (ESTCP ER-201126; currently under review by the ESTCP program office)

The basis for the modeling approach used during this project is the one-dimensional (1-D) diffusion equation (e.g. Freeze and Cherry, 1979) using Fick's second law. This law defines the diffusion of a chemical in solution in response to a concentration gradient. The analytical solution allows for the concentration at any depth to be determined based on the concentration at the interface:

$$\text{Fick's first law: } J_D = -\phi D_e \frac{\partial C_w}{\partial_z}$$

$$\text{Fick's second law for a sorbing species: } \frac{\partial C_w}{\partial t} = \frac{D_e}{R}\frac{\partial^2 C_w}{\partial z^2}$$

The following represents the analytical solution to Fick's second law for diffusion into semi-infinite porous media:

$$C_w(z) = C_o \; erfc\left[\frac{Z}{2\sqrt{t\; D_e / R}}\right]$$

Note that Grathwohl (1998) provides the finite difference form of Fick's Second Law, which allows for a solution for more complex scenarios such as with non-linear sorption isotherms or time dependent boundary conditions and can be easily implemented into an Excel Spreadsheet. This methodology was used for generating the profiles shown in **Figures 2.1 and 2.2**.

The goal of the approach being tested as part of this project is to use the vertical concentration profile within the low permeability zone to establish the interface concentration vs. time pattern that would best represent this profile. This is done by systematically adjusting the interface concentration (C_o) at various time intervals (t) until a representative "best" fit is obtained.

The tool generated by this project is a simple spreadsheet-based model that follows this approach and provides a source history estimate that best represents the soil concentration profile (see **Figure 2.5**). It also includes a vertical advection term and a first-order decay term to understand the potential impacts of these processes on contaminant fate and transport in addition to diffusion and sorption processes.

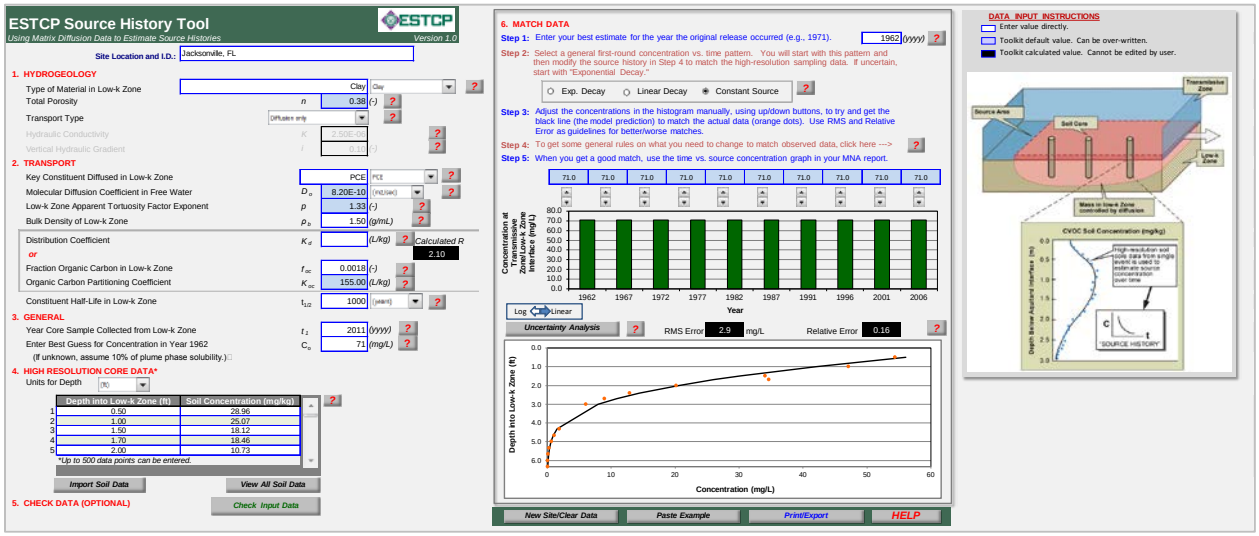


Figure 2.5. Screenshot of the Source History Tool. The tool is an Excel spreadsheet-based model that allows the user to input site-specific (or default) information obtained from soil cores (left hand side of screen) and then estimate the source history associated with these data (right-hand side of screen).

2.3 Advantages and Limitations of the Technology

The technology couples a detailed site characterization approach involving collection of high resolution profiles of contaminant concentrations in lower permeability zones with transport modeling to reconstruct the source history at a site. The advantages and limitations of this approach should be evaluated in terms of its ease of use, applicability, and the knowledge gained following implementation. **Table 2.2** summarizes the advantages and disadvantages within this context.

Technology performance is a function of site properties, and it is envisioned that this approach should be implemented primarily at those sites with favorable site conditions. Well-delineated source zones and plume zones are a key consideration to ensure that data collection is focused, cost-efficient, and is adequate for reconstructing source histories. Subsurface geology, including specific depths where high and low permeability zones are encountered, must be known or established as part of the characterization efforts. Geologic complexity can affect the outcome as well, for example sites with relatively simple geology and abrupt contacts between high and low permeability zones provides greater potential for providing meaningful insight on source attenuation history versus sites with greater geology complexity such as transitional changes between high and low permeability zones. However even these more complex sites can benefit from more detailed understanding of the contaminant mass distribution relative to permeability distribution.

The approach is more readily implemented at sites where direct-push techniques for depth-discrete sampling are viable (e.g. Geoprobe coring methods http://geoprobe.com/soil-sampling-equipment-continuous-discrete); sites where low permeability zones are present only at deep intervals may require alternative drilling techniques (e.g. Sonic drilling methods) and may prove to be more expensive to investigate. However more recently larger direct-push rigs (e.g. Geoprobe 80-series rigs) and Geoprobe / Sonic methods (http://sonictooling.com/) are making investigations at sites with more challenging and deeper contaminant conditions viable. As well coring methods that can provide higher quality cores with sonic rigs are also available, such as the AquaLock Piston Sampler (http://www.sonicsampdrill.com/sonic-tooling/aqualock-soil-samplers.htm). Steps to minimize cross-contamination must be part of the sampling program, particularly if drilling in source areas where some DNAPL may still be present. The technology involves a relatively passive technology with minimal potential for short-term site disruption or long-term negative impacts on subsurface conditions.

Table 2.2. Advantages and Potential Limitations of the Technology

Advantages	Limitations
May reduce need to implement costly source treatment technology	Requires presence and delineation of interface between two geologic strata with contrasting permeabilities
Increases acceptability of monitored natural attenuation as a remedy	Presence of multiple sources and/or commingled plumes can complicate analysis
Investigation is minimal in footprint and requires no permanent installations	Collection of high-resolution data can be costly at sites with complex geology or deep contamination
Improved understanding of contaminant fate and transport at a site and potential for back diffusion, even if characteristic diffusion profile in low permeability layer is not obtained	Modeling may generate multiple "source histories" solutions, such that some user knowledge is required to narrow down solutions to most appropriate
Applicable to multiple contaminant types	Occurrence of reactions (abiotic or biotic), non-linear sorption, etc. within the low permeability zones can complicate analysis

3.0 PERFORMANCE OBJECTIVES

For the purposes of evaluating the cost and performance of the field demonstration, the following performance objectives were envisioned (**Table 3.1**). A full description of the various components of the proposed approach listed in **Table 3.1** is provided in Section 5.0 (Test Design).

Note that **Table 3.1** includes multiple quantitative performance objectives related to the reconstruction of source histories. These involve spatial and temporal calibration of a 1-D diffusion model using data (depth-discrete soil and/or groundwater samples) collected as part of the field program. The details of model development are presented in Section 5.7. For the purposes of identifying data requirements and success criteria for performance objectives, it is sufficient to understand that the source history model uses field-measured vertical profiles of soil concentrations as the primary input data to generate the following output data at the same location: 1) source concentration over time since initial release occurred; and 2) modeled vertical profiles of soil concentrations for comparison to the measured profiles.

Table 3.1. Performance Objectives for the Field Demonstration

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
1. Reconstruct Source History - Accuracy	Data from depth-discrete and matrix-specific field samples (soil extracts, groundwater), source history estimate (modeling results)	Source history captures the style of measured field data: RPD $\leq \pm 30\%$ for majority of paired depth-discrete data (e.g., measured soil concentration vs. modeled soil concentration at same depths	***NO*** • Only 7 of 17 source histories met criterion • Criterion overly restrictive and not very representative • Passes "eyeball test" for style
		Source history captures the style of measured field data: Ratio of RMS error to maximum measured concentration for 75% source history estimates ≤ 0.3 (30%)	***YES*** • 17 of 17 source histories met criterion • More representative metric

Table 3.1. Performance Objectives for the Field Demonstration (continued)

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
2. Reconstruct Source History – Precision	Data from depth-discrete and matrix-specific field samples (soil extracts, groundwater), source history estimate (modeling results)	Similar source history generated from duplicate datasets from same location at same site: i) RPD ≤ 30% at majority of time points; or ii) same temporal concentration trend using non-parametric statistical test	***YES*** • Same source history trend (constant) observed using data from duplicates – confirmed using Mann-Kendall • RPD < 30% for 10 of 10 datapoints
3. Reconstruct Source History - Sensitivity	Data from depth-discrete and matrix-specific field samples (soil extracts, groundwater), source history estimate (modeling results); Monte Carlo sensitivity analysis	Quantify sensitivity of source history to individual input parameters: i) same temporal concentration change trend following ±10% change in each input parameter; ii) same style in soil VOC vs. depth profile following ±50% change in each input parameter	***YES*** • No changes to temporal concentration trends • No changes to style of soil VOC vs. depth profiles
4. Comparison of Modified Data Collection Method with Standard Data Collection Methods	Matrix-specific field samples (soil extracts, groundwater)	Identify consistent trends between field extracts analyzed using UG methods vs. Encore samplers analyzed at commercial lab: $R^2 \geq 0.9$ using regression analysis for paired data	***NO*** • $R^2 = 0.83$ • Significant low bias in unpreserved Encores contributed excessive variability
		Identify consistent trends between soil extracts analyzed at Guelph vs. soil extracts analyzed at commercial lab: RPD ≤ ±30% for majority of paired data	***YES*** • RPD < 30% for 37 of 39 analytes • Pattern relatively consistent for all analytes
		Median RSD of duplicates analyzed at Guelph < ±10% (i.e., similar to acceptable RSD for duplicates analyzed at commercial lab)	***YES*** • Median RSD = 7%

Table 3.1. Performance Objectives for the Field Demonstration (continued)

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Qualitative Performance Objectives			
Ease of Use	Feedback from field personnel regarding time required for data collection and ease of implementing methods	Single mobilization required per site to collect adequate level of data	***PARTIAL*** • Second mobilization required to accommodate expanded scope of work • Methods were easy to implement
Selection of Appropriate Locations	Historical site data used to select locations for detailed data collection	Assess what previous historical data was used to select locations and how this improved the results.	***YES*** • Existing data were sufficient to select test areas • Multiple coring locations per site proved valuable

3.1 Performance Objective: Reconstruct Source Histories - Accuracy

For the performance objective related to the accuracy of the reconstruction of source histories, the model was configured to account for site-specific contaminant and hydrogeological characteristics. Success was then assessed based on a reasonable fit of the style of the field data to the simulated data for each of the test sites.

3.1.1 Data Requirements

Accuracy was assessed based on the fit of the modeled soil concentration vs. the measured field data for soil concentration. A key component is selection of appropriate methods for field preservation, extraction and analysis of contaminants in low permeability media. This work used methods tailored to low permeability media (referred to here as the "UG methods") including field methanol preservation which has been shown to be the most efficient and robust method for VOC recovery (e.g. Hewitt, 1998), laboratory extraction methods tailored to ensure complete extraction (e.g. Dincutoiu et al., 2003, 2006; Parker et al., 2003) and analytical methods using direct methanol injection (Górecka et al., 2001) which provides exceptionally low MDLs (typically <1 µg/L in methanol extract for the target VOCs).

At each location tested, a high resolution concentration profile was obtained, primarily using soil samples collected at closely-spaced intervals within the pre-identified low permeability interval. In estimating the source history at the interface with the overlying high permeability interval that

would result in the measured soil profile in the underlying low permeability interval, the model generates a soil profile that minimizes the difference between measured and estimated soil concentrations. The modeled data was compared with the measured soil data to determine the relative accuracy of the fit at each test location, using the relative percent difference between each data point as the primary metric.

3.1.2 Success Criteria

At each location, the objective was considered met if the RPD between paired data points (i.e., measured soil concentration at a specific depth vs. modeled soil concentration at same depth) is less than 30% for the majority of depths where soil concentrations were collected. An additional success criterion based on the ratio of the RMS error to the maximum measured concentration for each soil profile was developed, also using the 30% limit.

3.1.3 Results

Seventeen different source history estimates were generated for the locations investigated as part of this project. This included separate source histories for different parent compounds, as well as additional source histories for parent compounds alone and parent compounds plus degradation products. For the soil concentration profiles (measured and simulated) associated with each of these 17 source histories, only 7 met the criterion that the median RPD was < 30%. This means that the performance objective was not met.

Despite this shortcoming, it was clear that the data comparisons generally passed a simple "eyeball test". For all of the cases, the simulated and measured soil data often appeared very similar in style throughout the entire low permeability interval, even if median RPD metric did not reflect this accuracy. In retrospect, it was the perhaps unrealistic to select a criterion that mandated that all of the source histories had to exhibit an RPD of < 30% to achieve success. This rigid criterion did not account for outliers. Even more importantly, it did not account for the inadequacies of RPD as a goodness of fit metric. This is particularly true when the concentration values approach zero, where even small absolute differences in concentration can result in very high RPD values.

As such, an additional performance metric was developed to provide a more representative assessment of accuracy. This used the ratio between: 1) the RMS error (i.e., the optimization metric for the modeling results); and 2) the maximum concentration measured throughout the entire depth profile. The RMS error represents the average error for the datasets, i.e., the average concentration difference between the measured and simulated data over the entire low permeability interval. As such, it captures the overall error associated with a source history estimate in a single number. Using the ratio of the RMS error to the maximum concentration provided a means for normalizing the error. A limit of 30% was set as the success criterion for a large majority of the simulations (75%). For the 17 source history estimates that were generated, the 30% limit (i.e., ratio of 0.3) was achieved in all 17 cases. Thus, the success criterion was achieved and is evidence for the relative accuracy of the modeling results.

3.2 Performance Objective: Reconstruct Source Histories - Precision

For the performance objective related to the precision of the reconstruction of source histories, data were collected with the intent of determining the reproducibility of the method. This applies to both the reproducibility of the model estimates using similar input data (from duplicate datasets). This also provides insight on our ability to obtain similar input data given the signal variability that can be encountered when determining soil concentrations.

3.2.1 Data Requirements

Precision was assessed based on a comparison of the modeled source histories using field duplicate data. At one location at one of the source areas, a duplicate soil concentration profile was collected using a separate but co-located borehole (i.e., within a meter or so of the first location), and field duplicate samples from the same borehole were collected at all locations (~5%). Each of these location-specific datasets matched up soil samples from the same (or nearest) depths, such that the modeled source histories (concentration vs. time) generated using each dataset was directly comparable. The two source histories from the same location were compared using two metrics for assessing precision: i) the relative percent difference at each time point; and ii) consistency in the overall trend for the modeled concentration vs. time profile using statistical trend analysis. The trend analysis was carried out using a standard non-parametric test (Mann Kendall) which requires duplicate data to be collected at multiple depths from one core (to quantify precision within that core) and then compared to similar data from a second core.

Note that the original demonstration plan included a second performance objective related to precision. Specifically, a comparison was to be made between source histories generated from data obtained at spatially-distinct locations from the same site. To perform this assessment, a 2-dimensional source history model would have been required to account for the influence of advection. Since a 2-dimensional source history model was ultimately not developed as part of this project, this second precision objective was dropped.

3.2.2 Success Criteria

At the location where duplicate soil concentration datasets were obtained, the objective was considered met if the RPD between paired data points for the two source histories (i.e., modeled source concentration at single time point vs. source concentration at same time point using duplicate datasets) is less than 30% for at least 70% of the paired data points. Alternatively, the objective was considered met if the same concentration vs. time trend is statistically-established using each of the two source histories generated from the same location.

3.2.3 Results

Both of the sub-objectives were successfully achieved. Duplicate cores were collected at location OU3-5 and the resulting source histories both exhibited the same constant concentration trend over time. The initial concentration differed slightly between the two (30 mg/L vs. 32

mg/L), but the RSD was less than 30% for all 10 timepoints that were generated via modeling. Because the source histories from both locations were constant, a uniform RPD of 7% was achieved for all timepoints.

The Mann-Kendall non-parametric test was performed on both datasets to confirm that the constant trends observed were statistically significant. The results of this test confirmed that the source histories both exhibited a stable trend (Mann-Kendall test statistic = 0, COV = 0, Confidence Factor = 45.6%), thus achieving the success criterion.

3.3 Performance Objective: Reconstruct Source Histories – Sensitivity

For the performance objective related to sensitivity, the output of the source history reconstruction method was monitored following changes to important model input parameters. It is important to quantify the extent to which these input parameters, which are generally a function of soil and contaminant characteristics, influence the source history estimates.

3.3.1 Data Requirements

Input parameters for the model were measured directly (e.g., soil VOC concentration, organic carbon) or assumed based on literature or site-specific values (porosity, tortuosity). Several different sensitivity evaluations were performed at one location per site:

- Values of select parameters were adjusted by a small percentage (±10%) to determine the impact on the overall concentration trend (i.e., the output data from the model). For each dataset evaluated, the concentration trend was established with the Mann-Kendall non-parametric test.
- Values of select parameters were adjusted by a larger percentage (±50%) as part of a Monte Carlo sensitivity analysis that is a built-in component to the spreadsheet model. For each dataset, all other parameters were held constant, and the resulting impact of the parameter adjustment on the "style" of the fit of the soil data were evaluated visually.

3.3.2 Success Criteria

For a given parameter, the objective was considered met if the same source history concentration trend was statistically-established using both the adjusted input dataset (+/- 10%) and the non-adjusted input dataset. The objective was also considered met if the Monte Carlo sensitivity analysis using +/- 50% adjustments in the selected input parameters yield the same style of fit to the soil VOC concentration vs. depth data (e.g., characteristic of constant source vs. decaying source).

3.3.3 Results

For all cases, small changes to the input parameters did not necessitate any changes to the source concentration trends to fit the data. The same trend was able to fit the data before and after the parameter value was adjusted. Consequently, the performance objective was achieved.

Larger changes were evaluated using the Monte Carlo sensitivity analysis. In all cases, the results of the simulations demonstrated that there was no change to the style of the soil data even following relatively significant changes to the input parameters. As such, this evaluation provided supporting evidence that the performance objective was achieved.

3.4 Performance Objective: Comparison of Data Collection Methods

This performance objective was designed to determine if the proposed data collection methods provide VOC data that are consistent with those obtained using standard methods. This included an assessment of both soil sampling methods (Encore sampler vs. field methanol preservation) and analyses methods (commercial laboratory vs. UG lab). Collectively, these are considered the "UG methods" for the purpose of this project. This approach provided a broad assessment of the value of using the UG methods in obtaining adequate input data for the source history model. Several sub-objectives were developed as part of this larger objective.

3.4.1 Data Requirements

For this case, the soil VOC concentration data collected using the project-specific methods (field preservation of soil samples with methanol and extraction and analysis using University of Guelph method) were compared with VOC data collected with two other methods: (1) unpreserved soil samples collected using EnCore samplers and analyzed at a commercial laboratory; and (2) soil preservation in methanol in field, extraction using the UG method, followed by analysis of the methanol extract at a commercial laboratory (i.e., split sample).

Duplicate samples were collected with the EnCore samplers (i.e. adjacent sample from the core at the same depth interval) at a representative number of depths where soil samples were collected using the project-specific methodology. These samples were sent to a commercial lab, where the detection limits for most VOCs using EPA methods 5035 (sample preparation) and 8260 (sample analysis) were expected to be higher than what will be achievable using the UG method. Consequently, the goal was to identify consistent trends between the two datasets using a regression analysis to determine the extent of variability and/or bias.

Similarly, a representative number of splits of the methanol aliquots from soil samples collected and preserved with methanol in the field and extracted using UG methods were sent to a commercial lab for VOC analysis via EPA method 8260 (but not using any additional extraction and/or preparation techniques not otherwise specified in EPA methods). For all samples where both analyses yielded detections (with the expectation that the UG method will provide lower detection limits for most VOCs, given the 8260 method requires a dilution step of methanol into water), an assessment of accuracy was performed using relative percent difference as the primary metric.

For all samples where VOC concentration data was obtained using both the UG method and a commercial lab (i.e., from split samples or duplicates), a final assessment of precision will be performed using relative standard deviation (coefficient of variation) as the primary metric. The

results of duplicate analyses performed at each lab will be evaluated collectively, such that the number of samples analyzed at each lab need not be identical to make a reasonable comparison.

3.4.2 Success Criteria

For the comparison between data obtained using splits of the methanol extracts, the objective will be considered met if the RPD between paired data points (i.e., methanol extract analyzed at a commercial lab vs. same methanol extract analyzed using UG methods) is less than 30% for at least 70% of the paired data points.

For the comparison between the dataset obtained using the Encore sampler/commercial lab and the dataset obtained using the UG methods, the objective was considered met if a regression with $R^2 > 0.9$ can be obtained for one or all of the primary VOCs of interest at the site.

For assessing precision, the objective will be considered met if the median relative standard deviation (RSD) obtained from the entire set of lab duplicates analyzed using the UG method is less than 10%. This limit was used to represent a typical and acceptable RSD for duplicate analyses by a commercial lab.

3.4.3 Results

Two of the three sub-objectives were successfully achieved. For the split samples, the RPD was less than 30% for 37 of the 39 samples that were sent to both a commercial laboratory and the UG laboratory. This represented 95% of the sample sets, meaning that, the criterion that 70% of analyses met the 30% RPD limit was achieved. Of note is that linear regression of the split sample datasets also demonstrated a strong correlation (slope = 0.99, $R^2 = 0.99$).

For the samples collected and analyzed using the baseline method (Encore, unpreserved) vs. the UG method, the R^2 following linear regression was 0.83, which was slightly lower than the objective of 0.9. As expected, the baseline method suffered from a significant low bias (slope = 0.79), presumably due to loss of volatiles that occurred when the field methanol preservation step was omitted and perhaps incomplete extraction from the soil matrix. This contributed to variability in the data, and resulted in a weaker correlation. While the success criterion for this sub-objective was not achieved, the results clearly demonstrated the importance of preservation in reducing variability and limiting volatile losses. The previously-described split sample results demonstrated that the laboratory analyses did not contribute to the variability, such that sample handling is the primary cause.

Finally, a median RSD of 7% was obtained for the set of field duplicates analyzed at the UG laboratory (22 samples, 60 analytes). This was well below the goal of median RSD of 10%, and for individual samples the RSD of 57 of 60 analytes was below this 10% value.

3.5 Performance Objective: Ease of Use

A qualitative performance objective is proposed based on the ease of implementing the proposed core collection and sub-sampling and analysis procedures. These procedures are relatively straightforward and can be adopted by most field personnel with minimal additional training.

3.5.1 Data Requirements

This will be judged primarily on the feedback from field personnel regarding time and effort required for data collection (relative to conventional techniques), as well as the utility of screening methods that provide information on hydrostratigraphy and contaminant distributions, such as tWaterloo^{APS} ™ (or other methods such as the Geoprobe HPT™ and MIP systems) for aiding selection of appropriate depth intervals for high resolution soil sampling.

3.5.2 Success Criteria

Success will be based on the amount of time required for completing the various procedures, specifically that sufficient data can be collected within a single rig and crew mobilization for using the source history reconstruction method.

3.5.3 Results

This qualitative objective was partially met. The procedures were easy to implement by the field personnel. Some of them were already experienced with the various methods, with others were relative newcomers. All were able to familiarize themselves rapidly and are confident that they could implement them again in future projects. While a technology specialist was contracted to supply and operate the Waterloo$^{APS\ TM}$, MIP, and Geoprobe HPT™ systems, a local drilling contractor was used to drive the tools and collect data. This drilling contractor was able to successfully execute the work plan with no complaints from the GSI/UG/Stone field personnel, despite the company's relative lack of experience in using several of the systems.

Due to project restrictions, the field work was actually completed in two separate mobilizations, one for gathering screening-level data and another for collecting cores. This was done for two reasons: 1) the two source areas were located at the same site, such that separating the expanded program phases (screening-level vs. coring) into separate mobilizations; and 2) to ensure that extra work done in support of another project involving this PI group (SERDP ER-1740) could also be completed. To meet the needs of both projects, multiple screening-level methods were used during the initial mobilization (including both MIP and Waterloo$^{APS\ TM}$). This made it too difficult to perform the soil coring during the same mobilization so the work was completed in two separate, shorter field programs. Note that all work associated with characterizing two different sites was completed in approximately 3 weeks, which is a reasonable duration for a field program focusing on collecting high-resolution characterization data.

3.6 Performance Objective: Selection of Appropriate Locations

A qualitative performance objective is proposed based on the ease or difficulty of selecting appropriate locations for further high-resolution characterization using existing site data. At sites where existing data are limited, implementing the source history approach likely will require more time (and cost) intensive upfront characterization efforts to limit uncertainty.

3.6.1 Data Requirements

Evaluation of this objective will involve a review of historical site-specific data used to select locations for detailed data collection.

3.6.2 Success Criteria

Success will be based on whether sufficient high-resolution data for reconstructing source histories at each site is possible based on a reasonable number of locations, or if collection of additional characterization data is required prior to the demonstration project.

3.6.3 Results

This qualitative objective was successfully achieved. Site documentation was sufficient to select test areas at each site. While groundwater monitoring data was limited, extensive mapping of the sites with MIP had already been completed, and these data were useful in understanding site conditions and selecting optimal locations for further investigation. The screening-level characterization data collected specifically for this project was sufficient to select specific coring locations and depth intervals for the more detailed soil coring investigations.

The collection of soil concentration profiles at multiple locations per site also proved valuable in understanding source history and attenuation patterns, particularly using locations along a downgradient flowpath,

4.0 SITE DESCRIPTION

4.1 Site Selection

Selection of an appropriate site for the demonstration was the first task to be completed. A preferred site was not identified at the proposal stage. Because of the widespread occurrence of heterogeneities within subsurface environments containing chlorinated solvents, it was anticipated that this technology would be applicable at many sites where source material is still present. Consequently, it was assumed that there would be a large number of DoD sites that would be suitable for this technology demonstration.

A list of potential demonstration sites was generated based on recommendations from the program office and contacts with DoD site managers. Site selection criteria were developed, and sites from the preliminary list were screened against these criteria. Necessary factors included: i) sites where a chlorinated solvent source zone is present; and ii) sites where a well-defined low permeability layer underlies the source zone. Specifically, sites where the source was initially released to a transmissive zone that is in contact with an underlying lower permeability layer were considered ideal because they best fit the diffusion-based source history reconstruction approach. Other favorable factors included sites where the spatial extent or time period of release(s) is known; sites where the source zone is dominated by one constituent; sites with favorable conditions for application of direct-push drilling techniques; sites where there is significant discrete-depth soil concentration data from low permeability intervals (e.g., sites already investigated to some extent with this methodology by the project team or others); and sites with a large database of historical temporal concentration records. The candidate list also focused on facilities that have previously been involved in successful innovative technology demonstration projects or that were receptive to the proposed technology demonstration.

The complete site selection criteria, as well as an evaluation of the characteristics of each site versus these criteria, were included in the Site Selection Memorandum that was submitted to ESTCP in January 2011. The sites selected for the demonstration included **NAS Jacksonville (with separate investigations completed at Building 106 and Building 780 at OU3).** Hill AFB (OU2) was included in the demonstration plan, but later dropped from the project due to schedule and cost considerations. The following section provides additional detail on relevant site characteristics for the two source areas that were included in the project.

4.2 Site Location and History

Naval Air Station (NAS) Jacksonville is a large site located within the city limits of Jacksonville, Florida with at least eight operable units (OUs) that are part of extensive investigation and cleanup efforts under Superfund. OU3 is a 134-acre area located in the eastern part of the facility near the eastern boundary (St. Johns River) and south of the flightline (**Figure 4.1**). Historically, OU3 has housed the Naval Aviation Depot where aircraft reworking activities and other support operations were centered. There are at least 50 buildings present at the site, and

pavement covers most of the remaining area. Investigations to identify releases of hazardous materials to the environment were initiated in 1982.

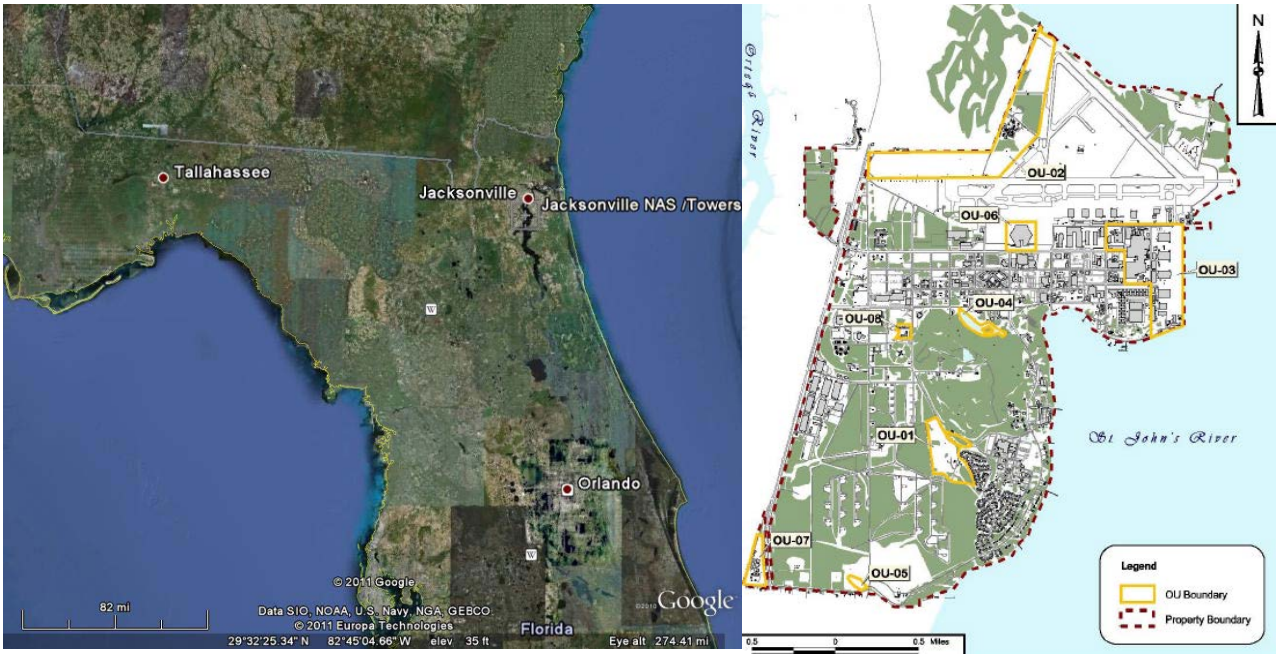


Figure 4.1. (a) Location of NAS Jacksonville; (b) Various Operating Units at the Site.
(Modified from figure supplied by site manager)

As a result of these earlier investigations, several potential sources of contamination have been identified within OU3. The primary areas of focus for the current project are Building 106 and Building 780 (**Figure 4.2**). These are separate source areas (though with commingled plumes) that are considered (by the site manager and regulatory authorities) to be distinct enough to be evaluated individually.

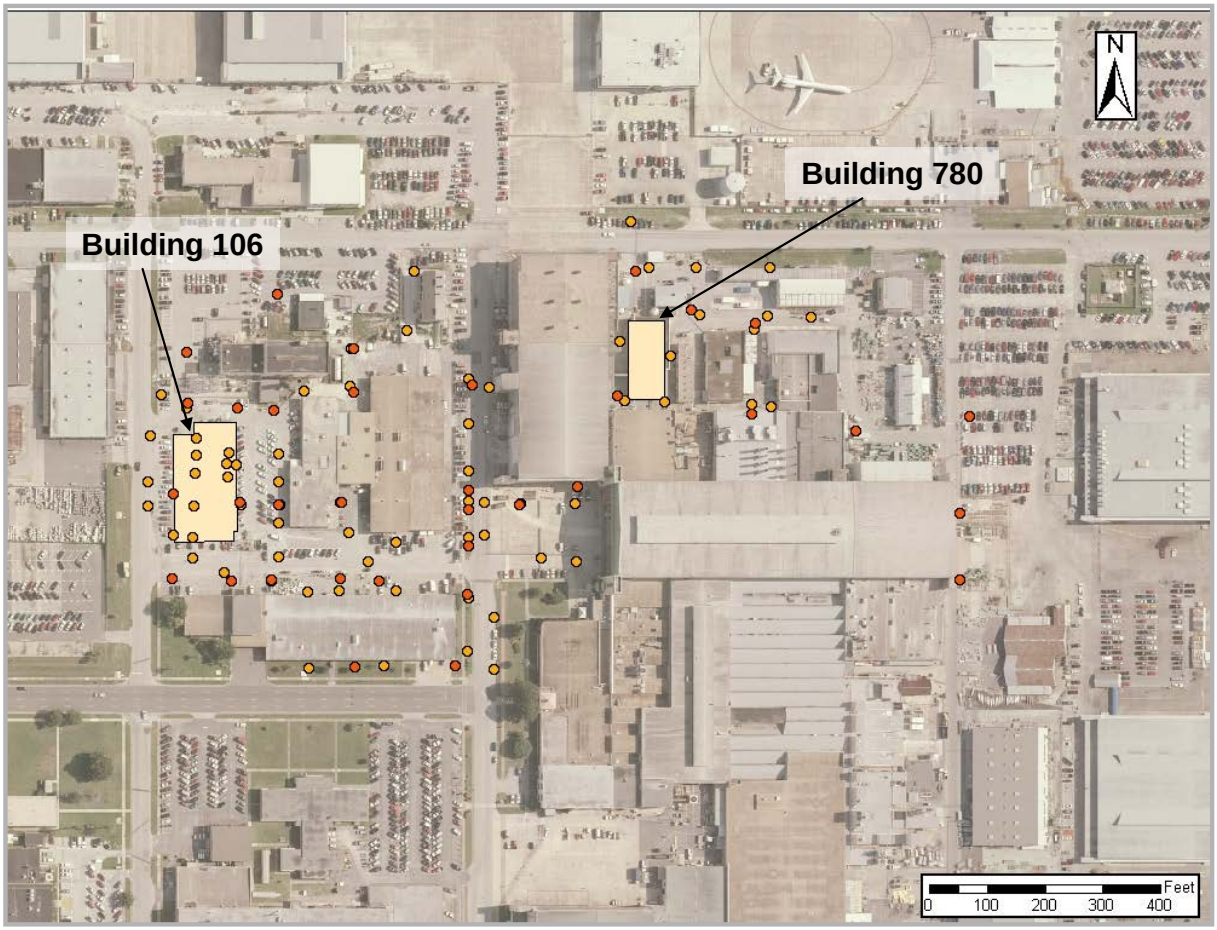


Figure 4.2. Site Map of OU3 at NAS Jacksonville. Figure shows only a portion of OU3, specifically the focus areas for the current project, including Building 106 and Building 780. Colored dots represent investigation points (primarily MIP and/or CPT) that were part of previous site characterization activities. (Modified from figure supplied by site manager)

4.2.1 NAS Jacksonville OU3, Building 106

This building was the former dry cleaner for the air station and is located in the north/northwest portion of OU3. It was operated as a dry cleaner beginning in 1962 and was believed to have used approximately 150 gallons of PCE per month until 1990 or so when dry cleaning operations were discontinued and the building was demolished shortly afterwards. This area was identified as a potential source of contamination in 1993. Currently the immediate area remains free of structures and is paved. It is surrounded by surface parking and there are several large buildings and access roads on all four sides. Interim remedial measures including air sparging and soil vapor extraction were implemented at the site in 1998 as part of the Record of Decision for OU3, but were discontinued following an optimization review completed in 2004-2005 (as part of the Five-Year Review). As of early 2013, the need for additional remedies is currently being evaluated as part of an addendum to the original RI/FS (from 2000). Based on communication

with site personnel, it is our understanding that a large-scale pilot test of electrokinetic methods for enhancing biostimulation are scheduled to implemented in a portion of the source area sometime in 2013.

4.2.2 NAS Jacksonville OU3, Building 780

This building housed a paint stripping and solvent recycling operation and currently is used as a general (non-hazardous) recycling facility. The building occupies a relatively small footprint (approximately 1000 m^2 including outbuildings) and is located in the northern portion of OU3 (approximately 200 m NE of Building 106). Currently, the area surrounding Building 780 includes several other permanent structures of various sizes, and all spaces where no buildings are present are paved. The exact start date for solvent use is unknown but it reportedly occurred throughout the 1970s and 1980s to strip paints from aircraft and parts (as well as disposal of spent jet fuels). It was identified as a potential source of contamination in 1990 when high concentrations of VOCs were encountered in exposed subgrade soils during major construction activities at the site. Subsequent investigation activities identified elevated concentrations of multiple types of VOCs (primarily chlorinated ethenes and chlorinated ethanes) as well as numerous inorganics in the soil and groundwater. In 1998, a soil-vapor extraction system and a groundwater pump-and-treat system were implemented at Building 780 to address contamination associated with this source as part of the Record of Decision. These systems were shut down temporarily following the 2004-2005 optimization review. Similar to the situation at Building 106, further remedial activities are being evaluated as additional data are collected at the site in support of an addendum to the 2000 RI/FS.

4.3 Site Geology and Hydrogeology

The site geology and hydrogeology at OU3 have been extensively characterized as part of previous investigations at the site. The soils underlying the site are part of Coastal Plain marine sediments, although surface soils have been extensively modified and there are extensive areas where fill was used, especially in previously low-lying areas. As a result, surface topography is relatively flat. Below the surface fill, interbedded layers of sand, clayey sand, sandy clay, and clay are encountered to depths of approximately 150 ft bgs. Each of these layers are somewhat discontinuous and not encountered at all locations, but the upper soil intervals are generally dominated by sands. Representative cross sections showing these units are included in **Appendix B**. Laterally extensive clays have been encountered in the northern portion of the site in particular, and the extent of the clay layer near Building 106 and Building 780 has been mapped more recently in this area as part of a comprehensive CPT survey in 2006 (**Appendix B**). These investigations established that the clays were generally first encountered at depths of 10 to 20 ft bgs and ranged in thickness between 2 and 10 ft. In this portion of the site, the clay is often present as two smaller lenses, separated by thin sublayers of sandier soils. When present, the clayey sands are either interbedded in the clay or present in transitional zones between the upper sands and clay. In general, similar stratigraphy was encountered at the two source areas that are part of this project (Building 106 and Building 780). More complex layering (i.e., thinner and more discontinuous clay layers) has generally been observed near Building 780,

which is consistent with base-wide observations that the shallow low-k zones diminish moving in an easterly direction.

The deposits at OU2 form a surficial aquifer unit that consists of two different layers within the northern portion of the site: 1) unconfined upper sand layer that extends from the surface to the depth of the clay (approximately 10 to 20 ft bgs); and 2) an intermediate sand layer that is confined by the clay (**Table 4.1**). The total thickness of the surficial aquifer (upper plus intermediate layers) is generally considered to be 30 to 100 ft (USGS, 2000). Because releases of hazardous materials occurred with the upper layer and came into contact with the low permeability clay, the upper layer of this surficial aquifer is the focus of the current investigation.

Groundwater in the surficial aquifer generally flows in an easterly direction away from the Building 106 source area and northeasterly from the Building 780 source area. Flow is complicated by the presence of a seawall on the eastern boundary of OU3 (at the St Johns River) and an extensive storm sewer network, but previous groundwater flow modeling has confirmed the E/NE flow directions within the areas of interest. Groundwater is first encountered at depths between about 4 to 7 ft bgs, and water levels reportedly vary little throughout the year. Hydraulic gradients in the surficial aquifer are relatively small, in the range of about 0.001 to 0.005.

The horizontal hydraulic conductivity for the upper sands based on pumping tests is approximately 20 ft/day. Horizontal hydraulic conductivities in the clay layer have not been established, but it is described in site reports as having "a very low hydraulic conductivity" and USGS modeling efforts (1998, 2000) used a hydraulic conductivity of 0.001 ft/day for this layer. These solute fate and transport models also assumed a vertical leakage rate between the upper and intermediate layers of 1 to 2 x 10^{-6} ft/day per ft (USGS, 1998; USGS, 2000).

Reported groundwater velocities within the surficial aquifer sands vary between 2 ft/yr (USGS, 1998) and 70 ft/yr (USGS, 2000). The latter value is based on an effective porosity of 0.125 (total porosity of 0.25) that was used during solute fate and transport modeling (USGS, 2000). Based on the length of the plumes associated with the Building 106 and Building 780 source areas (a minimum of several hundred feet) and the assumed release timeframe (30 – 50 years ago), the 70 ft/yr groundwater velocity is likely a more representative value for further modeling efforts.

Table 4.1. Summary of NAS Jacksonville OU3 Stratigraphy

Unit	Soil Type	Typical Thickness (ft)	Hydraulic Conductivity (ft/day)
			Maximum
Surficial	Sand	10-20	20
	Clay	2-10	0.001

Notes: (1) Units are described starting at the surface and then proceeding to deeper depths (surface fill not included); (2) Hydraulic conductivities represent field-based measurements when available; (3) Model values cited in site investigation reports used for units where field-based measurements were not performed.

Groundwater geochemical data were not available prior to the start of the demonstration. Given the presence of significant concentrations of reductive dechlorination products of PCE and TCE (i.e. cis-1,2-DCE, VC) at multiple locations at the site, it was assumed that the groundwater is at least mildly reducing. This was later confirmed by the project data, which demonstrated that the groundwater below both the Building 106 and Building 780 sources areas is mildly reducing (ORP typically below 0 mV; dissolved oxygen typically 0 to 4 mg/L), mildly acidic (pH typically near 6), and relatively low in sulfate and other electron acceptors (note that geochemical conditions differ slightly depending on depth and location). Based on available information, there were no matrix effects that were expected to affect the field data collection methods used during the current project (data collected in support of this project later demonstrated that high chloride levels in the lower permeability zones limited our ability to use chloride a positive tracer for biodegradation.)

4.4 Contaminant Distribution

The field demonstration at the two source areas focused on the unconfined portion of the aquifer, including both the upper sands and the underlying clay-rich layer. Within this interval, the most recent comprehensive groundwater data available at the time that the demonstration plan was prepared was from 2010. Note that the number of permanently-installed monitoring wells screened in the surficial aquifer is extremely limited (1 for Building 106 and 1 for Building 780). There are a few temporary piezometers that have been installed in these areas, though they were monitored for relatively short periods (several years in the early 2000s when interim remedial measures were being implemented). At various times, investigations of groundwater conditions have been supplemented using i) groundwater samples collected from temporary piezometer points; and ii) depth-discrete groundwater samples collected during from direct-push borings. Both of these methods allow for one-time sample collection from the investigation point.

4.4.1 NAS Jacksonville OU3, Building 106

Constituents of concern at Building 106 include PCE, TCE, and associated degradation products (including 1,1-DCE, cis-1,2-DCE, trans-1,2-DCE, and VC). In the one permanently-installed monitoring well in the area (MW-28 located immediately east of the former building), total CVOC concentrations in 1998 approached 30 mg/L with PCE as the major constituent. Concentrations in this well have fluctuated over time but remain well above regulatory screening limits for several chlorinated ethenes. Similarly high levels were seen in a series of temporary piezometers that were installed in the area and monitored periodically during the period from 2000 to 2004 when the interim remedy was operating. A more comprehensive assessment of groundwater concentrations that was completed in 2006 as part of a direct push investigation (**Appendix B**) encountered total CVOC concentrations that are generally highest in the area immediately under the former building and extending eastward (downgradient) for several hundred feet. There are several locations where the concentration of metabolites (particularly cis-1,2-DCE) exceed the concentration of parent compounds. The most recent groundwater data from February 2010 (**Figure 4.3**) suggest that concentrations are significant (total CVOCs approx. 6 mg/L in MW-28) but still declining, with evidence of extensive biodegradation.

4.4.2 NAS Jacksonville OU3, Building 780

Constituents of concern at Building 780 include 1,1,1-TCA, methylene chloride, PCE, TCE, and associated degradation products (including 1,1-DCA, 1,2-DCA, 1,1-DCE, cis-1,2-DCE, trans-1,2-DCE), as well as several aromatic hydrocarbons (benzene, toluene, xylenes). During early characterization of the site (1990), total CVOC concentrations exceeded 200 mg/L in the one permanently-installed monitoring well in the area (MW-780-1 located immediately west of Building 780). Concentrations decreased markedly in this well by 2000. Concentrations of chlorinated ethenes and ethanes varied widely in the series of temporary piezometers that were installed and monitored during the early 2000s. A more comprehensive assessment of groundwater concentrations completed in 2006 as part of a direct push investigation (**Appendix B**) also established that relatively low concentrations were present in the areas downgradient (northeast) of Building 780. The most recent groundwater data (**Figure 4.4**) indicated that total VOC concentrations are < 100 µg/L and the number of constituents detected is much more limited (cis-1,2-DCE, trans-1,2-DCE, TCE, and VC).

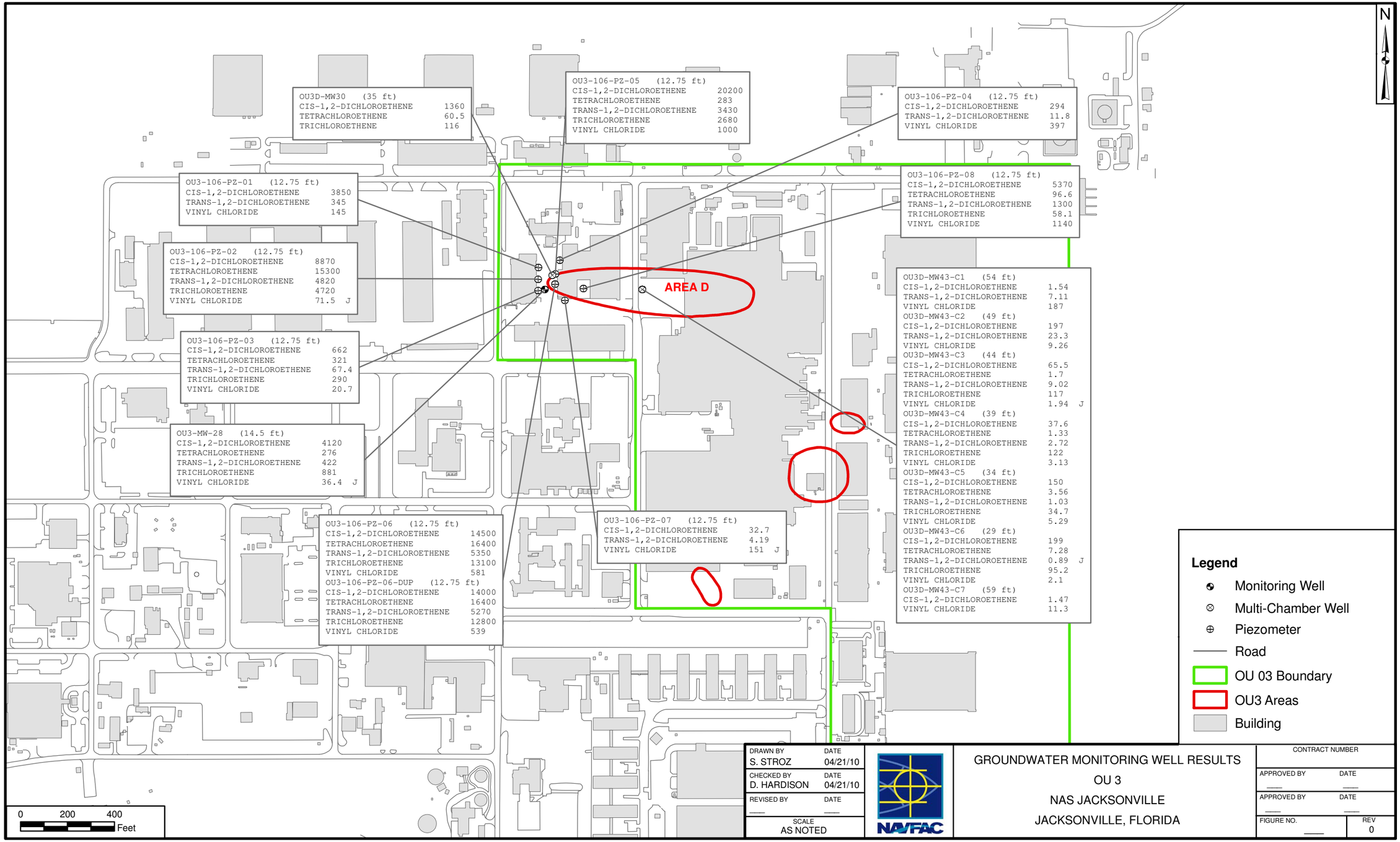
4.4.3 Site-Wide Investigations

Limited soil concentration data have been collected at the site. As part of a direct-push investigation in 2006, soil samples were collected at various locations near Building 106 and Building 780 (**Figure 4.5**). Depths of these samples typically coincide with the start of the lower permeability clays identified across OU3. These data demonstrate that near the Building 106 source area, the VOC profile is generally dominated by PCE (maximum concentration of 77 mg/kg), with higher contributions from lesser chlorinated ethenes at downgradient locations. At Building 780, the highest concentrations by far were encountered within the source area at the southeast corner, including 5100 mg/kg of 1,1,1-TCA and >100 mg/kg of PCE, TCE, and toluene. Note that these soil concentrations are much higher than what would be estimated based on groundwater samples in the area (which collect primarily from sandy intervals), reflecting the influence of mass storage within lower permeability zones in the surficial aquifer. Also of note are that 1,1,1-TCA concentration data exhibit significant spatial variability at this site; large drops in the concentration of this constituent are seen over small distances.

As noted in Section 4.3, detailed CPT/MIP surveys were completed at OU3 in 2006 to map low permeability layers and obtain a semi-quantitative indicator of contaminant concentrations above and below this layer. A subset of these results is presented in **Appendix B** and demonstrate that considerable mass is present in the lower permeability clays at both Building 106 and Building 780.

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FIGURE 4.3



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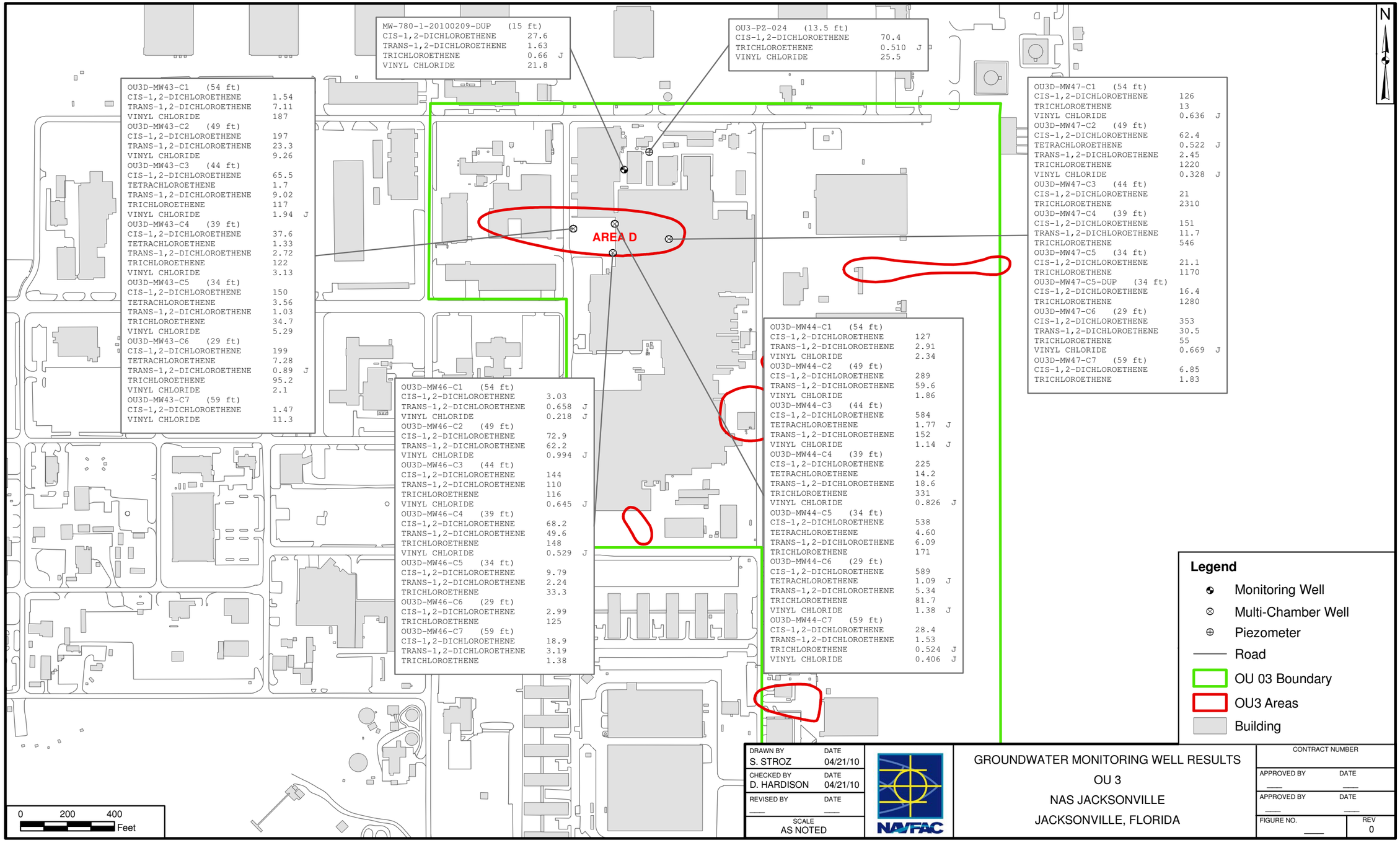
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GROUNDWATER MONITORING WELL RESULTS
OU 3
NAS JACKSONVILLE
JACKSONVILLE, FLORIDA

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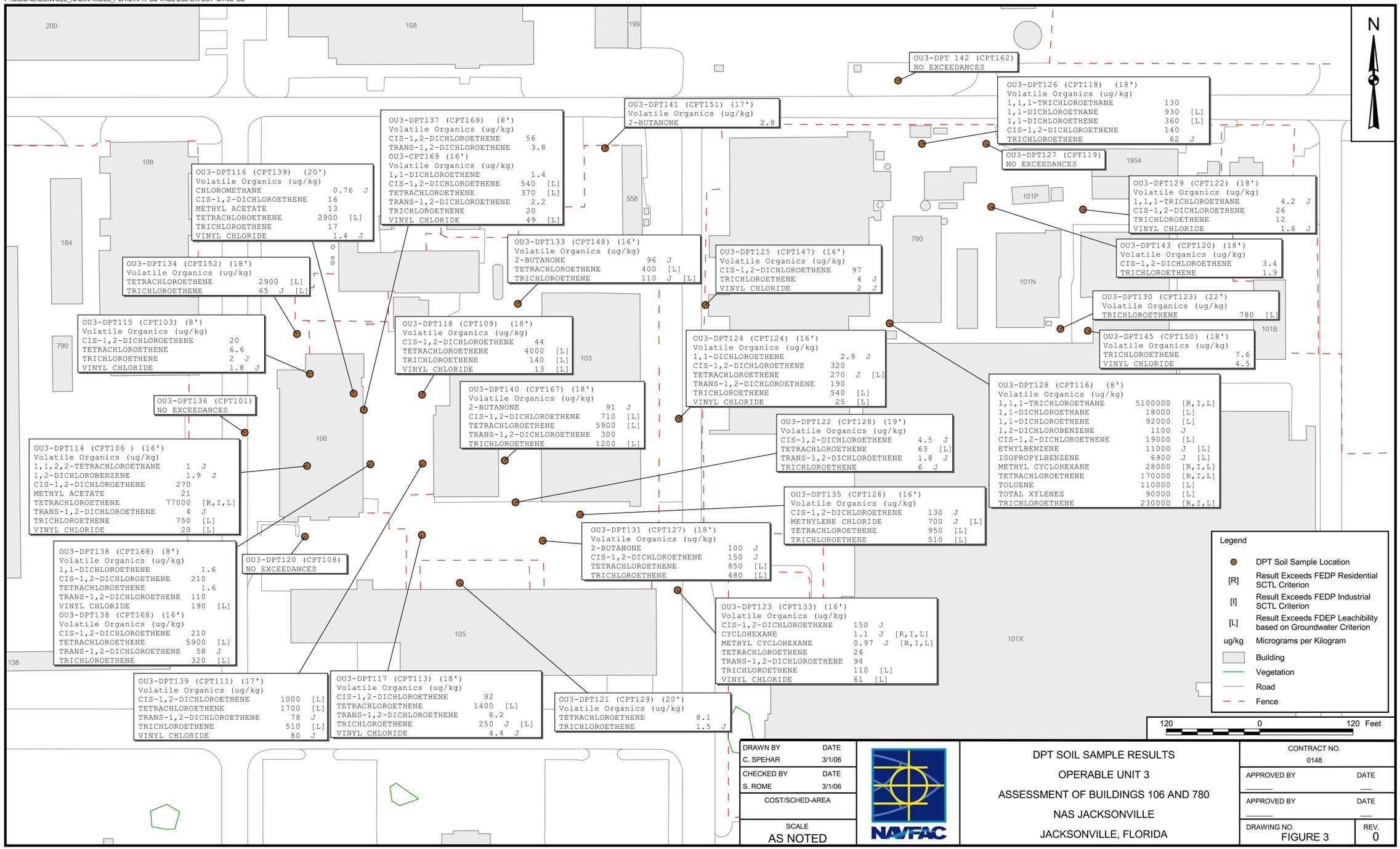
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FIGURE 4.4



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FIGURE 4.5



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NAVFAC

DPT SOIL SAMPLE RESULTS

OPERABLE UNIT 3

ASSESSMENT OF BUILDINGS 106 AND 780

NAS JACKSONVILLE

JACKSONVILLE, FLORIDA

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5.0 TEST DESIGN

5.1 Conceptual Experimental Design

The field program was designed to collect high-resolution depth-discrete data from low permeability zones at multiple sites and then to reconstruct the historical source history at each site using a diffusion-based transport model. The specific sampling methodology used during this project involved the collection of depth-discrete soil samples near geologic interfaces with lower permeability zones to generate a detailed contaminant profile with depth within these zones. In cases where the characteristic back diffusion profile within the lower permeability zones from locations within the source and in the downgradient plume are encountered, they can be used to demonstrate a decreasing concentration trend at the interface resulting from source decay due to natural processes causing source depletion and/or active remedial measures that has occurred in the time elapsed following release (assuming a reasonable estimation of the time of release can be made). This is done by back-calculating the source loading (i.e., concentration history at the low permeability interface) that would have resulted in the measured soil concentrations in the low-permeability layers as the result of diffusion-dominated transport in these layers. Other parameters required for this type of modeling, such as porosity, sorption and diffusion coefficients, are obtained from laboratory measurements on sites samples or estimated within reasonable ranges.

A similar protocol was followed at each site. Specifically, multiple locations were characterized at each site to generate several vertical soil profiles to serve as input data for source history modeling. This allows for a more comprehensive assessment of spatial differences in historical source loading (e.g., persistence of DNAPL), as well as location-specific influences related to advection, sorption, degradation, and other processes. At each location, soil sub-sampling was preceded by detailed vertical stratigraphic profiling to optimize the selection of soil sampling depths, as well as to provide groundwater data to refine conceptual and quantitative modeling at each location (**Figure 5.1**, see also Section 5.5.2).

Screening-level characterizations were completed at a minimum of 4 locations per site, with full characterization (i.e., continuous soil coring and high-resolution subsampling) completed at 3 or more of these locations per site. Note that while the focus was on source areas, downgradient locations were also included at each site. The rationale is that—relative to source areas—data from areas downgradient are less influenced by the presence/absence of DNAPL at the specific location being characterized. Thus, data from a downgradient location has the potential to represent the "average" source history over the entire extent of the representative upgradient source area. Furthermore, data from downgradient locations provide a more detailed picture of attenuation processes during transport. Data from these locations can also be used to develop and validate numerical-based source history modeling.

5.2 Baseline Characterization Activities

This field component of this project involved a detailed subsurface characterization at multiple locations at several sites. These efforts involved the use of screening-level characterization tools

at many locations (e.g, Membrane Interface Probe, Waterloo Advanced Profiling System (Waterloo APS®), Geoprobe Hydraulic Profiling Tool (Geoprobe HPT®)—see Section 5.3) followed by high-resolution soil coring (**Figure 5.1**). As such, there was no separate baseline characterization component to this project.

5.3 Design and Layout of Technology Components

The following sub-sections describe the primary components of the field demonstration and the locations at each source area where these procedures were utilized. For the two source areas at OU3 at NAS Jacksonville, **Figure 5.2** displays the locations characterized at the former Building 106 source area, and **Figure 5.3** displays the locations characterized at the Building 780 source area. **Table 5.1a** summarizes the characterization methods used at each location.

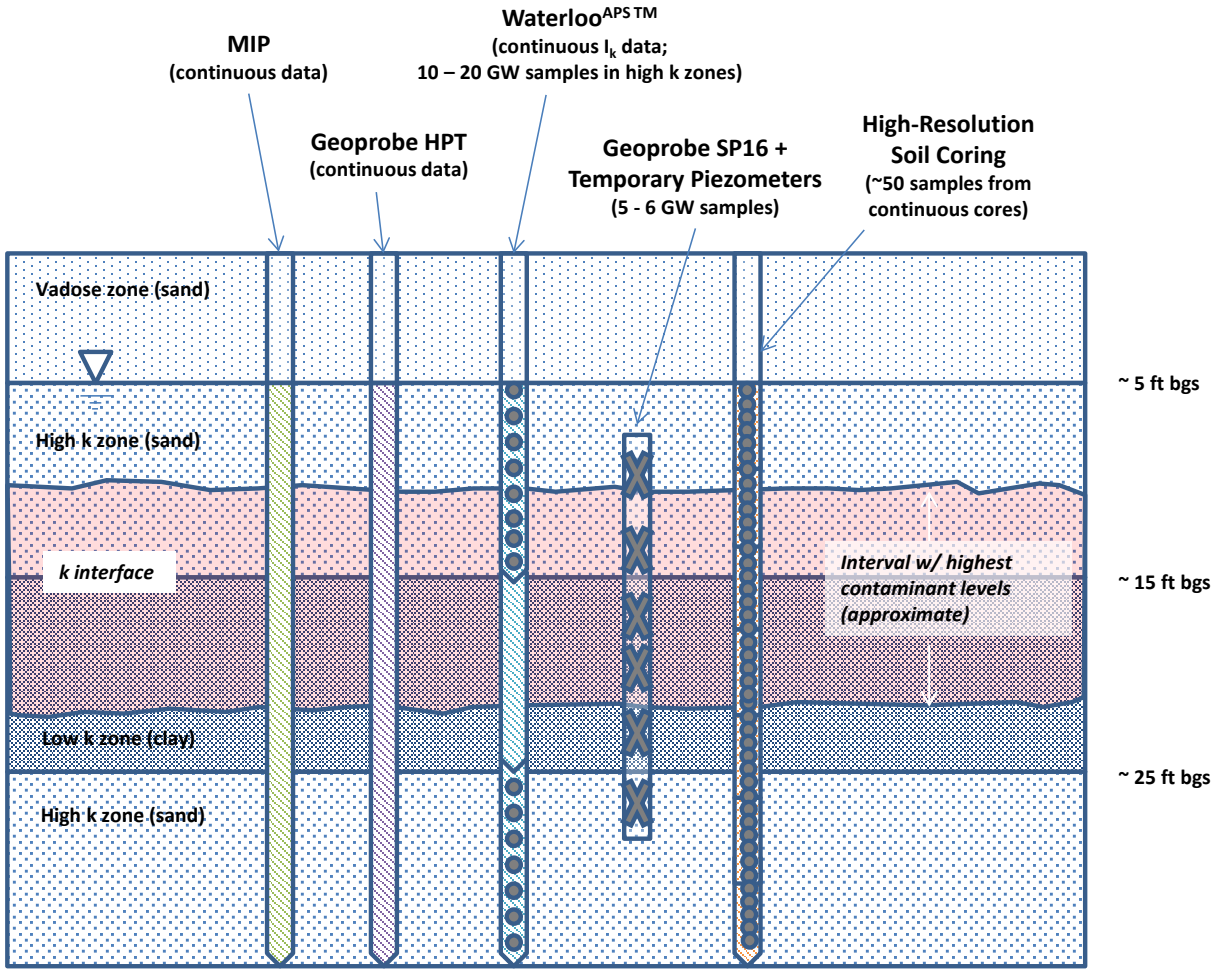


Figure 5.1. Characterization Methods Used During Field Demonstration at NAS Jacksonville.

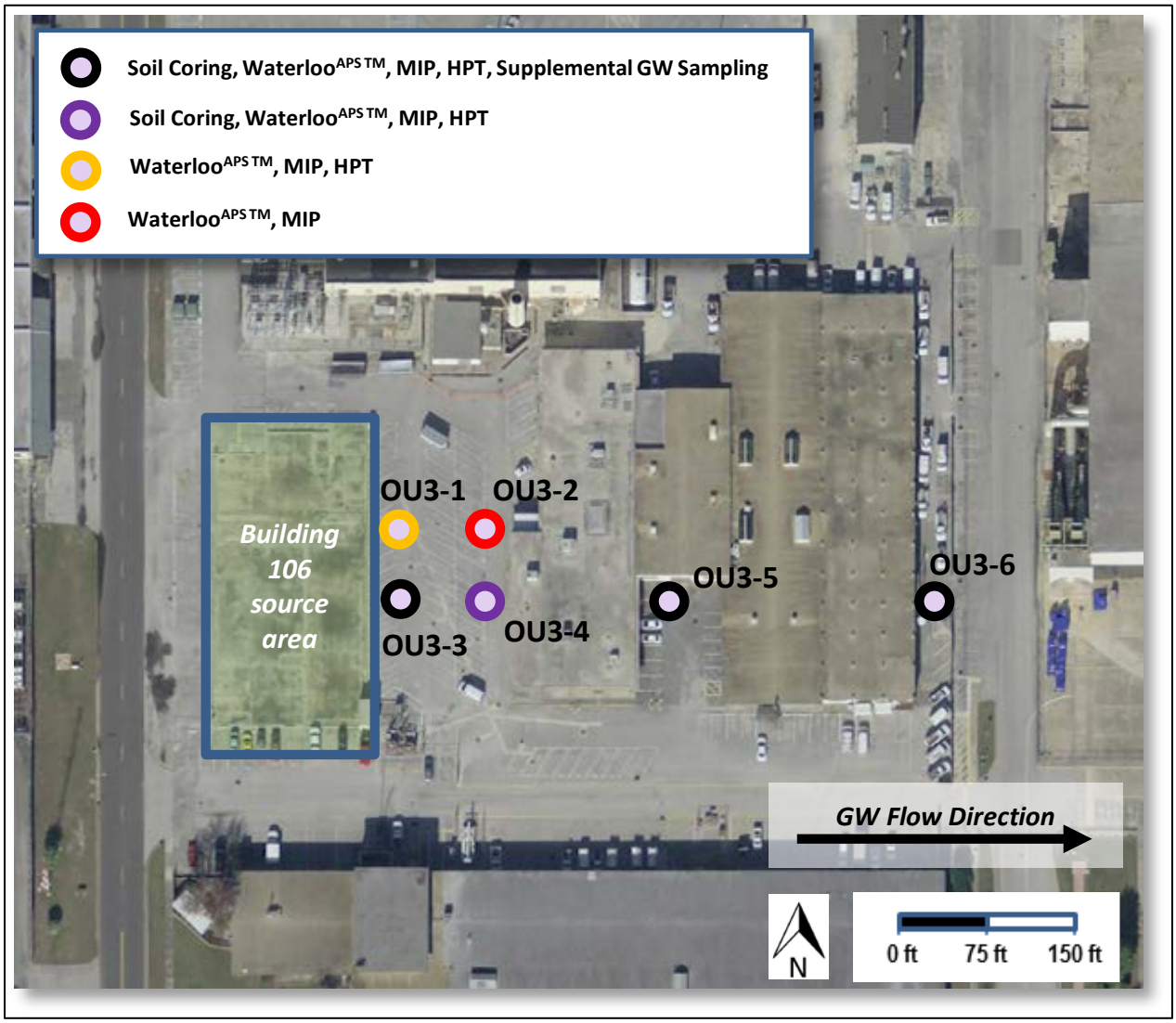


Figure 5.2. Test Locations for Field Demonstration at OU3 Former Building 106 Source Area at NAS Jacksonville.

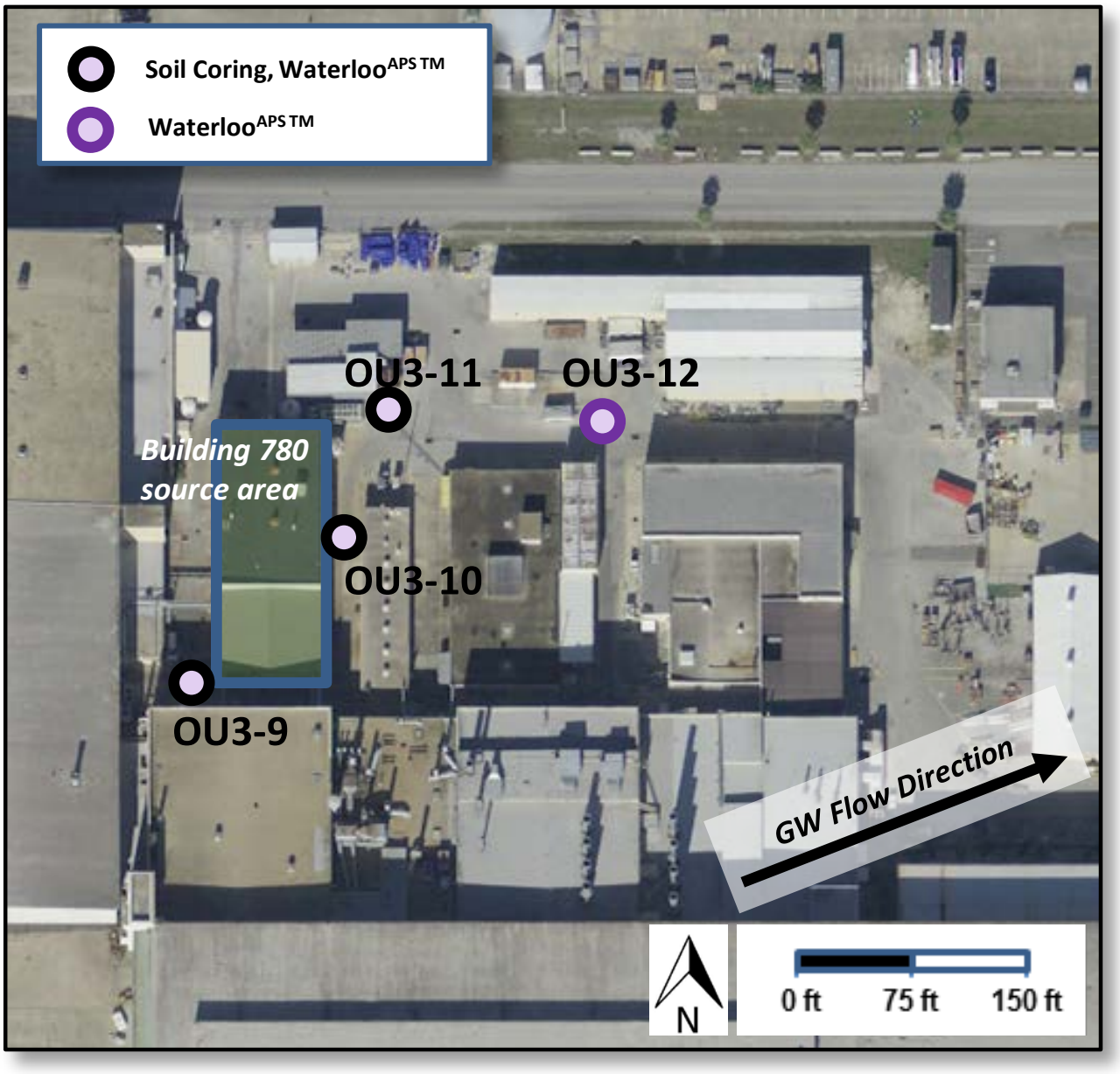


Figure 5.3. Test Locations for Field Demonstration at OU3 Building 780 Source Area at NAS Jacksonville.

Table 5.1. (a) Summary of Characterization Methods Used at NAS Jacksonville OU3 Locations

Location	MIP	Soil Coring	Waterloo$^{APS\ TM}$ (5)	HPT	Supplemental Groundwater Sampling (4)
Former Building 106 Source Area (1)					
OU3-1	x		x	x	
OU3-2	x		x		
OU3-3	x	x	x	x	X
OU3-4	x	x	x	x	
OU3-5 (3)	x	x	x	x	X
OU3-6	x	x	x	x	x
Building 780 Source Area (2)					
OU3-9		x	x		
OU3-10		x	x		
OU3-11		x	x		
OU3-12			x		

Notes: (1) See Figure 5.1 for sampling locations at Former Building 106 source area; (2) See Figure 5.2 for sampling locations at Building 780 source area; (3) A second (duplicate) soil core was collected at location OU3-5 (within 1 m): (4) Supplemental groundwater sampling completed using Geoprobe SP16 and/or temporary piezometers; (5) Groundwater samples were also collected using Waterloo$^{APS\ TM}$.

5.3.1 Screening-Level Characterization Tools

Three different screening-level characterization tools were used at one or more of the source areas. This included the Membrane Interface Probe (MIP), the Waterloo Advanced Profiling System (Waterloo$^{APS\ TM}$), and the Hydraulic Profiling Tool (HPT). Section 5.5.2 describes how each of these methods fit into the overall sampling strategy for the project.

5.3.1.1 Membrane Interface Probe

The MIP system was used at one source area (OU3 Building 106 and OU3 Building 780 at NAS Jacksonville) in a joint program with SERDP ER-1740 (which involves several of the same investigators and field personnel). One of the objectives of the latter project was to examine and MIP as a tool for low permeability zone investigations and develop a recommended standard operating protocol for these zones (Adamson et al., 2013).

MIP was developed by Geoprobe (2012) to provide real-time, high resolution vertical profiling data for establishing lithography and relative contaminant concentrations. It collects nearly continuous, depth-discrete characterization data in unconsolidated soils where it can be advanced using direct push equipment (**Figure 5.4a**). The acceptance of MIP as a site characterization tool is illustrated by the publication of an ASTM standard (ASTM, 2007). The tool has a semi-permeable membrane on a stainless steel screen housed within a temperature-controlled heater block (**Figure 5.4b**). As the tool is advanced, contaminants in adjacent soils and groundwater are volatilized and diffuse across the membrane, where the vapor is entrained in a carrier gas that

transports the contaminants to the surface (via an internal trunk line) to a data acquisition system. This system typically consists of a set of detectors, including an electron capture detector (ECD), photoionization detector (PID), and flame ionization detector (FID), each of which can provide a gross response to the total contaminant load to which they are sensitive. This setup allows collection of real-time data on CVOC distribution rapidly (up to 200 linear ft per day) and at a high density (generally data collected every 0.05 ft). The MIP tool is typically equipped with an electrical conductivity (EC) detector and thus also can provide useful stratigraphic characterization data.

Consequently, MIP can be used to screen potential locations for more detailed investigations and to guide subsequent soil sampling activities. However, MIP does not provide hydraulic conductivity profiling data or actual VOC concentrations in soil or groundwater, limiting its utility for the proposed demonstration, which relies on a more quantitative understanding of the contaminant concentration profiles. As such, MIP was used a supplemental tool for the purposes of this project.

Initial MIP data collection efforts focused on characterizing six locations within the former Building 106 source area (**Figure 5.1**). **Table 5.1b** lists the operating conditions for conventional MIP logs that served as baselines for further comparisons. These are based on recommendations from the manufacturer and the ASTM standard. All work was completed by Stone Environmental Inc. (Montpelier, VT).

Table 5.1. (b) Operating Conditions for MIP Investigation

Parameter	**Operating Condition during MIP** [(1)]
Trunk Line	Heated stainless steel
Drive Rate	1 ft/min
Carrier Gas Flow Rate	40 mL/min
Probe Temperature	120ºC
Direction of Data Collection	Data collected from surface to deepest point
Detector Types	ECD, PID, FID, EC

Note: (1) Does not include supplemental MIP trials using modified operating conditions that were performed in support of SERDP ER-1740.

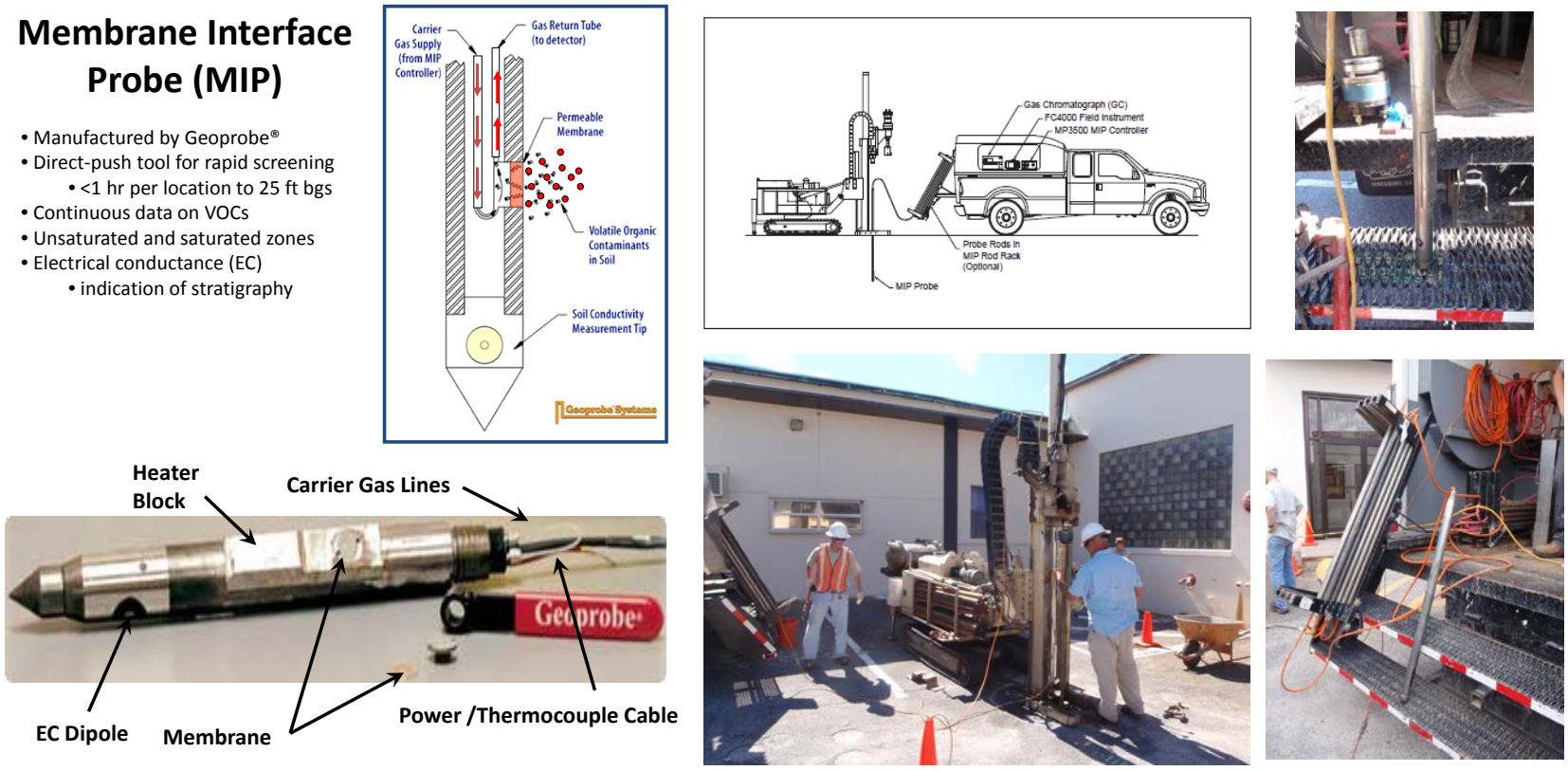


Figure 5.4. Schematic of Geoprobe MIP system, including use of the system during the ESTCP ER-201032 field demonstration (Source: Geoprobe SOP, 2012; http://geoprobe.com/literature/mip-logging-sop).

5.3.1.2 Waterloo Advanced Profiling System (Waterloo$^{APS\ TM}$)

A detailed vertical characterization was completed at two of the source areas using the Waterloo$^{APS\ TM}$. This is a subsurface data acquisition system developed by Stone Environmental Inc. (Montpelier, VT), an adaptation of the original Waterloo Groundwater Profiler Tool (Pitkin et al., 1999), that collects both discrete-depth groundwater samples and an integrated set of companion data in a single, continuous direct push. The Waterloo$^{APS\ TM}$ is capable of sampling using a very short vertical interval screen and at a close vertical spacing. The objective is to capture small-scale changes in contaminant concentrations and geological stratigraphy, while reliably providing defensible quality groundwater samples. Integrated sensors provide hydrostratigraphic data (i.e. index of hydraulic conductivity or I_k) displayed graphically as the Waterloo$^{APS\ TM}$ tooling is advanced, allowing real-time identification of optimum sampling locations. In particular this tool allows field identification of lower permeability zones in real time, and targeting of discrete depth ground water samples from the higher permeability zones immediately adjacent to such interfaces. While groundwater samples were being collected at desired discrete depths, physiochemical parameter data was also generated using a YSI-556 MPS multi-parameter probe, including pH, specific conductance (SC), dissolved oxygen (DO) and oxidation/reduction potential (ORP). Stabilization of parameter data also ensures that high quality samples are collected. Groundwater samples were collected in standard 40-mL VOA vials which were immediately field preserved (acidified).

For the characterization work completed as part of this project, the Waterloo$^{APS\ TM}$ (1.75-in diameter stainless steel tool, 6-in in length) was advanced using a direct-push drilling rig (Geoprobe Model 6620DT; supplied and operated by ProbeDomain, Middleburg, FL), with the Waterloo$^{APS\ TM}$ tooling and drill rods supplied by Stone Environmental. The tool included a profiling tip equipped with 16 recessed ports (4 rows of 4 ports) that are covered with a fine stainless steel mesh. To prevent intrusion of groundwater during advancement and prevent clogging of the ports, clean water is pumped through the tubing that runs within the interior of the drive rod that connects directly to the series of ports of the sampling tool. Monitoring of the injection rates and pressures during advancement also provides the data for the I_k. Groundwater samples were collected at designated intervals by halting advancement of the tool at desired sampling depths, then purging and sampling with a positive displacement pump using compressed nitrogen. The rate of advancement depended on site-specific conditions (soil type) but was generally between 5 and 20 ft/min. The overall time to characterize each location was dependent on the advancement rate, the total depth, and the frequency of sample collection, but was generally less than 1 hour per location. The tool was driven to the depth of the underlying low permeability unit and then advanced through this unit to the extent possible, until reaching the desired maximum depth (or alternatively, the depth of refusal). Following completion, the boreholes were sealed and filled per standard operating protocol for the site.

The Waterloo$^{APS\ TM}$ was used to characterize six locations within the former Building 106 source area (**Figure 5.1**) and four locations within the Building 780 source area using standard techniques (**Figure 5.2**).

Waterloo APS™

- Advanced version of Waterloo Profiler
  - Stone Environmental Inc.
- Modified screen design
- Real-time index of hydraulic conductivity (I_k) -- stratigraphy
- Groundwater samples for VOCs
- Field physical-chemical data (pH, DO, ORP, EC)
- Hydraulic head measurement
- Gas drive pump for deep sampling



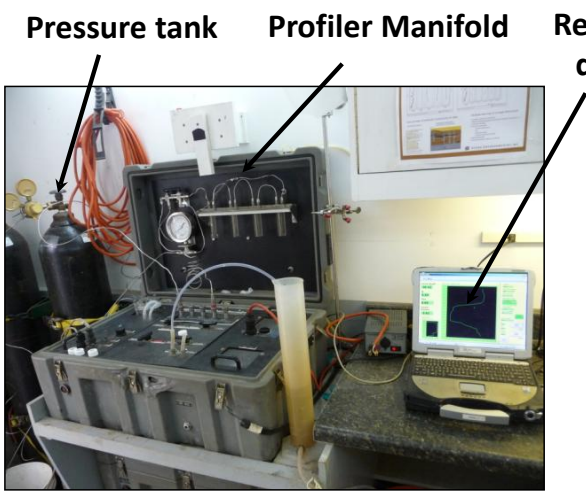






Figure 5.5. Schematics of the Waterloo$^{APS\ TM}$, including use of the system during the ESTCP ER-201032 field demonstration.

5.3.1.3 Geoprobe Hydraulic Profiling Tool (Geoprobe HPT®)

The Geoprobe Hydraulic Profiling Tool (Geoprobe HPT®) is a direct-push tool described by McCall (2011) Additional information, including a standard operating protocol, can be found on the Geoprobe web-site [http://geoprobe.com/hpt-hydraulic-profiling-tool]. Similar to the Waterloo$^{APS\ TM}$ tool, the Geoprobe HPT tool provides a real-time indication of hydraulic conductivity via logging water injection rates and pressures during tool advancement. Software tools are available for evaluating the data including use of empirical correlations for direct estimation of hydraulic conductivity. The tool also includes an EC sensor array providing another means of assessing presence of lower hydraulic conductivity (i.e. silt and clay-rich) zones.

At the study site, the Geoprobe HPT® was applied at six locations to provide a comparison to the Waterloo$^{APS\ TM}$ datasets. The as-tested version of the tool did not have groundwater sampling capability, although this is a more recent addition [http://geoprobe.com/hpt-gws-a-combined-hpt-and-groundwater-sampler-probe].

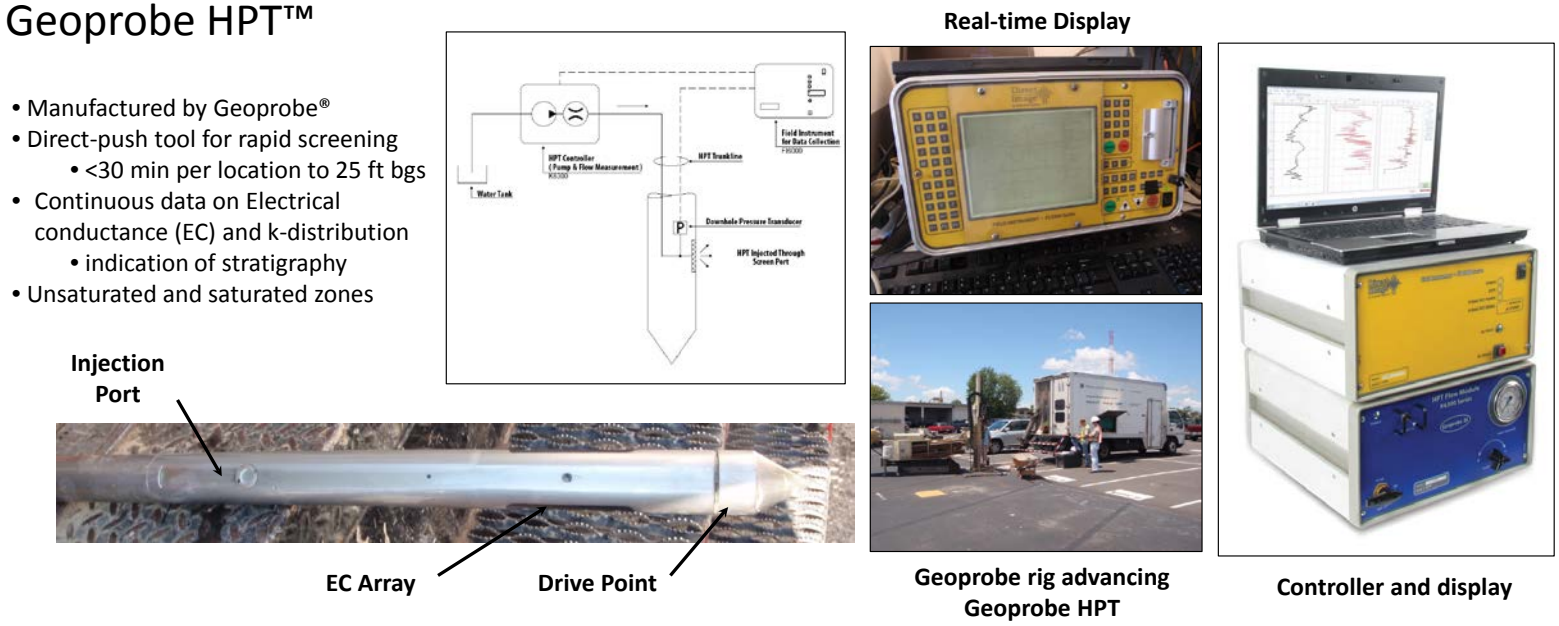


Figure 5.6. Schematics of Geoprobe HPT System, including use of the system during the ESTCP ER-201032 field demonstration. (Source: http://geoprobe.com/literature/hpt-sop)

5.3.2 High-Resolution Vertical Soil Sub-Sampling

A parallel vertical characterization was completed at selected test locations by collecting high-resolution soil concentration data. This involved the collection of relatively undisturbed soil cores from the saturated soil intervals located above the low permeability units, within the low permeability units themselves, and at some locations below the low permeability units (depending on their thickness). The objective was to quantitatively establish the contaminant concentration profiles and amount of mass present in each of these layers using refined sampling and analytical techniques appropriate to extraction and analysis of contamination in fine-grained material.

For the characterization work completed as part of this project, soil cores were obtained using a direct push rig (Geoprobe Model 6620DT; supplied and operated by ProbeDomain, Middleburg, FL). At each location, these cores were collected within several feet of the location where the Waterloo$^{APS\ TM}$ and other characterization methods (MIP and Geoprobe HPT) were completed to ensure that similar subsurface conditions were encountered. Continuous cores were collected from an interval starting near the surface to a depth several feet through the targeted low permeability unit at each location. To the extent possible, core collection was tailored to minimize disturbance of cores and to maintain the in situ stratigraphy and contaminant conditions. This included the use of equipment-appropriate liners within the core barrel and careful core handling during removal from the core barrel and subsequent splitting and subsampling activities. Cores were collected in 5-ft lengths using the Geoprobe dual-tube sampling method (DT325, 1.85-in diameter cores).

Soil samples were collected from each core at closely-spaced vertical intervals with a sampling frequency based on data obtain during the Waterloo$^{APS\ TM}$ characterization and visual inspection of cores as well as experience of the field team for characterizing contamination in low permeability zones (**Figure 5.7**). At a minimum, soil samples were collected every 1 ft within the intervals of interest, and higher collection frequencies (i.e., as tight as every 2 to 6 in) were used within intervals with fine-grained material, as well as in the intervals where transitions between fine and coarser-grained materials were encountered. The rate of core advancement depended on site-specific conditions as well as the frequency of sample collection and the ability of the field crew to collect samples and log the cores. Because it was desirable for cores to be processed within a short time after collection to minimize the potential for volatilization loss, the drilling progress was controlled to accommodate the rate of sample collection. Direct-push techniques proved suitable for advancing coring tools through the entire interval of unconsolidated material to the desired depths. Following completion, the boreholes were abandoned by site personnel per standard protocol for the site (i.e., refilled with soil cuttings generated during borehole preparation followed by patching the asphalt).

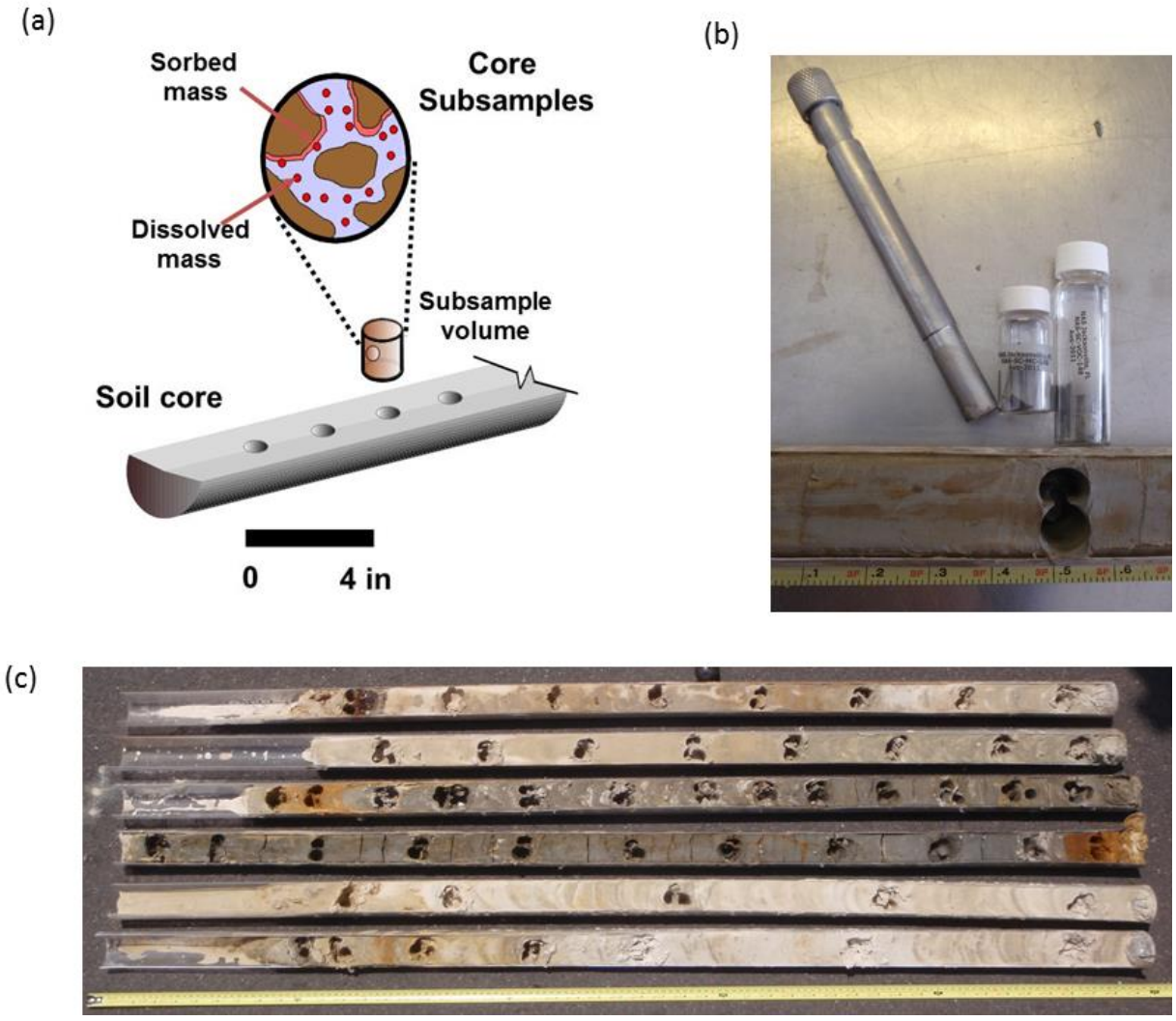


Figure 5.7. **High-Resolution Soil Sub-Sampling:** (a) schematic, (b) stainless steel subsampler and samples from one depth (one preserved in methanol for VOCs, one for moisture content), and (c) example of subsampled cores from OU3-4 (collected from 5-35 ft bgs).

Soil coring was completed at four locations within the former Building 106 source area and three locations within the Building 780 source area (**Figure 5.2**).

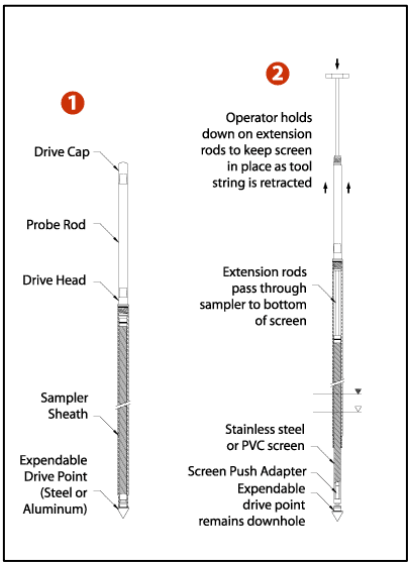
5.3.3 Multi-Level Groundwater Sampling

Multi-level groundwater sampling was completed at two of the source areas using a combination of methods. The first method was the Waterloo$^{APS\ TM}$, which was used to collect groundwater samples at six locations within the former Building 106 source area and four locations within the Building 780 source area using the procedures described in Section 5.3.1.2. These samples were collected in the zones of higher permeability, because the method generally precludes sampling in lower permeability zones (due to limited and/slow entry of water into the tool causing

extending waiting times while the Geoprobe rig is idle). Additional methods used to collect groundwater samples in lower permeability zones (as well as higher permeability zones) included the Geoprobe SP16 sampling system and temporary piezometers. These methods were used at three locations at the Building 106 source area.

The Geoprobe SP16 groundwater sampler is a direct-push tool used for collecting water samples from direct-push holes [http://geoprobe.com/sp16-groundwater-sampler]. The SP16 sampler tool is often used to complement the Geoprobe HPT® datasets (i.e., first use HPT to assess the stratigraphy and hydraulic conductivity distribution, then follow-up with the SP16 sampler to collect groundwater samples at key intervals). The tool is comprised of a stainless-steel screen coupled to drive rods with a 1.6-in OD screen sheath which covers the screen as the tool is advanced. The tool is driven to the desired sampling interval, then the sheath is retracted to expose a portion of the screen and the length of the screen (sampling interval) can vary from a few inches up to a maximum of 41 inches. Development and collection of groundwater samples is then conducted using either a discrete interval sampler, Waterra (inertial) pump, or peristaltic or positive displacement pump. The tool is not a continuous sampling tool but must be removed, decontaminated and the sheath reset between sample depths. At the study site, the SP16 sampler was used to collect supplemental groundwater data at three locations at the Building 106 area (**Figure 5.2**), focused on the more permeable sandy intervals above the clay layer at 2 or 3 different depths, including at the interface, and then immediately below the clay layer.

It was also desired to collect groundwater samples from within the clay layer. For this purpose, it was not feasible to use the SP16 sampler due to the expected long recovery times (and thus high cost) since drilling equipment would be tied up waiting for groundwater recovery. Therefore temporary piezometers were installed at the three locations with three piezometers at different depths at each location. These were comprised of 0.75-in Schedule 40 flush-thread PVC casing and screens with 2.0-ft screen intervals. The piezometers were installed within Geoprobe casing utilizing expendable drive-tips. Sand packs were placed around the screens followed by bentonite hole plug immediately above the screen to the top of the clay acting as a seal to prevent shallower groundwater from the aquifer entering the screened interval. Using the temporary piezometers, it was possible to purge these a few times using a peristaltic pump and allowing them to recover prior to collecting representative groundwater samples from the clay layer.

(a) 

(b) 

Figure 5.8. **Multi-Level Groundwater Sampling:** (a) Schematic of Geoprobe SP16 sampler operation (from http://geoprobe.com/sp16-groundwater-sampler); (b) Groundwater sampling during the ESTCP ER-201032 field demonstration, using Geoprobe SP16 system (via the direct-push rig) and temporary piezometers (installed in small diameter boreholes in foreground).

5.4 Field Testing

The field portion of this project involved a characterization approach that collects a suite of complementary datasets at a single timepoint (or closely-spaced timepoints) from each location, such that the duration of field testing is relatively compact and involves few phases. As a result, there was no specific system start-up, no extended system operation, and no system shutdown.

The implementation schedule for each of these project phases for the field program at NAS Jacksonville is presented as a Gantt chart (**Figure 5.9)**. The implementation schedule for the field program was designed to collect data in manner that was both efficient (in terms of personnel and equipment utilization) and that provided an opportunity for optimizing subsequent soil sampling strategies. The actual schedule was influenced by two main factors:

- ***Joint work with SERDP ER-1740.*** Several of the same field personnel were involved in both projects, and the SERDP ER-1740 work was added to front end of the SERDP ER-201032 program as an initial step. This increased the length of the work phase that was focused on gathering screening-level data (i.e., MIP, Waterloo$^{APS\ TM}$).
- ***Two source areas at the same site.*** Completing work at two different source areas simultaneously provided several advantages in terms of coordination, but it also increased the length of each work phase (e.g., soil coring extended beyond one week).

Collectively, these factors meant that it was more practical to complete the work in two separate mobilizations. This provided a break for field personnel travelling from out-of-town locations,

and also allowed data from the first episode to be utilized for refining data collection activities during the second field episode.

Consequently, the following program was implemented:

- Completed MIP, Geoprobe HPT®, and Waterloo$^{APS\ TM}$ at both NAS Jacksonville OU3 sites (Building 106 and Building 780) simultaneously (i.e., during the same field mobilization)
- Completed soil sub-sampling at both NAS Jacksonville OU3 sites (Building 106 and Building 780) simultaneously, as well as supplemental groundwater sampling using the Geoprobe SP16 sampler and temporary piezometers, during a follow-up field mobilization.

Figure 5.9. Gantt Chart for Implementation of Field Activities

FIELD ACTIVITY	Week of July 18	Week of July 25	Week of Aug 15	Week of Aug 22 (partial)
Screening-level characterization at NAS Jacksonville OU3 Building 106 (all locations)				
Screening-level characterization at NAS Jacksonville OU3 Building 780 (all locations)				
Soil sub-sampling at NAS Jacksonville OU3 Building 106 (all locations)				
Soil sub-sampling at NAS Jacksonville OU3 Building 780 (all locations)				

Notes: (1) All weeks comprised of 5 workdays with the exception of the week of August 22 (2 workdays).

There was little site preparation required for the field program at NAS Jacksonville. The primary responsibility was identifying investigation points, gaining utility clearance for those locations (through the state agency), and ensuring site access for project personnel. All investigation points were located in exterior areas that were covered by asphalt. As such, asphalt cutting was required as a first step at all points, regardless of characterization method (soil, MIP, Waterloo$^{APS\ TM}$, Geoprobe HPT®). This was completed using a Geoprobe attachment, and the initial several feet of soil were removed using a hand auger.

Demobilization activities were relatively limited but consistent with the project approach. None of the components resulted in permanent installations at the demonstration sites. As a result, there were no specific decommissioning considerations. Cuttings and/or bentonite hole plug were used to refill the investigation points per site specifications. All investigation-derived waste was disposed of in this manner. For applicable locations, temporary piezometers were pulled prior to refilling and disposed of off-site by the drilling contractor. If there was evidence of surface settling, then additional fill was provided. Surface asphalt was then patched as a final step prior to site departure.

5.5 Sampling Methods

5.5.1 Overview

A summary of the sampling plan for this project is provided in **Table 5.2**, and the analytical program for these samples is summarized in **Table 5.3**. Collectively, the sampling and analysis plan generated data that provided sufficient understanding of contaminant distribution at each site. As described in the previous sections, the sampling and analysis program includes several major components: (1) Screening-level hydrostratigraphic and concentration data collected by a combination of MIP, Waterloo$^{APS\ TM}$, and Geoprobe HPT®; (2) Groundwater data collected by a combination of Waterloo$^{APS\ TM}$, temporary piezometers, and Geoprobe SP16 sampling (including VOC concentration, groundwater field parameters, ethene/ethane, various geochemical parameters, and ^{13}C isotopic data); and (3) Soil data collected via high-resolution subsampling of continuous high quality soil cores (including VOC concentration, organic carbon, physical property data, and biomarkers).

The analytical methods listed in **Table 5.3** are based on methodologies that are used extensively in the industry. Modifications to specific preparation and/or analytical procedures have been made to several methods in order to improve the data integrity (e.g., improved recovery, lowered detection limits). A brief summary of preparation and/or analytical methods that differ slightly from those used by commercial labs is provided below:

- ***Volatile Organic Compounds via UG Methods (Soil):*** Field methanol preservation was used in combination with extraction methods tailored to ensuring complete extraction of mass from low permeability zone soil samples (e.g. Dincutoiu et al., 2003, 2006) and analytical methods (Górecka et al., 2001) tailored to provide exceptionally low MDLs (typically <1 µg/L in methanol extract for the target VOCs). Extraction in the lab occurs via a shake flask technique over an extended period (2 to 4 weeks) with microwave-enhanced extraction as needed. Analyses rely on GC/MS techniques similar to EPA 8260, with the exception that an on-column direct methanol injection was used as opposed to methanol dilution in water. For the purposes of this project, these were labeled the *UG methods* because all analyses were completed at UG personnel at UG labs.
- ***Volatile Compounds via Rapid Field Extraction (Soil):*** Field methanol preservation followed by rapid field extraction was performed on a subset of samples. This is a proprietary method currently being developed by Stone Environmental using an approach that is based on the UG methods, and it was included in the project to evaluate its feasibility for generating high-resolution data from soil cores. The samples are physically agitated (shaken) in the field for about one hour to promote extraction of mass from low permeability zone soil samples. Shaking is aggressive to ensure the low permeability soils are disaggregated for efficient extraction. Analysis of the methanol extract was completed using EPA 8260 at Stone Environmental's accredited lab (splits were sent to UG and analyzed using their modified EPA 8260 method) (see **Appendix O** for additional explanation)

- ***Fraction of Organic Carbon (Soil):*** Analyses via two different methods for comparison (Walkley Black wet oxidation method and combustion methods).Both methods were used to assess potential inherent biases associated with each method (e.g. USEPA, 2002).

Note that to evaluate the data quality generated by modified (project-specific) methods, duplicate and/or split samples were also collected and analyzed using conventional techniques and methods (see **Table 5.2**). This rigorous evaluation is included as part of the performance objectives for the project.

Table 5.2. Summary of Sampling Plan for Field Demonstration

Project Component	Matrix	Collection Method	Number of Samples	Analyte(s)	Location
Screening-Level Characterization					
Membrane Interface Probe (MIP)	Groundwater/ Vapor	Downhole tooling using membrane/probe	Continuous to a total depth of at least 34 ft bgs per location	Electrical Conductivity (indicator of soil type); GC Detector Response (indicator of contaminant presence)	6 locations at former Building 106 source area; (including all locations where high-resolution soil sub-sampling was completed)
Waterloo Profiling (Waterloo$^{APS\ TM}$)	Groundwater	Downhole tooling using positive displacement pump	Continuous to a total depth of at least 34 ft bgs per location	Index of Hydraulic Conductivity (I_k)	6 locations at former Building 106 source area; 4 locations at Building 780 source area (including all locations where high-resolution soil sub-sampling was completed)
Hydraulic Profiling Tool (Geoprobe HPT)	Groundwater	Downhole tooling using positive displacement pump	Continuous to total depth of at least 34 ft bgs per location	Electrical Conductivity (indicator of soil type); Estimated hydraulic conductivity	5 locations at former Building 106 source area (including all locations where high-resolution soil sub-sampling was completed)
High-Resolution Soil Sub-Sampling					
Soil Coring	Soil	Geoprobe w/ liner for core; UG soil sub-sampling device; field preservation w/ methanol	374 (approximately 50 per location from multiple depths; includes 29 duplicate samples collected at	CVOCs (analysis at UG lab)	4 locations at former Building 106 source area; 3 locations at Building 780 source area (combination of source and downgradient areas)
			33 (9 to 13 per location from multiple depths)	organic carbon	4 locations at former Building 106 source area
			178 (28 to 52 per location from multiple depths)	Physical properties: particle size distribution, porosity	3 locations at former Building 106 source area; 1 location at Building 780 source area

Table 5.2. Summary of Sampling Plan for Field Demonstration *(continued)*

Project Component	Matrix	Collection Method	Number of Samples	Analyte(s)	Location
High-Resolution Soil Sub-Sampling (continued)					
Soil Coring	Soil	Geoprobe w/ liner for core; UG soil sub-sampling device; field preservation w/ methanol and rapid extraction	27	CVOCs (analysis of methanol split samples at commercial lab)	Same locations where high-resolution soil sub-sampling/analyses completed
	Soil	Geoprobe w/ liner for core; EnCore samplers for soil samples (no field preservation)	26	CVOCs (analysis of field duplicates at commercial lab)	Same locations where high-resolution soil sampling/analyses completed
	Soil	Geoprobe w/ liner for core; EnCore samplers for soil samples; preservation upon arrival at lab	32	CVOCs (analysis of field duplicates following delayed preservation)	Same locations where high-resolution soil sampling/analyses completed
	Soil	Geoprobe w/ liner for core; UG soil sub-sampling device; field preservation w/ methanol	29 (duplicate dataset)	CVOCs (analysis of field duplicates at UG lab)	1 location at former Building 106 source area as duplicate dataset (OU3-5)
	Soil	Geoprobe w/ linear for core; UG soil sub-sampling device	18 (8 to 10 per location from multiple depths)	Dehalococcoides (DHC), Vinyl Chloride Reductase (VCR)	2 locations at former Building 106 source area
Groundwater Sampling					
Waterloo Profiling (Waterloo$^{APS\ TM}$)	Groundwater	Downhole tooling using positive displacement pump	93 (6 to 12 per location from multiple depths)	CVOCs, field parameters[1]	6 locations at former Building 106 source area; 4 locations per site (including all locations where high-resolution soil sub-sampling was completed)
Temporary Piezometers	Groundwater	Peristaltic pump	19 (6 to 7 per location from multiple depths	CVOCs, dissolved gases (ethene, ethane, methane), sulfate, chloride, carbon isotopes ($^{13}C/^{12}C$)	3 locations at former Building 106 source area; (including all locations where high-resolution soil sub-sampling was completed)
Geoprobe SP16	Groundwater	Tubing equipped with check valve		CVOCs, dissolved gases (ethene, ethane, methane), sulfate, chloride, carbon isotopes ($^{13}C/^{12}C$)	

Notes: (1) Field parameters for groundwater include temperature, pH, oxidation-reduction potential, electrical conductivity, and dissolved oxygen; (2) Represents number of samples collected; actual number of samples analyzed may be lower; (3) CVOCs = chlorinated volatile organic compounds; UG = University of Guelph.

Table 5.3. Summary of Analytical Methods for Samples Collected During Field Demonstration

Matrix	Analyte	Method(s)	Container and Preservative	Laboratory
Soil	CVOCs	EPA 5035 and EPA 8260	EnCore samplers with no preservative; 48 hr holding time prior to preservation[1]	TestAmerica
	CVOCs	Proprietary preparation method (rapid field extraction of methanol-preserved soil) and EPA 8260	40-mL glass vial containing 15 mL methanol (only methanol extract is sent to lab in 5mL glass vials)[2]	Stone Environmental
	CVOCs	Proprietary (purge-and-trap method based on modified EPA 5035 and EPA 8260)	40-mL glass vial containing 15 mL methanol	UG
	Particle Size Distribution	Sieve for coarser fraction; Hydrometer for finer fraction as applicable	4-oz plastic sealable jar; no preservative	UG
	Hydraulic Conductivity	Repacked Permeameter (modified EPA 9100) using similar methods as Sudicky (1986).	4-oz plastic sealable jar; no preservative	UG
	Field moisture content of soils	SM-2540 G	40 mL glass vial, no preservative. Sample weighed in field immediately after sample collection and then dried in lab and reweighed.	UG
	Organic carbon	Proprietary (using either Walkley-Black wet chemical oxidation (USDA 90.3) or combustion methods)	40-mL glass vial (same sample as moisture content; post-drying)	UG
	Biomarkers (DHC, VCR)	Proprietary (qPCR-based)	2 to 8-oz plastic or glass sealable jar; no preservative	SiREM

Table 5.3. Summary of Analytical Methods for Samples Collected During Field Demonstration *(continued)*

Matrix	Analyte	Method(s)	Container and Preservative	Laboratory
Groundwater	CVOCs	EPA 8260	3 40-mL glass vials; HCl to pH < 2	UG
	Dissolved Gases	RSK-175	3 40-mL glass vials; no preservative	TestAmerica
	Chloride	EPA 300	1 500-mL plastic; no preservative	
	Sulfate	EPA 300		
	$^{13}C/^{12}C$	Proprietary (GC/IRMS method)	3 40-mL glass vials; HCl to pH < 2	University of Waterloo
	Field parameters (dissolved oxygen, electrical conductivity, oxidation-reduction potential, pH, temperature)	YSI Mulitmeter	> 100 mL; no preservative	Not applicable (field measurement)

Notes: (1) Field duplicates; (2) Split samples of methanol extracts; (3) Option to use alternate commercial lab designated by site (e.g., same lab supporting on-going LTM efforts); (3) CVOCs = chlorinated volatile organic compounds; UG = University of Guelph.

5.5.2 *Sampling Strategy*

To supplement the information in **Table 5.2** and **Table 5.3**, a brief description of how the sampling and analysis program was used to meet project objectives is provided.

Screening-Level Characterization:

1. Provide initial information on hydrostratigraphy and contaminant profiles at multiple locations to inform conceptual site models. MIP was used as the initial step at one of the source areas, followed by Waterloo$^{APS\ TM}$ at both source areas. The Geoprobe HPT® also provided complimentary hydrostratigraphic data at one source area. All tools provided a more comprehensive picture of site geologic and contaminant heterogeneity, with data displayed real-time for on-site interpretation of results and adjustment of sampling intervals. At both of the NAS Jacksonville OU3 source areas, these methods confirmed that a lower permeability layer was present starting at depths of approximately 15 ft bgs.
2. Identify promising locations for further soil coring based on positive indicators for relatively high levels of contamination within lower permeability soils. The MIP data provided initial qualitative information on contaminant distribution throughout the entire vertical profile at each location. The VOC data from depth-discrete groundwater sampling using Waterloo$^{APS\ TM}$ was also available by the time the soil coring locations were selected and provided a more quantitative basis for the selections. Based on these data, coring efforts were focused on longsects from the presumed source areas to downgradient locations. These data also established optimal depths for samples based on stratigraphy (as opposed to relying on preset intervals).
3. Generate high-resolution profiles using multiple different characterization tools to allow for a side-by-side comparison of depth-discrete data. The Geoprobe HPT® was added to the program after the demonstration plan once it was clear that the MIP work that was part of SERDP ER-1740 was going to be completed at NAS Jacksonville. By generating data using several different high-resolution characterization methods at the same locations, the PIs felt that this project had the unique opportunity to rigorously evaluate the utility of each method for low permeability zone investigations. The datasets also demonstrated how multiple complementary techniques can provide a more thorough understanding of stratigraphic and contaminant conditions.

Soil Coring

4. Generate input data for the source history model by determining the soil VOC concentration profile within the low permeability zone. A detailed VOC concentration profile was generated at each location, along with a definitive soil classification for each sampled interval. The established the mass distribution, including the mass associated with layers of differing permeability and the depth where the peak concentrations were encountered. These are the critical input data for the source history model. Further supporting information collected at this stage was the fraction of organic carbon, which allowed for site-specific interpretation of the impact of sorption of contaminant transport. Selected soil samples were collected for grain size analysis to supplement visual characterization methods.

5. Quantify specific biomarkers as a line of evidence for biodegradation. At two key locations at one source area, the presence and abundance of genes encoding for *Dehalococcoides* species and vinyl chloride reductase were evaluated. This involved the analyses of soil sub-samples from the low permeability zone (as well as the more transmissive sands located above and below this zone). The presence of organisms and/or enzymes that mediate the reductive dechlorination pathway were seen as positive indicators that biological degradation was occurring (and where) and should be accounted for modeling the natural attenuation over time (i.e., source history).
6. Comparison of sampling and analysis methods. Differences between data generated by the project-specific methods ("UG Methods") and data generated by commercially-available soil sampling and analysis methods (e.g. EnCore™ sampling, soil VOC extraction and analyses at fixed commercial labs using standard EPA methods) were evaluated through a systematic QA/QC program. This was undertaken to demonstrate that equal or higher data quality was obtained using the project-specific methods, and to demonstrate the importance of key steps in the sampling and analysis protocols.

Groundwater Sampling

7. Generate complementary VOC concentration data for understanding and calibrating soil VOC concentration profiles. The soil VOC concentration profiles with depth were the primary input data for the source history modeling, but groundwater VOC data provided supplemental information for understanding contaminant distribution. It was particularly useful for quantifying vinyl chloride, which can be problematic using soil analyses due to volatile losses (also was not quantified in the UG analysis, as a limitation of the analytical technique applied to methanol extracts). Groundwater VOC data were collected using a combination of Waterloo$^{APS\ TM}$, the Geoprobe SP16 sampling system, and temporary piezometers. The latter allowed collection of groundwater samples in lower permeability layers, since collecting samples in these zones with the Geoprobe SP16 and Waterloo$^{APS\ TM}$ is technically challenging due to flow limitations. However, the Waterloo$^{APS\ TM}$ generates data that is easier to assign to particular depths since it provides a depth-discrete sample using a very small screen interval and requires minimal purging. As such, the Waterloo$^{APS\ TM}$ data also provided a basis for adjusting soil depths in certain cases where there was uncertainty (e.g. due to less than 100% recovery in soil cores).
8. Understand geochemical conditions and other potential lines of evidence for biodegradation. A series of parameters were measured in groundwater samples to determine whether conditions are favorable for degradation and to serve as lines of evidence that degradation has occurred. Most of these are typical natural attenuation parameters, such as dissolved gases (methane, ethene, ethane), competing electron acceptors (e.g. sulfate), and chloride. (Note that site-specific information provided as part of another ESTCP demonstration project (ER-0705) was used to eliminate several analytes with negligible concentrations at this site, including iron, nitrate, and manganese.) Compound specific carbon isotope analysis (CSIA) data was also collected via analysis of groundwater samples and water extracted soil samples from lower permeability zones to provide additional information on potential fractionation patterns resulting from contaminant degradation. Waterloo$^{APS\ TM}$ utilizes a multiparameter probe

(YSI-556 MPS) placed in the sample line at surface to measure parameters including pH, electrical conductivity, DO, and ORP at the selected discrete sample depths. Samples collected from the temporary piezometers and/or Geoprobe SP16 were sent to off-site labs for analysis of dissolved gases, $^{13}C/^{12}C$, chloride, and sulfate.

5.6 Sampling Results

5.6.1 Screening-Level Characterization Data

Former Building 106 Source Area: MIP and Waterloo$^{APS\ TM}$ were used at all six locations, while HPT was used at five locations. Typical results are shown in **Figure 5.10** and **Figure 5.11** (full results are shown in **Appendix C** (MIP), **Appendix D** (Waterloo$^{APS\ TM}$), and **Appendix E** (Geoprobe HPT®)). Locations were typically logged to a total depth between 35 and 50 ft bgs. The results of the MIP survey suggested that the majority of contaminant mass (based on the ECD/PID/FID signals) was present within and immediately above a lower permeability layer first identified (using the EC signals from MIP/HPT and the K estimates from Waterloo$^{APS\ TM}$/HPT) at a depth of 15 to 20 ft bgs. This low K layer was generally 5 to 15 ft thick, with downgradient locations characterized by thinner low K intervals and a higher degree of geologic heterogeneity. In most locations, the MIP logs suggested that some contaminant mass may have penetrated to the underlying more transmissive zones below the clay layer, although some of this is attributed to MIP carry down effects. A distinct contaminant peak was also indicated in the shallow transmissive zone at OU3-2 and OU3-3. Contaminant concentrations appeared to be significantly higher near the presumed source location and typically exceeded the upper limit of the most sensitive MIP detector (ECD) for these contaminants. The PID was generally less responsive and provided limited information at several of the locations with apparently low CVOC concentrations. The MIP signals decreased significantly in locations moving downgradient in the direction of groundwater flow, particularly at OU3-6. Based on these results, the four locations along the downgradient longsect (OU3-3, OU3-4, OU3-5, OU3-6) were selected for additional characterization via soil coring.

Building 780 Source Area: The only screening-level tool that was employed at this source area was Waterloo$^{APS\ TM}$, such that the data generated during the initial stage was limited to an index of hydraulic conductivity (I_k) profile from four locations. Typical results are shown in **Figure 5.12**. The profiles suggested that a relatively distinct lower permeability interval was present starting at approximately 20 ft bgs at most locations, and extended to approximately 27 ft bgs. Below this interval, additional low k zones were evident. These deeper lower permeability zones were typically encountered below 30 ft bgs, and depending on the location, were either thinner (2 - 3 ft at OU3-9 and OU3-10) or similar in thickness (6 – 8 ft at OU3-11 and OU3-12) to the shallow zone that was consistently observed in the interval between 20 – 27 ft bgs. Finally, subintervals of lower permeability were observed at shallower depths at all locations, though the apparent permeability of these shallow soils were still consistently higher than that of the primary low permeability interval encountered between 20 – 27 ft bgs. In general, the I_k data suggest that the Building 780 soils were more heterogeneous in nature than those of the former Building 106 source area. Based on the results, the first three locations along a downgradient longsect (OU3-9, OU3-10, OU3-11) were selected for additional characterization via soil coring.

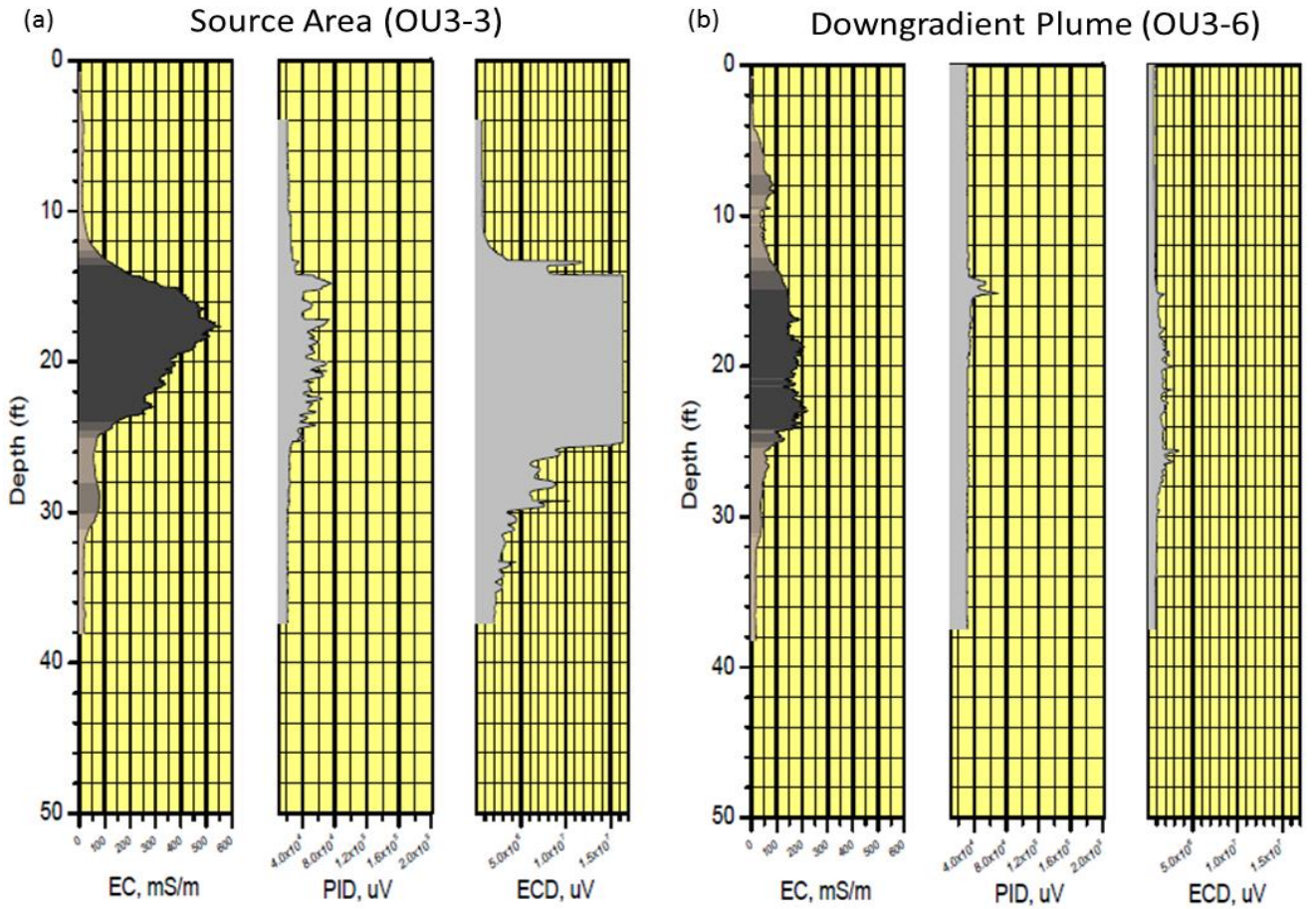


Figure 5.10. Example of MIP Dataplots along Plume Flowpath at Former Building 106 Source Area: (a) near source area, and (b) downgradient plume area.

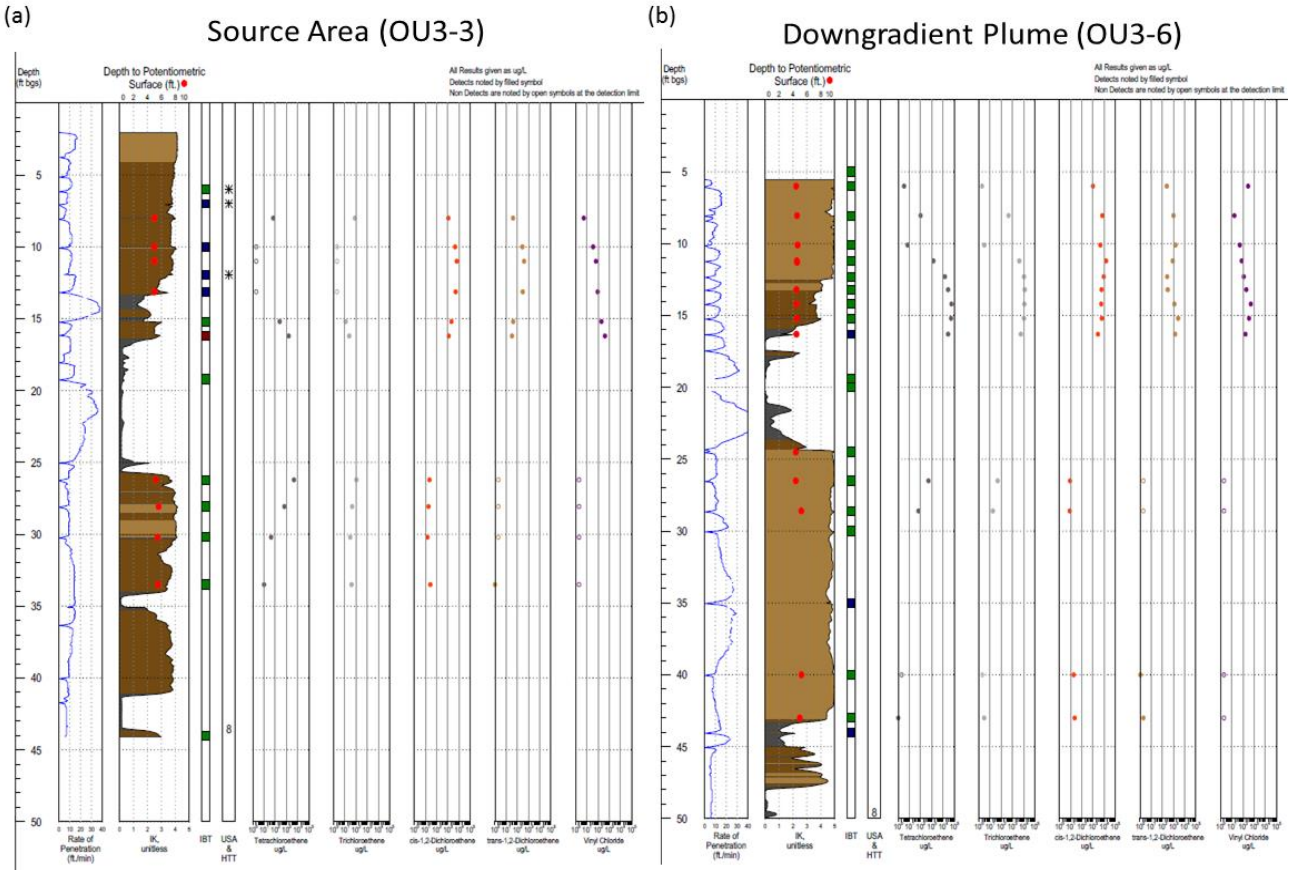


Figure 5.11. **Example of Waterloo APS ™ Results at Two Locations at Former Building 106 Source Area:** (a) near source area, and (b) downgradient plume area showing the I_k, groundwater VOC concentrations, along with other complementary data collected including drive rate and potentiometric surface.

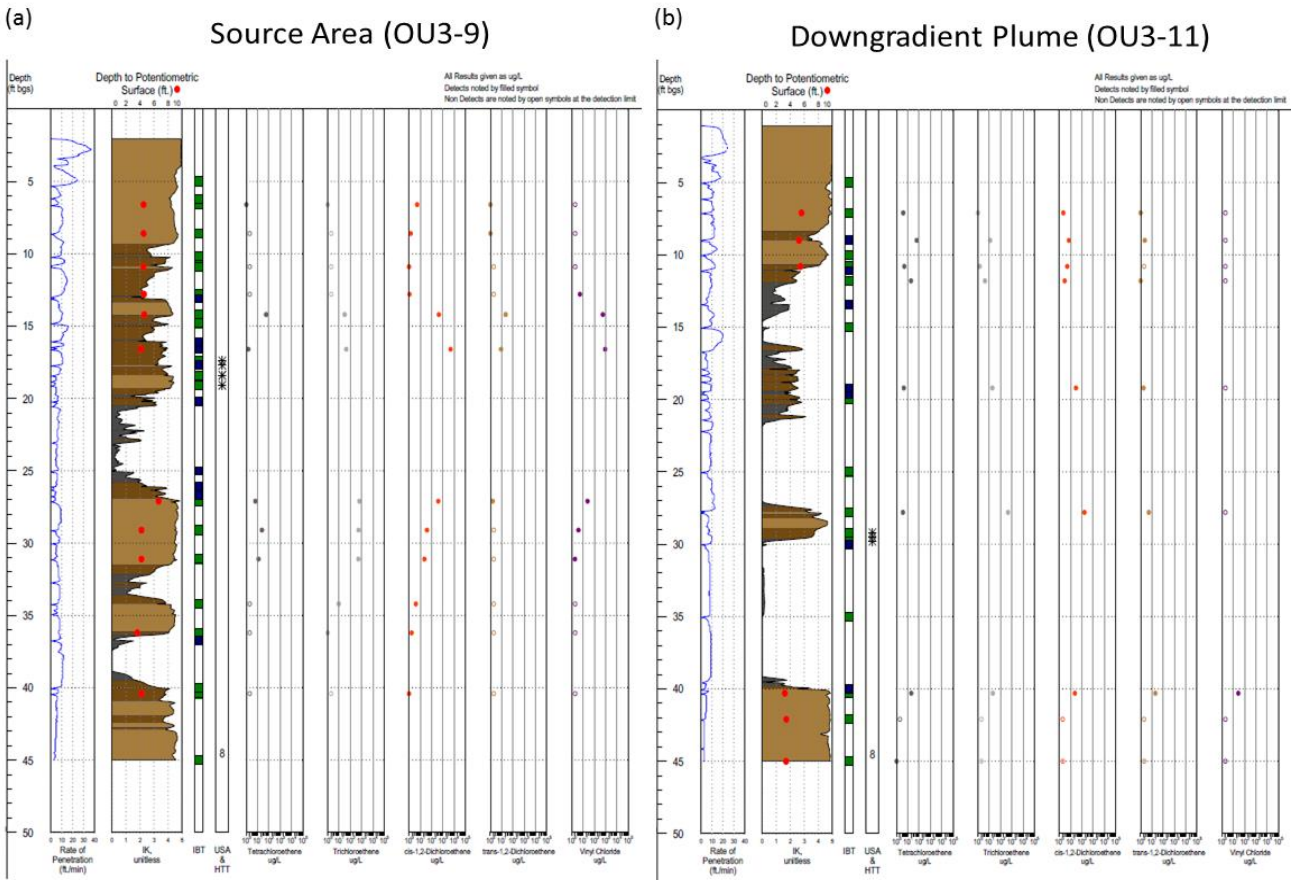
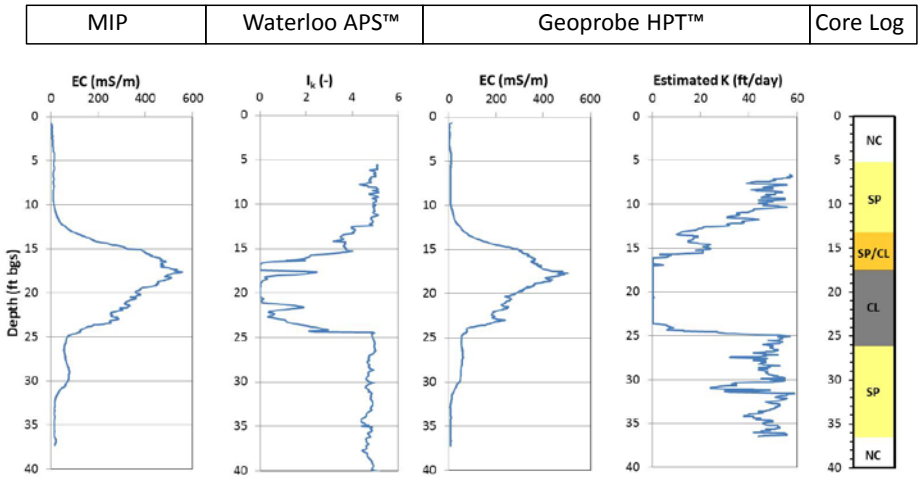


Figure 5.12. Example of Waterloo APS TM Results at Building 780 Source Area: (a) near source area, and (b) downgradient plume area showing the I_k, groundwater VOC concentrations, along wth other complementary data collected including drive rate and potentiometric surface.

Stratigraphic Methods Comparison: Each of the three primary methods used at the former Building 106 source area generated information related to subsurface hydrostratigraphy. Plots showing side-by-side comparisons of data from these locations are included as **Figure 5.13** (and also are in **Appendix F**). In general, the MIP EC data correlated well with stratigraphy observed through soil coring and inferred stratigraphy using the Waterloo$^{APS\ TM}$ and Geoprobe HPT® methods. Elevated EC readings coincided with the lower permeability clayey units, and the EC data could be used to generally identify the upper and lower boundaries of these units.

The primary disadvantages of MIP-based stratigraphic information (EC data) were: (1) it differentiates between sands and clays due to their conductive properties, and is less able to distinguish relative permeability like Waterloo$^{APS\ TM}$ or Geoprobe HPT® methods; and (2) it was not able to capture small-scale heterogeneities as readily as the Waterloo$^{APS\ TM}$ or Geoprobe HPT® methods. Also EC logs can also be affected by factors unrelated to clay content such as groundwater chemistry (e.g. Schulmeister et al., 2003). The EC profiles are generally "smoother" and not able to reflect particularly abrupt changes in actual soil permeability indicated by the other methods. The EC logs collected using the MIP tooling was nearly identical to those obtained using the Geoprobe HPT®, indicating that there is no inherent difference in the approaches with respect to generating EC data.

(a) **OU3-3**



(b) **OU3-4**

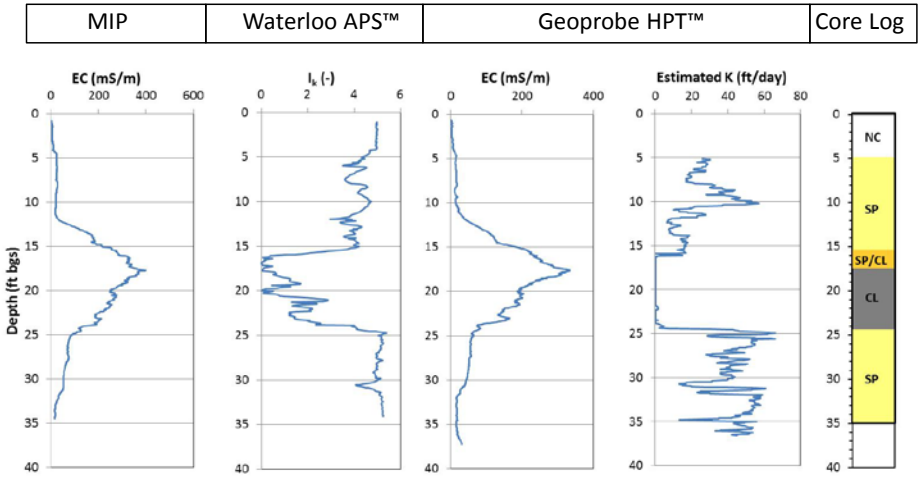
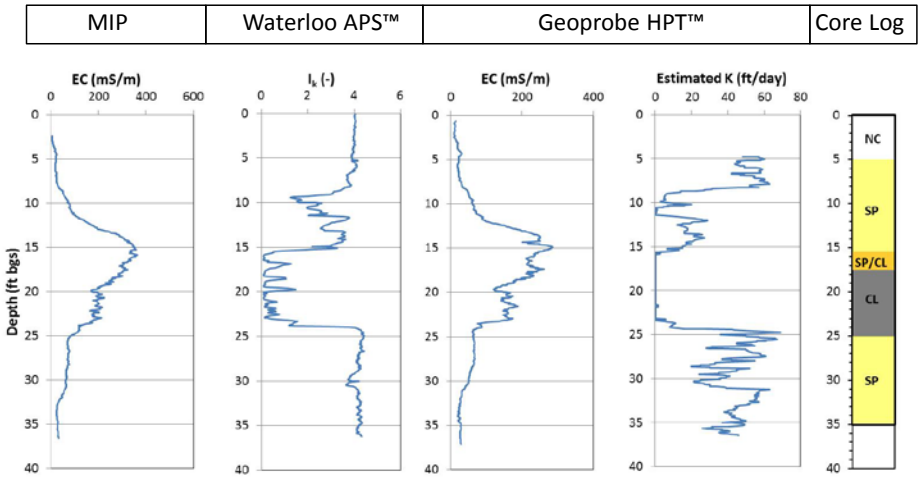


Figure 5.13. Stratigraphic Data Collected by Various Screening-Level Methods at Former Building 106 Source Area: (a) Location OU3-3; (b) Location OU3-4. Panels from left to right show data from MIP; Waterloo$^{APS\ TM}$; (c) Geoprobe HPT, and Soil Coring.

(c) **OU3-5**



(d) **OU3-6**

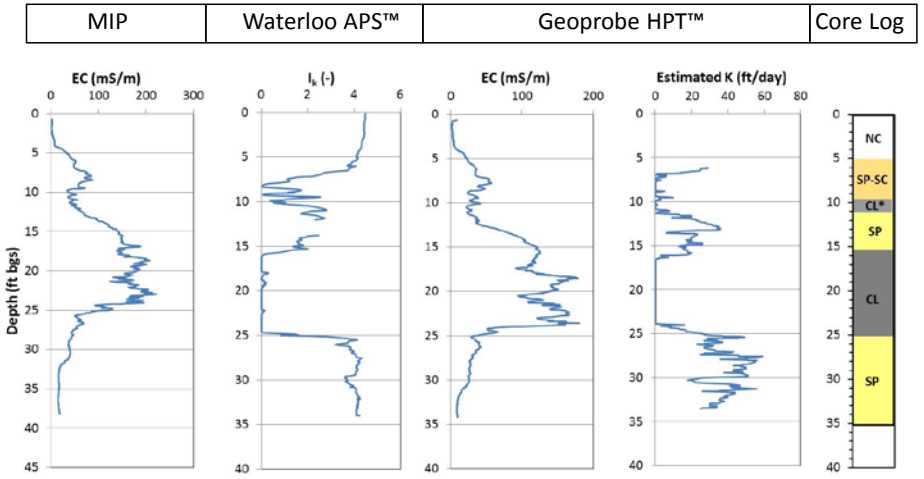


Figure 5.13. Stratigraphic Data Collected by Various Screening-Level Methods at Former Building 106 Source Area: (c) Location OU3-4; (d) Location OU3-5. Panels from left to right show data from MIP; Waterloo$^{APS\ TM}$; (c) Geoprobe HPT, and Soil Coring.

5.6.2 Soil Coring Data

Boring logs are included in **Appendix G** and are based on a combination of visual inspection of cores and grain size analyses of soil sub-samples. Complete soil VOC concentration data are included in **Appendix H**. The graphs provided in this section show the consistency between lithology from the core logs and the I_k datasets obtained from the Waterloo$^{APS\ TM}$.

Former Building 106 Source Area: Soil cores were collected at four locations (as well as a duplicate core at one of these locations). The soil lithology based on coring was consistent with the stratigraphic information generated using the screening-level characterization tools. In general, a lower permeability clay was first encountered at approximately 15 ft bgs with thickness between 5 to 7 ft. At each location, sands with low to moderate fine-grained content were present above and below the distinct clay intervals (referred to as transition zones). More thin clay layers (< 1 ft thick) were encountered at shallow intervals at the farthest downgradient location (OU3-6), suggesting a higher level of geologic heterogeneity moving away from the contaminant source area. This is also more consistent with more complex conditions observed in Building 780 area cores.

CVOC concentration data collected at these locations confirmed that the majority of contaminant mass was present within the low permeability clays and in the transition zone immediately above the clay layer (**Figure 5.14**). At the near source location, OU3-3, the CVOC profile is dominated by PCE and TCE, with maximum total CVOC concentrations of approximately 30 mg/kg at 16 ft bgs. At least 80% of the total mass at this location was present between 15 and 21 ft bgs within the clay layer, with little indication of penetration through this layer and the shape of the profile indicative of diffusion controlled transport. Moving downgradient to OU3-4 and OU3-5, the maximum total CVOC concentrations were similar to slightly lower (approximately 20 to 40 mg/kg), but the relative contribution of cis-1,2-DCE was significantly higher, particularly in the higher K sands where it typically represented >50% of the total mass. At these locations, the majority of the total CVOC mass (at least 80%) was encountered in these sand and transitional intervals above the clay layer. This overall trend continued at the furthest downgradient location, OU3-6, where an even greater shift to cis-1,2-DCE was observed (approximately 90% of the observed mass). At this location, the maximum CVOC concentration was approximately 15 mg/kg at was present in the shallow sands at 13 ft bgs.

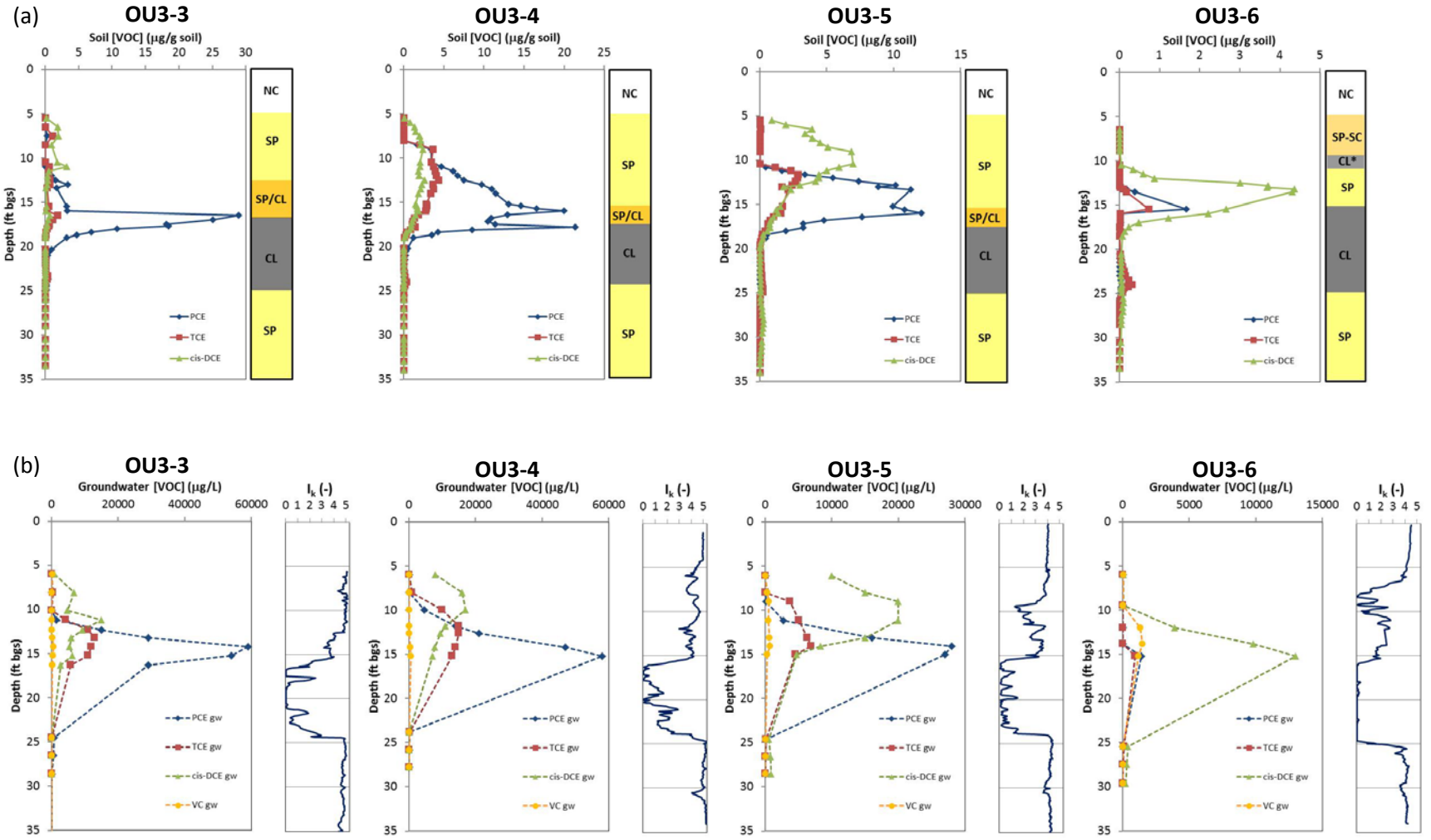


Figure 5.14. Soil and Groundwater VOC Concentrations from Former Building 106 Source Area Locations. Locations from left to right represent plume flowpath from near source (OU3-3) to downgradient plume (OU3-6). (a) Soil VOC concentrations and core logs; (b) Groundwater VOC concentrations and and I_k data from the Waterloo$^{APS\ TM}$.

The concentration vs. depth profiles at the two locations nearer the source (OU3-3 and OU3-4) indicate that the peak concentrations (of individual constituents and total CVOCs) are encountered near or just below the interface between the sand and clay layers. These are consistent with a source loading that has only recently begun to diminish, such that back diffusion from the lower permeability zones is only beginning to occur. At the two farther downgradient locations, the peak concentrations are encountered in the more transmissive sandy layers located above the clay. These profiles are consistent with continued loading of the clay, suggesting concentration declines from reduced source loading have not yet been transmitted this far downgradient (see Section 5.7 for modeling results).

The concentration vs. depth profiles from the two duplicate cores collected at location OU3-5 were nearly identical (**Figure 5.14c**), confirming a relatively high level of precision in the results generated from the project-specific coring and analyses methods. Note that these cores were collected within one meter of each other, and the results suggest that spatial differences were minimal at this scale.

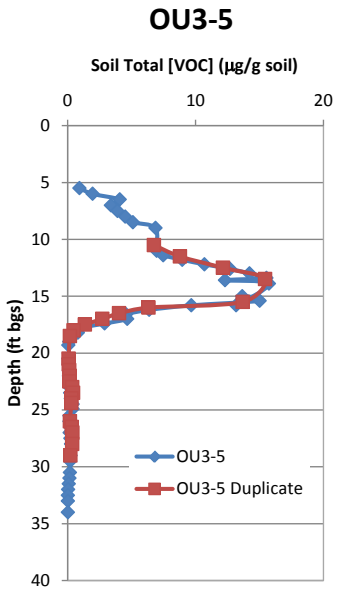


Figure 5.14c. Soil VOC Concentrations from Duplicate Cores Collected at Location OU3-5 (Former Building 106 Source Area). Cores were collected from holes located approximately 1 meter apart.

Soil organic carbon was determined using cores from several locations at the former Building 106 source area (see **Appendix I** for full results). As summarized in **Table 5.4**, the clay samples generally had higher levels of organic carbon relative to sandier soil samples. As discussed in Section 5.6.5, biomarker data was also collected using soil samples.

Table 5.4. Results of Soil Organic Carbon Analyses

Soil Type (USGS Classification)	No. of Samples Analyzed	Organic Carbon (%)	
		Median	Range
Sand (SP)	12	0.05	< 0.05 – 0.15
Sand/Clay (SP/CL)	6	0.10	0.10 – 0.15
Clay (CL)	16	0.15	0.15 – 0.30

Notes: (1) Median value include samples with non-detectable organic carbon; (2) All data are from lab-specific organic carbon analysis method (combustion-based), which had a lower detection limit (0.05) than parallel analyses completed using Walkley-Black (oxidation-based) method (0.10).

Building 780 Source Area: The soil lithology based on the cores collected at three locations was again largely consistent with the stratigraphic information generated using the screening-level characterization tools. The shallowest depth at which a distinct clay layer of significant thickness was encountered at these locations was approximately 20 or 22 ft bgs, and these generally extended for 5 to 7 ft thickness. At the farthest downgradient location (OU3-11), the presence of several thin (< 2 ft) lenses of lower permeability silty or sandy clays was confirmed. This location also contained a thicker (11 ft) clay below the shallower clay layer.

Similar to the other OU3 source area, CVOC concentration data collected at these locations confirmed that the majority of contaminant mass was present within the low permeability clays and in the transition zone immediately above (**Figure 5.15**). The primary differences at this source area are: (1) the presence of chlorinated ethanes in addition to chlorinated ethenes; and (2) the maximum total CVOC concentrations are generally lower (10 mg/kg or less). At the farthest upgradient location, OU3-9, the concentration profile is characterized by significant levels of TCE, DCE, and 1,2-DCA in the lower permeability zones. The overlying sandy layers contain much lower levels of DCE and negligible DCE and 1,2-DCA, but 1,1-DCA is present at a peak concentration of approximately 1 mg/kg. At the next location, OU3-10, 1,2-DCA is absent, but the vast majority of contaminant mass (primarily TCE with lower levels of DCE) is associated with the low permeability clay. 1,2-DCA is mostly confined to narrow clay-rich subintervals at 13 ft bgs and 21 ft bgs. The farthest downgradient location, OU3-11, is characterized by much lower concentrations (maximum total CVOC concentration of less than 0.3 mg/kg) and a lack of chlorinated ethanes. TCE is the primary contaminant and the peak concentration coincides with a depth below that of the primary clay unit, where a thin sand layer (3 ft) was encountered.

Within peak concentrations located within the clay layers, the concentration profiles at OU3-9 and OU3-10 are consistent with decreased source loading over recent periods, at least for the apparent parent compounds (TCE and 1,2-DCA), with the highest concentrations within the clay layer and lower concentrations nearer the interfaces. At the final location, OU3-11, the situation is more complicated because the peak concentration is lower, at a deeper depth, and associated with a thin sand layer. However, continued diffusion from the sand layer into both of the bounding adjacent clay layers is possible based on the concentration profile. It is notable that neither PCE nor 1,1,1-TCA are detected in significant quantities at these locations, despite reports that these compounds were used as part of site operations and potentially released within this area suggesting degradation of these parent compounds.

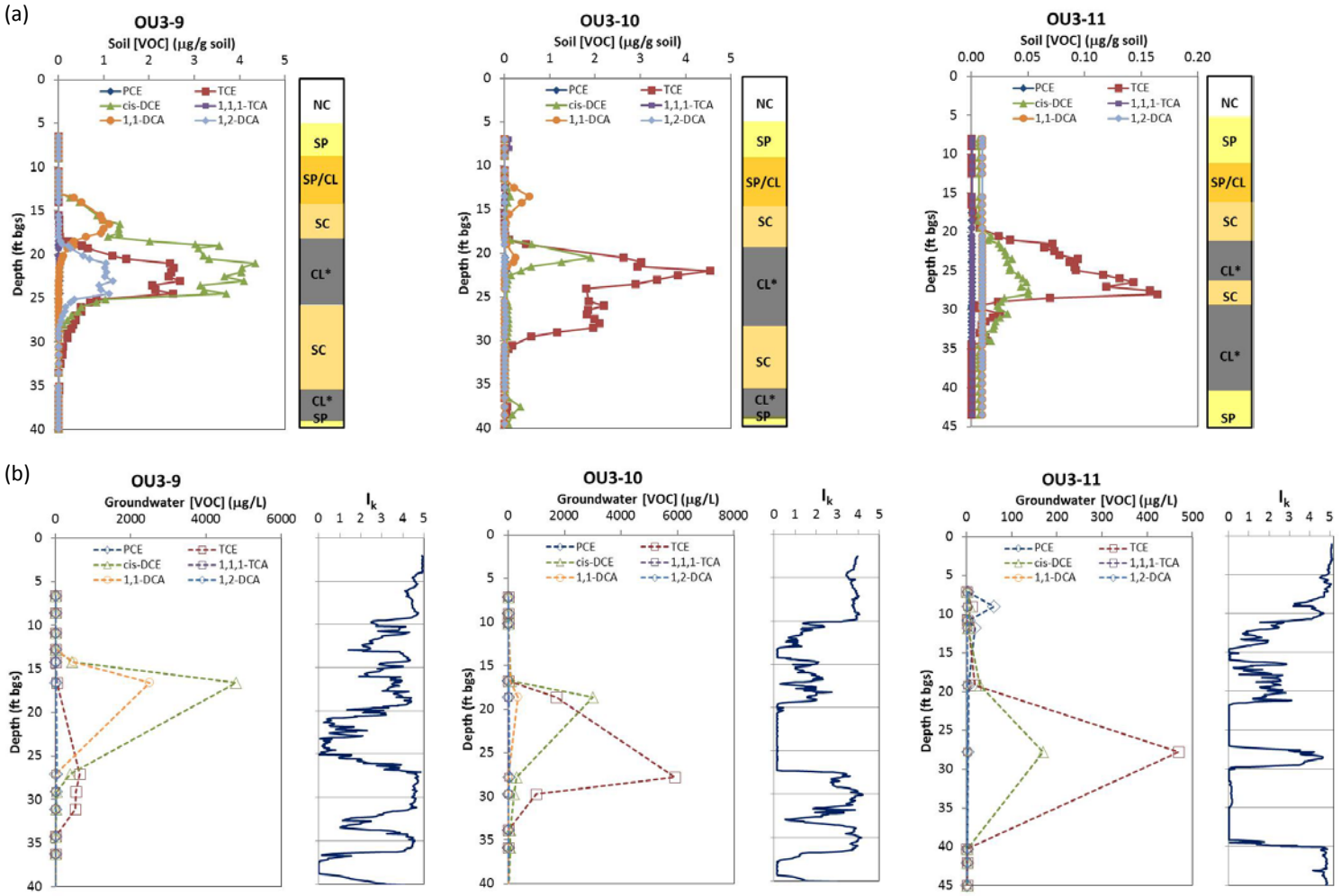


Figure 5.15. Soil and Groundwater VOC Concentrations from Building 780 Source Area Locations. Locations from left to right represent plume flowpath from near source (OU3-9) to downgradient plume (OU3-11). (a) Soil VOC concentrations and core logs; (b) Groundwater VOC concentrations and and I_k data from the Waterloo$^{APS\ TM}$.

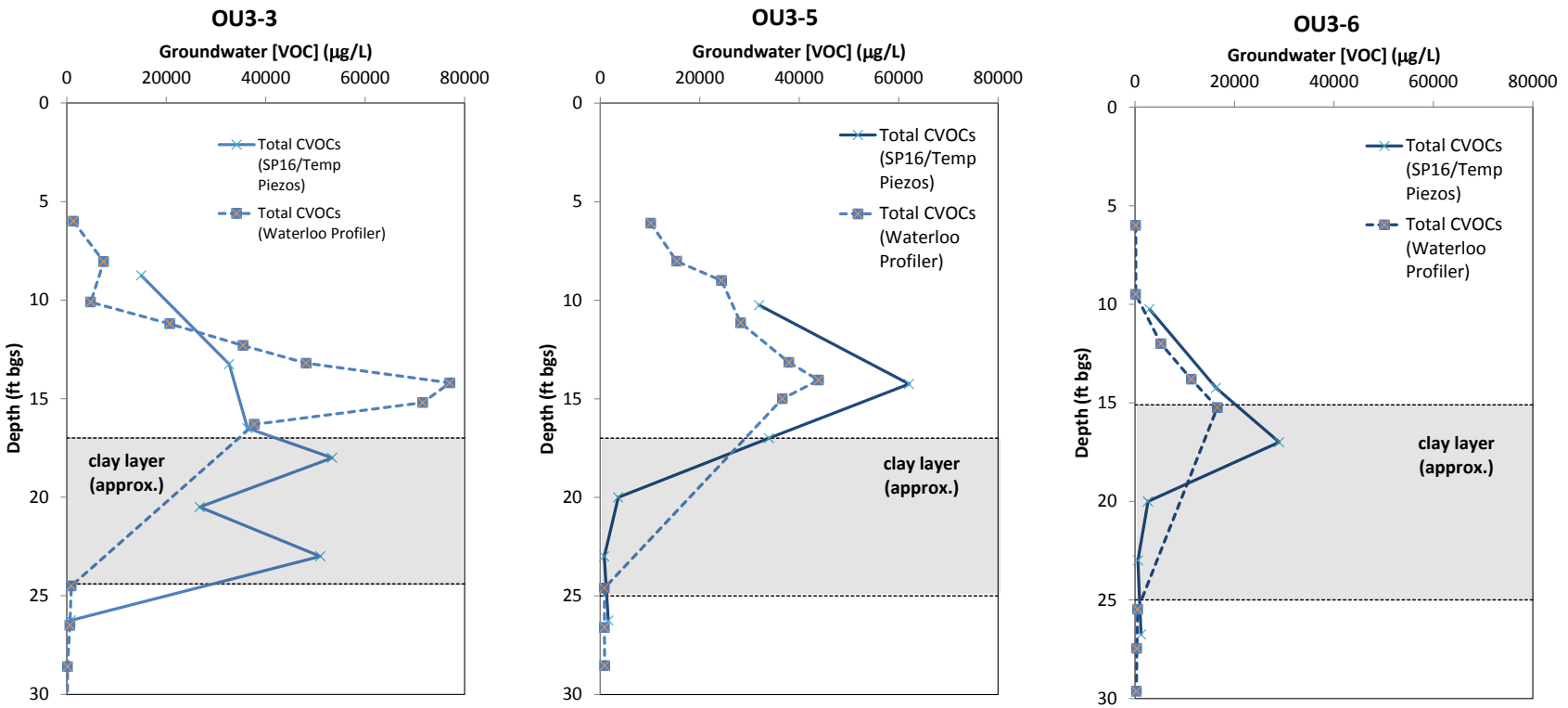


Figure 5.16. Groundwater Total CVOC Concentrations from Former Building 106 Source Area Locations. Locations from left to right represent plume flowpath from near source (OU3-3) to downgradient plume (OU3-6). Data were collected using either Geoprobe SP16/Temporary Piezometers or Waterloo APS TM.

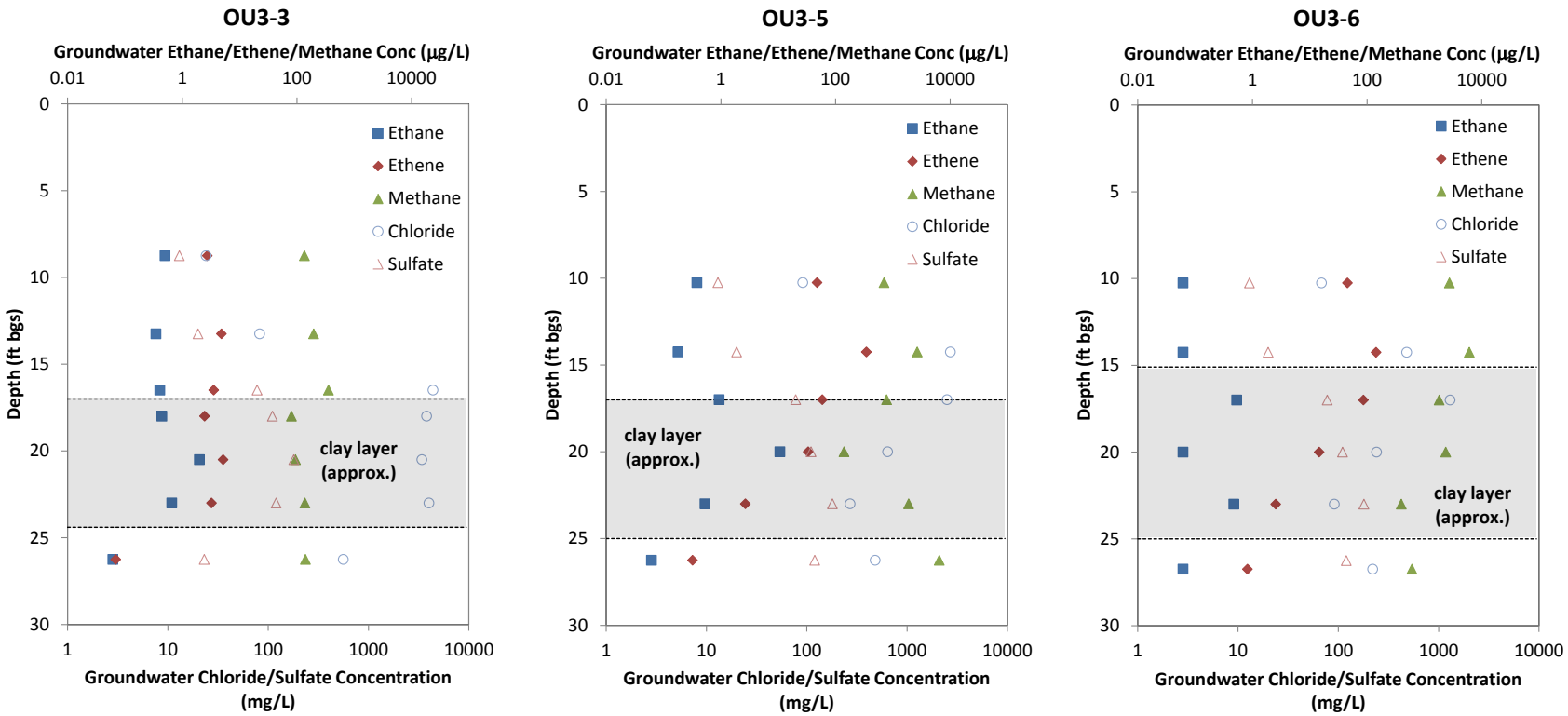


Figure 5.17. Other Groundwater Data from Former Building 106 Source Area Locations. Locations from left to right represent plume flowpath from near source (OU3-3) to downgradient plume (OU3-6). Data were collected using either Geoprobe SP16/Temporary Piezometers or Waterloo$^{APS\ TM}$. Analytes included ethane, ethene, methane, chloride, and sulfate.

5.6.3 *Groundwater Data*

Former Building 106 Source Area: Groundwater data was collected in six locations within this area using Waterloo$^{APS\ TM}$, including all four locations where soil cores were collected (**Appendix D**). Results of groundwater VOC analyses on the Waterloo$^{APS\ TM}$ samples are shown along with the soil VOC data in **Figure 5.14**, along with the I_k data for comparison with the core logs. Additional groundwater sampling at three locations (OU3-3, OU3-5, and OU3-6) were collected using a combination of temporary piezometers and the Geoprobe SP16 sampling system (**Figure 5.16**, **Figure 5.17**, **Appendix K**).

Waterloo$^{APS\ TM}$ sampling necessarily focused on the more transmissive zones, and generated data on CVOC concentrations and field geochemical parameters (electrical conductivity, DO, pH, and ORP). The groundwater CVOC concentration profiles at most locations were supportive of those obtained using soil data, in terms of both the shape of the profile and relative concentration. An exception is at location OU3-3, where the peak concentration within the overlying sand layer was encountered at a slightly shallower depth (14.2 ft bgs) as opposed to the depth nearest the interface (15.2 ft bgs). Small but significant amounts of VC were also present, typically representing less than 5% of the total CVOC concentration, with the highest contribution observed at the downgradient location OU3-6. VC was not quantified in the soil VOC analyses. The results of field parameter measurements showed that the groundwater was mildly acidic, with pH values frequently below 6 (but never below 5) and rarely above 7. ORP values generally fell between -100 and +100 mV. There appeared to be a positive correlation between low ORP and more neutral (less acidic) pH values.

Groundwater samples collected from both high and low permeability zones using the temporary piezometer/Geoprobe SP16 methods were analyzed for CVOCs, sulfate, chloride, and several dissolved gases. The CVOC concentration profiles were again similar to those obtained using the Waterloo^{APS} and soil subsampling at all locations. The two groundwater-based approaches yielded similar results within the more permeable zones (**Figure 5.16**). Within the low permeability clays, the groundwater-based concentration confirmed that significant contaminant mass was present within these zones, particularly at OU3-3, though little was in the form of VC. Because these sampling methods have relatively long screens (at least 2.0 ft), the groundwater collected is representative of the more permeable portions of a potentially heterogeneous vertical interval. As such, there is inherent uncertainty in assigning specific depths to individual groundwater datapoints. This means that the groundwater data is appropriate as a guide, but there is a higher level of confidence if the shape of the contaminant vs. depth profiles is established using soil data with samples collected at a much higher resolution. Also groundwater samples do not include the sorbed mass, which can be appreciable, particularly in the finer grained zones.

Ethene and ethane were detected in most samples from both the high and low permeability zones (**Figure 5.17**), but at low levels that were typically much less than 1% of the total CVOC concentration. The highest ethene (0.3 mg/L) and ethane (0.01 mg/L) concentrations were encountered at the downgradient locations (OU3-5 and OU3-6) consistent with more degradation occurring along the plume flowpath and higher ratios of degradation products to parent

compounds. Methane was detected in all groundwater samples regardless of depth or location, generally at levels between 0.1 and 1.0 mg/L (**Figure 5.17**). The highest concentrations were from samples collected at the farthest downgradient location (OU3-6).

Groundwater sampling results showed that chloride levels were consistently elevated in low permeability clays relative to the sand layers (**Figure 5.17**). The higher-end chloride concentrations were greater than 1000 mg/L, which is at least an order of magnitude higher than the total CVOC concentrations in co-located samples. Sulfate was relatively low and uniform regardless of location and sampling depth (the median and standard deviation of the entire sulfate dataset were both equal to 44 mg/L) (**Figure 5.17**). As discussed in Section 5.6.5, carbon isotope data was also collected using groundwater samples from the former Building 106 source area.

Building 780 Source Area: Waterloo^{APS} was the sole groundwater sampling method used at this area. As such, samples could only be collected from the more transmissive zones, and are limited to CVOC concentration and field geochemical parameters (**Figure 5.15**, **Appendix D**).

At the three locations where soil cores were also collected, the groundwater CVOC concentration profiles were consistent with those obtained in the same depth intervals (i.e., the transmissive zones) using soil data, meaning that the shape and relative concentrations for sampled intervals were similar. Low levels of VC (0.4 – 0.9 mg/L) were detected at OU3-9 and OU-10, but VC was not detected at OU3-11. Significant 1,1-DCE was encountered at OU3-9 and OU-10, particularly at the latter location where 1,1-DCE accounted for approximately 58% (7.6 of 13.2 mg/L) of the total CVOC concentration (at 18.6 ft bgs).

Field parameter data were collected at all four locations where Waterloo^{APS} was used. The results indicated that the groundwater was generally mildly acidic, never falling below pH of 5 and only occasionally exceeding pH of 7 (shallow depths of OU9-10). ORP values typically fell within a narrow range centering around 0 mV. Again, the lowest ORP values (< -100 mV) were generally associated with intervals where neutral pH values were detected (e.g., shallower intervals of OU3-10.

5.6.4 Composite Plots

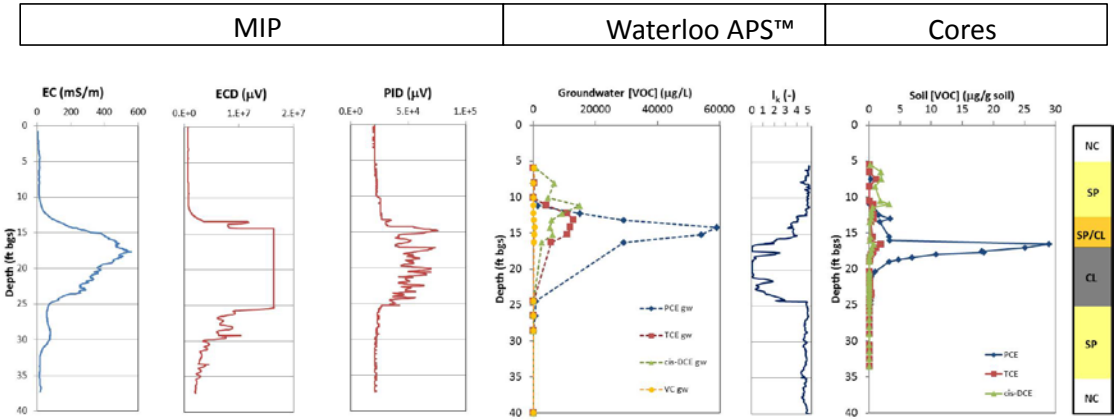
For each location at the former Building 106 source area, high-resolution characterization data are presented in the form of composite plots that show method-specific depth-discrete data side-by-side (or in some cases, as data overlays). These plots provide the most complete picture of the datasets, and allow for comparison of complementary characterization methods. Plots for characterized locations are shown in **Figure 5.18** and **Appendix L**.

These plots demonstrate that the various stratigraphic characterization methods generated data that was consistent with those obtained by soil coring and classification. They successfully identified the critical low permeability zones for further characterization efforts using soil and groundwater sampling. CVOC trends (in terms of magnitude and distribution of contaminants) were largely similar regardless of the sampling matrix or approach.

It should be emphasized that the soil concentration data are considered the more reliable input data for subsequent source history modeling. In part, this is because the groundwater sampling methods within the low permeability zones have relatively long screened intervals (2.0 ft), meaning that the groundwater collected is representative of the more permeable portions of a potentially heterogeneous vertical interval and also does not include the sorbed mass component. Also groundwater data from low permeability zones is more susceptible to bias from sample collection methods (e.g. volatile loss with slow recovery and different sampling methods). As such, there is inherent uncertainty in assigning specific depths to individual groundwater datapoints within low permeability zones, more so than soil samples that are collected at more frequent intervals at more defined depths. Also the soil sampling data includes sorbed mass, which can be appreciable in low permeability zones. This means that while groundwater data can be appropriate as a guide, there is generally a higher level of confidence in using soil data to establish the shape of the contaminant vs. depth profiles. The datasets also demonstrate how collection of both groundwater and soil data is very complementary. Groundwater data collected with discrete interval sampling techniques (such as Waterloo$^{APS\ TM}$ or Geoprobe SP16 sampler) provides much insight about the contaminant distribution in higher permeability zones and at interfaces, but is generally ineffective in lower permeability zones where obtaining representative samples is problematic and also since groundwater samples do not provide insight on the sorbed mass component which can be appreciable in such zones. Soil sampling is more effective for lower permeability zones where sampling resolution can be very high which is necessary for defining the smaller scale variability and profile shapes in diffusion dominated zones, and given that the methods quantify both the dissolved and sorbed mass components.

Note that the soil concentrations can be converted to an equivalent porewater concentration for a more direct comparison with groundwater sampling data via partitioning calculations that factor out the sorbed mass component (via empirical estimates of sorption based on organic carbon content) and correct for water volume using estimated (or measured, if available) porosity and bulk density values. While these calculations were performed for the OU3 datasets (data not reported), the soil data from all locations are presented in the composite plots in their original units (μg/g). This is because the correction to porewater concentrations proved difficult to implement uniformly across all locations. Primary contributors to this difficulty included: (1) variability/uncertainty in key parameters (e.g., porosity, organic carbon) required for the conversion; (2) potential discrepancies in depth assignment for groundwater samples vs. soil samples; and (3) potential loss of contaminant mass from soil samples due to the use of water during core collection to maintain a head in the outer casing and avoid heaving sands (an issue with the Geoprobe dual-tube method that was used for this project). Instead of reporting all concentrations as equivalent (or measured) porewater concentrations, the soil and groundwater concentrations are presented on different axes on the plots. The units for the respective axes were selected to ensure that the style of each concentration profile was apparent, thus allowing for reasonable comparison between the two datasets.

(a) **OU3-3**



(b) **OU3-4**

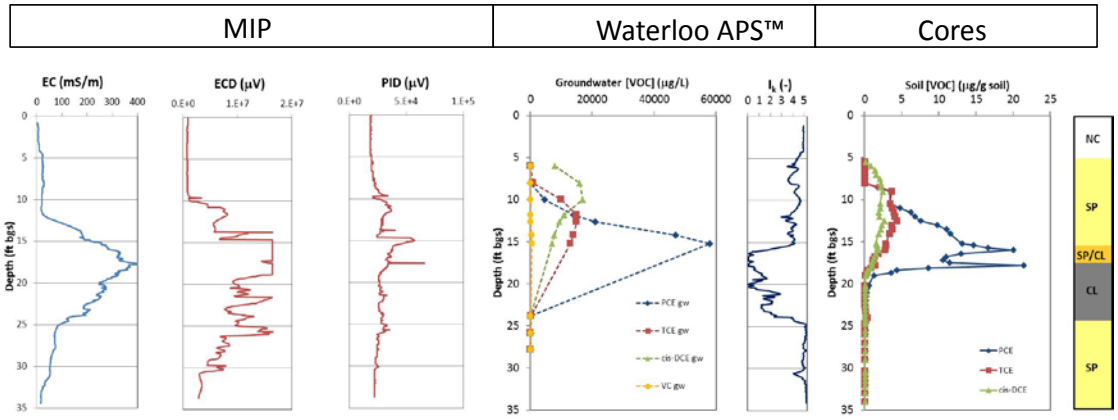
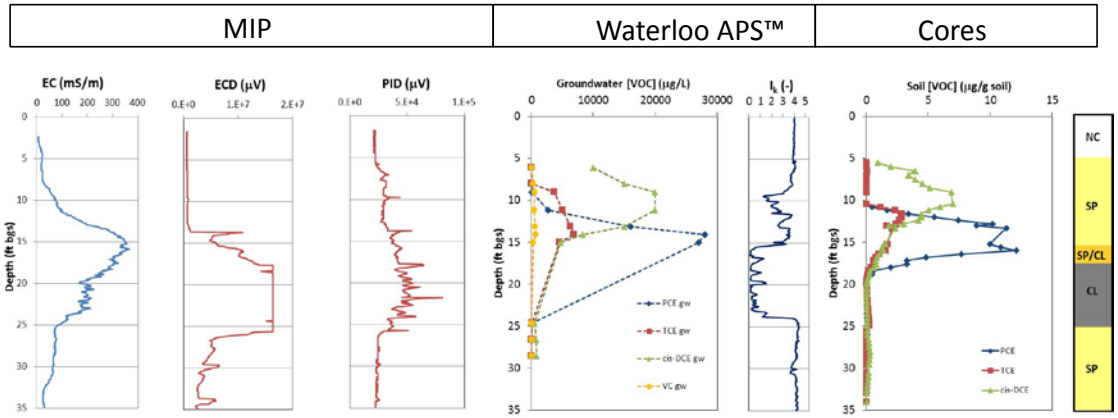


Figure 5.18. Composite Plot of Characterization Data Collected at Former Building 106 Source Area: (a) Location OU3-3; (b) Location OU3-4. Shown from left to right are results from MIP, Waterloo$^{APS\ TM}$ (groundwater VOC concentrations and I_k data, and soil cores (soil VOC concentrations and geologic log). EC = electrical conductivity; ECD = electron capture detector; PID = photoionization detector; VOC = volatile organic compound; I_k = index of hydraulic conductivity.

(c) **OU3-5**



(d) **OU3-6**

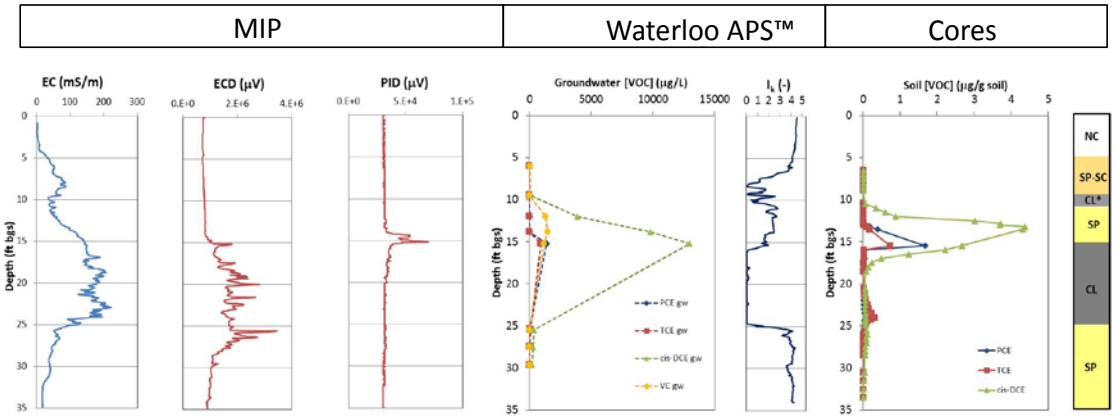


Figure 5.18. Composite Plot of Characterization Data Collected at Former Building 106 Source Area: (c) Location OU3-5, (d) Location OU3-6. Shown from left to right are results from MIP, Waterloo$^{APS\ TM}$ (groundwater VOC concentrations and I_k data, and soil cores (soil VOC concentrations and geologic log). EC = electrical conductivity; ECD = electron capture detector; PID = photoionization detector; VOC = volatile organic compound; I_k = index of hydraulic conductivity.

5.6.5 *Lines of Evidence for Degradation – Transmissive Zone vs. Low-k Zone*

The impact of degradation should be accounted for during source history modeling, either directly by incorporating degradation rates and by-products into the models, or indirectly by demonstrating various lines of evidence that degradation processes are active at the site. The latter is the focus of this section.

Absence of parent compounds: Both PCE and 1,1,1-TCA were reportedly released at the Building 780 source area, but these compounds were only detected at negligible concentrations in soil and groundwater samples from this area. Their absence points to extensive degradation following release. [PCE may have been only a minor component of Building 780 operations, at least based on the relative percentage of TCE present in site samples. Using similar logic, it appears to have been the primary component of former Building 106 operations.]

Presence of degradation products: There are significant concentrations of degradation products at both source areas. This includes cis-1,2-DCE and vinyl chloride (VC) at former Building 106 source area (along with minor amounts of other DCE isomers, ethene, and ethane) and cis-1,2-DCE, VC, 1,1-DCE, and 1,1-DCA (along with minor amounts of chloroethane, ethene, and ethane). None of these compounds were reported to have been released, and thus confirm that degradation has occurred. Cis-1,2-DCE, VC, and ethene are by-products of the reductive dechlorination pathway for chlorinated ethenes parent compounds. 1,1-DCA, chloroethane, and ethane are the by-products of the reductive dechlorination pathway for chlorinated ethane parent compounds, while 1,1-DCE is a by-product of the abiotic dehydrohalogenation pathway.

Elevated concentrations of several of these compounds are also encountered in the lower permeability layers. This is attributable to either degradation of parent compounds that have diffused into these layers, or diffusion of by-products into these layers after degradation of parent compounds occurred in more transmissive zones. Patterns in the relative concentration of parent compounds vs. degradation products can be used to infer where degradation may have occurred:

- At several locations such as OU3-4 and OU3-5, the percentage of mass encountered in the high permeability zones relative to low permeability zones is much higher for degradation by-products (particularly cis-1,2-DCE) than for parent compounds (particularly PCE). This suggests that degradation primarily occurred in the high permeability zones.
- At locations such as OU3-6 and OU3-11, the shape of the concentration profiles across the entire characterized interval is relatively similar for both parent compounds and degradation products. This similarly suggests that either: i) the majority of degradation occurred in the high permeability zones (and early in the release period) followed by diffusion of these degradation products into the low permeability zones (at similar rates as the parent compound(s); or ii) degradation is occurring as contaminants diffuse within the low permeability zones.
- At locations such as OU3-3 (source area), the concentrations of degradation products are much lower than parent compounds and nearly negligible in the low permeability zones. This suggests that degradation is limited at these locations and primarily confined to the

high permeability zones. Alternatively, any degradation signal could be masked by the continuous input of parent compounds from the source (e.g., DNAPL dissolution).

- At locations such as OU3-10, the peak concentration of a parent compound (TCE) and its primary degradation product (cis-1,2-DCE) occur at similar depths, but the parent compound penetrates much further into the low permeability layer than the degradation product. This suggests that degradation may have been initiated at a later date (in either the high or low permeability zones), such that advective-based transport of cis-1,2-DCE from upgradient locations lagged that of TCE.
- The pattern at OU3-9 is harder to categorize, in part because there are multiple compound classes that may behave differently with respect to degradation. It is notable that the concentration of cis-1,2-DCE is consistently higher within the low permeability zone than the apparent parent compound (TCE) and penetrates to a similar depth. This indicates that degradation started near the original release time (1971) and/or may be occurring within the low permeability zone.

These patterns in the degradation product concentrations are further discussed in the section on carbon isotope analysis.

Concentration vs. distance trends: At the former Building 106 source area, the total CVOC concentration generally decreases moving downgradient from the presumed release area. Conversely the relative contribution (i.e., mole fraction) of degradation products to the total CVOC concentration increases moving downgradient. These patterns suggest that degradation is occurring within the aquifer but is relatively limited close to the source area, possibly attributable to inhibition from the higher contaminant levels. At the Building 780 source area, significantly lower concentrations were observed at the farthest downgradient location (OU3-11), but the relative contribution of degradation products to the total CVOC concentration was much higher at the near source locations. This is consistent with stronger degradation capacity within the source area.

Geochemical conditions: The concentration of naturally-occurring electron acceptors (e.g., sulfate, nitrate, iron, oxygen) that would compete with desirable contaminant degradation processes are relatively low at both source areas. The formation of low but measurable levels of methane, along with ORP readings that tended to be near zero or negative, confirms that conditions are reducing. These conditions favor anaerobic reductive dechlorination, assuming adequate microbial populations exist. However, the pH is generally lower than optimal for promoting biological activity, with the range of site values centering on a pH of 6 and frequently approaching a pH of 5. There was a clear relationship between pH and ORP, with higher pH values correlating with lower ORP (**Figure 5.19**). This is potentially related to higher levels of biological activity (i.e., utilization of natural organic carbon and electron acceptors to reduce ORP) within intervals with more favorable pH conditions.

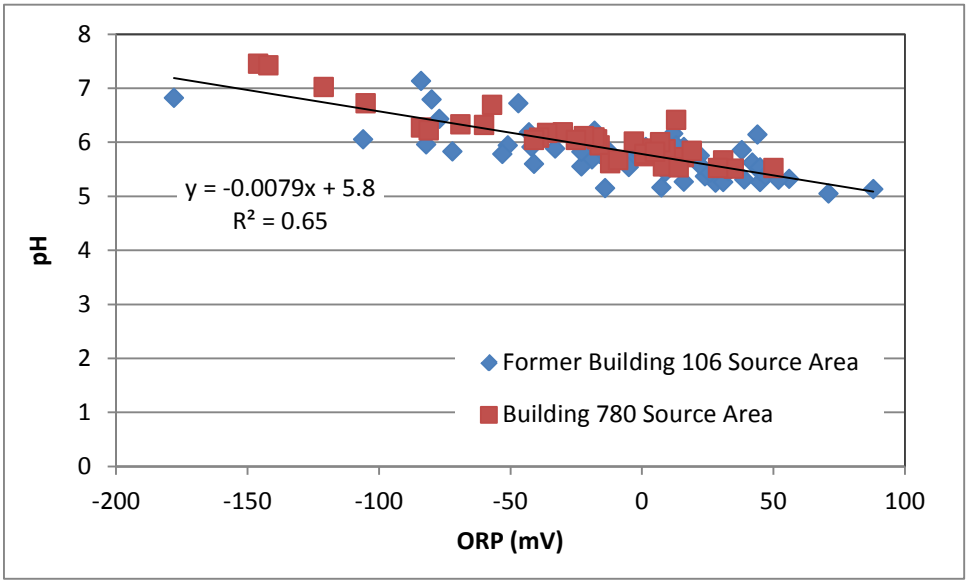


Figure 5.19. Relationship Between pH and Oxidation-Reduction Potential (ORP). Results of field measurements of groundwater samples.

Chloride data: For every mole of CVOCs that is degraded, one mole of chloride is released, such that elevated chloride can be an indicator of degradation. However, chloride did not prove to be diagnostic at this site because the concentrations within the clay intervals were high, presumably due to natural sources in the aquifer reflecting historical sea water influence and/or depositional environment. At most locations, the chloride concentrations in the clays were greater than 1000 mg/L (or 28 mM). Given that the total CVOC concentrations in groundwater samples never exceeded 1 mM, it is not possible to discern any chloride released via degradation from the background chloride levels.

Biomarker data: The presence of key organisms and enzymes that mediate reductive dechlorination can be a strong line of evidence that degradative capabilities exist at a particular site. qPCR-based methods were used to identify and quantify *Dehalococcoides*-encoding genes and the functional gene vinyl chloride reductase. The former represents a key group of organisms that have the ability to fully dechlorinate PCE and/or TCE to ethene, while the latter demonstrates expression of the enzyme that performs the final step in the dechlorination pathway.

At three locations within the former Building 106 source area, soil samples from multiple depths, including both the higher and low permeability zones, were analyzed (**Table 5.5,** see **Appendix M** for full results). In general, *Dehalococcoides* were detected infrequently (4 of 18 samples) and at relatively low levels (up to 4 x 10^4 cells/gram). For context, *Dehalococcoides* levels of greater than 10^7 - 10^8 cell/mL are generally considered viable candidates for MNA (ESTCP ER-0518 Guidance Protocol, 2011). All samples where *Dehalococcoides* was detected were also positive for vinyl chloride reductase, confirming that the complete dechlorination pathway should be present at locations where viable microbial populations are active. Higher detection

frequencies were noted in the samples from the sand intervals relative to samples from the clay intervals.

Table 5.5. Summary of Biomarker Data from Former Building 106 Source Area

Location	Soil Type	*Dehalococcoides* detected?	Vinyl Chloride Reductase gene detected?
OU3-3	Sands (shallow and deep)	2 of 3 samples (up to 4 x 10^4 copies/gram; 0.002-0.007% of total)	2 of 2 samples (up to 1 x 10^6 copies/gram; 0.07-0.2% of total)
	Clays	1 of 5 samples (2×10^4 copies/gram; 0.001-0.003% of total)	1 of 1 samples (5×10^3 copies/gram; 0.0003-0.001% of total)
OU3-6	Sands (shallow and deep)	0 of 3 samples	Not tested
	Clays	1 of 7 samples (2×10^4 copies/gram; 0.001-0.003% of total)	1 of 1 samples (1×10^4 copies per gram; 0.0009-0.003% of total)

Notes: (1) vinyl chloride reductase assay not completed on samples that were negative for *Dehalococcoides*; (2) See **Appendix M** for full results.

These results provide little evidence for abundant dechlorinating populations at this source area. However, it is clear that these data were negatively affected by inhibition during qPCR analyses. Specifically, DNA was successfully extracted from all soil samples, but it was unable to be amplified using the target-specific primers. This suggests that significant microbial populations were present, but individual groups within those populations could not be quantified. Consequently, there is a high probability for false negatives in this dataset, as well as lower cell concentrations in the positive samples than would otherwise be encountered in the absence of inhibition. Inhibition during qPCR analysis of soil samples is a recognized but not well-understood problem, and is thought to be associated with the presence of metals or other specific factors that can restrict gene expression. Furthermore, it does occur universally. For this project, soil analyses were selected over groundwater analyses because the soil subsampling strategy provided depth-discrete samples for better delineating dechlorinating activity with depth.

Despite these limitations in the biomarker dataset, the results do confirm that positive biomarkers for dechlorination are present (albeit sporadically) within the lower permeability zones at multiple locations at this source area. There are very few published reports of biological activity in these soil types (clays), and these results should be viewed positively in terms of long-term attenuation capabilities at the site.

Carbon isotope data: Compound-specific isotope analysis (CSIA) has increasingly been applied as a complementary tool to assess the degree of reductive dechlorination (Chartrand et al. 2005; Hunkeler et al., 1999; Sherwood Lollar et al., 2001; Song et al., 2002; Hunkeler et al., 2009). The

method relies on differences in degradation rates between molecules with light and heavy carbon isotopes in the compounds, which lead to the preferential degradation of lighter isotopes and subsequent enrichment of heavy isotopes in the remaining compound. The degree of biodegradation over time and/or space can be reflected by an expected isotope pattern. As the concentration of the parent compound (PCE) decreases, the isotopic composition of the remaining parent get enriched in ^{13}C (i.e., tend toward more positive values) and the daughter (TCE) is depleted in ^{13}C compared to the parent compound.

For this project, CSIA was completed on groundwater samples collected from multiple depths in the transmissive and low-k zones at three locations within the former Building 106 source area. [Note that soil samples designed for CSIA analysis following water extraction were collected, but ultimately were not analyzed]. At each location, sampled depths included both the low permeability interval as well as the higher permeability zones above and below this interval. The isotope data for each location are shown in **Figure 5.20** along with concentration data (see **Appendix N** for full results).

The major findings from the isotope data include the following:

- There was a general trend of increasing degree of degradation moving from upgradient (OU3-3) to downgradient locations. This is evidenced by the measurement of less negative $\delta^{13}C$ values at downgradient locations for each of individual constituents, including both parent and daughter products. For samples from the same boring and depth, the $\delta^{13}C$ values for daughter products were lower (more negative) than the $\delta^{13}C$ values for the corresponding parent compound(s). This is the expected behavior when degradation is occurring.

- While the patterns described above confirm that degradation is occurring at the site, a comparison between values obtained in low k zones vs. high k zones suggests that a **majority of the degradation activity is associated with the high-k zones compared to low-k zones.** At each location, the $\delta^{13}C$ values for a particular constituent are generally higher (less negative) within the high-k zones than the values associated with the low k zone. This is true regardless of whether the shallow high-k zone (above the clay layer) or the deeper low-k zone (below the clay layer) is considered. The pattern also holds true for each of the constituents (PCE, TCE, cis-1,2-DCE, and VC).

The isotope pattern is in agreement with the CVOC concentration distribution, which showed that at the upgradient location, PCE has been affected by biodegradation but is still the predominant CVOC present at the upgradient location. The extent of degradation increases moving downgradient, but the data support the hypothesis that a higher degree of biodegradation was occurring in the sand units compared to the clay units.

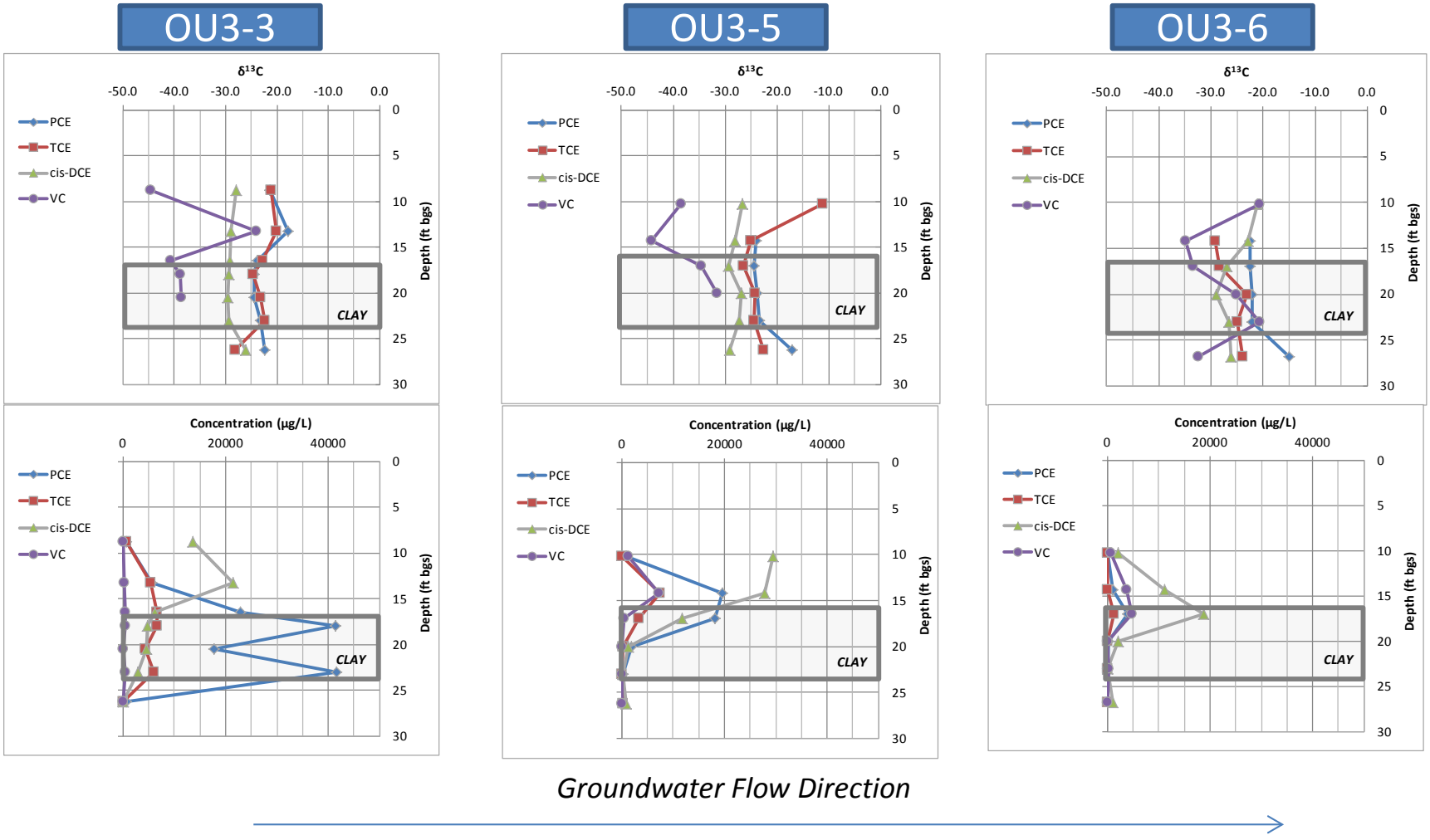


Figure 5.20. Summary of Carbon Isotope and Concentration Data from Former Building 106 Source Area. Increasing $\delta^{13}C$ values are associated with enrichment (biodegradation). Both isotopic and CVOC concentrations are based on analyses of groundwater samples collected using Geoprobe SP16 or temporary piezometers.

5.6.6 *Extraction and Analytical Methods Comparison*

In support of the performance objectives for this project, soil concentration data were collected using several different methods to demonstrate their relative influence on data quality. This included methods that focused on sample collection / storage and sample extraction and analyses. The objective was to demonstrate the importance of certain steps in the data collection process, including those associated with the "UG methods" used extensively during this project.

Soil Sampling and Field Preservation: The USEPA recommends that soil samples be collected using appropriate equipment and procedures to minimize loss of volatiles during analysis (see EPA Method 5035A). This typically involves the use of a plunger-based sampler, such as the Encore® sampler [http://www.ennovativetech.com/pages/the-en-core-sampler.php] that collects either 5- or 25-gram mass of soil from a core into a plastic container. Options for handling and shipping the sample for analysis include capping the core subsample in the container with no headspace with a cap providing an airtight seal without field methanol preservation. However, volatile losses due to the lack of field preservation are a well-established phenomenon (e.g. Hewitt, 1998). The UG method for soil sampling uses a similar coring device (made of stainless steel, not plastic) but relies on immediate field preservation with methanol as well as enhanced extraction techniques. During the current project, soil CVOC concentration data were collected using both a conventional method (Encore without field preservation) and the UG method to quantify the differences that could be expected.

A total of 26 co-located field duplicate samples were collected using the two different approaches, with the Encore samples sent to a commercial laboratory for analysis. A linear regression plot of the data is shown as **Figure 5.21** (see **Appendix J** for full results). A strong low bias for the Encore data was observed (slope = 0.79), along with significant variability (R^2 = 0.83) indicating generally lower results for the Encore samples submitted to a commercial laboratory. Similarly, the median relative percent difference (RPD) between the two datasets was -110%. These metrics demonstrate that, at a minimum, forgoing the field preservation results in a significant compromise in data quality. However, it is uncertain how much of this variability was due to the storage and volatile loss in the Encore samplers versus differences in the way samples are extracted and analyzed by the commercial laboratory versus the methods employed by UG. Other studies have shown similar results between Encore and field methanol preservation (Vega et al., 2004).

To assess effects of storage in Encore samplers, a second set of split samples was collected using Encore samplers where the methanol preservation step was delayed by 24 to 72 hours. Samples were then sent to the UG laboratory, and extracted and analyzed using the same methods as the other soil samples that were immediately field preserved in methanol. The linear regression plot of these data (**Figure 5.22**) illustrates that the delayed methanol preservation step reduced the low bias (slope = 0.93) and variability (R^2=0.87) slightly (median RPD = -33%). However, these results are still indicative of minor volatile losses from the Encore samplers due to the delay in methanol preservation. The differences between correlations of the standard UG method-generated data (field methanol preservation) with data obtained from the commercial laboratory (using Encore and unpreserved samples; i.e., the data plotted on the y-axis of **Figure 5.21**) and

the data obtained from the UG laboratory with delayed preservation (i.e., the data plotted on the y-axis of **Figure 5.22**) are also of interest. While correlations between the latter two datasets cannot be made directly (because they represent samples from different depths), they reflect the differences associated with the sampling preparation and analysis methodologies at each of the two laboratories. Specifically, the UG lab generated data of apparently higher quality than the commercial lab, where non-methanol preserved samples were processed within 24 to 72 hours of arrival (i.e., similar to the delay in preservation for this set of UG-analyzed samples).

Field and Laboratory Extraction Procedures: Stone Environmental Inc. has developed a method for shortening the normal extraction time for CVOC analysis by adapting the typical UG lab "shake flask" method to a field technique building off Dincutoiu et al. (2003) (see **Appendix O** for additional information). This "rapid field extraction" attempts to recover all VOC mass from a soil sample in a matter of an hour or so as opposed to the longer period that is commonly employed by the UG laboratory in a research lab setting. The Stone method, which relies on vigorous agitation of samples in methanol, is currently in development for commercial use.

To assess the validity of this technique, a total of 27 co-located field duplicate samples were extracted using either the rapid field extraction method or the standard UG laboratory method and then methanol extracts were analyzed using the same methods. A strong correlation was obtained using linear regression of all analytes (**Figure 5.23a**), with no bias (slope = 1.00) and a moderate level of variability (R^2=0.88). The median RPD between the two datasets was 20% (see **Appendix J** for full results). However, several datapoints were clear outliers, associated with two samples, one from a sandy interval and the other from the clayey sand transition zone. Removing these outliers reduced the variability significantly (R^2 = 0.99) but suggested a slight low bias for the data collected using the rapid field extraction technique (slope = 0.96) (**Figure 5.23b**). The low bias likely reflects slightly incomplete extraction within the field, but overall, the results provide strong evidence that the rapid field extraction method can generate data of comparable quality.

To further demonstrate the impact of the laboratory extraction period of the data, a time-series extraction experiment was conducted at the UG laboratory. The methanol extracts of 11 soil samples (including both coarse and fine-grained soils) were analyzed at 1, 2, 3, and 4 weeks of extraction. The time-series results (shown in **Appendix J**) indicate that extraction appeared to be complete within 2 weeks. Concentrations of each of the CVOC analytes (PCE, TCE, and cis-1,2-DCE) were generally consistent regardless of the extraction period. These results suggest that shorter extraction periods may be technically justifiable, though the potential influence of site-specific characteristics may need to be investigated prior to making such a decision. Note that the soil CVOC concentration data presented in Section 5.6.2 were generated using the standard 6-week extraction period to specifically minimize any issues related to incomplete extraction.

Laboratory Analysis Variability: Field duplicate samples (side by side samples from same depth) from soil cores were analyzed to confirm that the UG sample analysis methods were sufficiently precise. These samples were handled identically in the field, using the UG coring device and immediate methanol preservation. Similarly, sample preparation and analysis at the

laboratory were identical for these duplicate samples, using an extended (multi-week) extraction period prior to analysis via a GC/MS method. A total of 22 co-located field duplicate samples were collected. As shown on the regression plot in **Figure 5.24**, a high level of precision was demonstrated using these datasets, with a slope of 1.00 and an R^2 value of 0.98 when all analytes were plotted. The median relative standard deviation (RSD) was 7%, well below the typical limit of 20 to 30% RSD used for QA/QC purposes (see **Appendix J** for full results).

Methanol extracts from a subset of the soil samples that underwent the rapid field extraction method were also split and sent to both a commercial laboratory and the UG laboratory. Based on the analysis of these 27 split samples (with 39 analytes that were present above reporting limits), a strong correlation was obtained between the data obtained at the commercial laboratory and the UG laboratory (slope = 0.99, R^2 = 0.99, median RPD = -3.5%) (**Figure 5.25**) confirming both analytical techniques provide similar results. However the UG analytical method (direct on-column methanol extraction onto GC) provides much lower MDLs than the commercial laboratory, which relies on dilution of the methanol extract into water prior to analyses using Method 8260. Typical reporting limits for the commercial lab analyses were 2 to 5 µg/L for the target compounds but were occasionally as high as 2000 µg/L because additional sample dilution was necessary (dilutions of 10 or greater were required for approximately 10% of the samples). For the UG method, the reporting limits were all below 1 µg/L for PCE (0.1 µg/L), TCE (0.1 µg/L), and 1,1,1-TCA (0.5 µg/L), with slightly higher limits for cis-1,2-DCE (3.5 µg/L) and 1,2-DCA (5.0 µg/L).

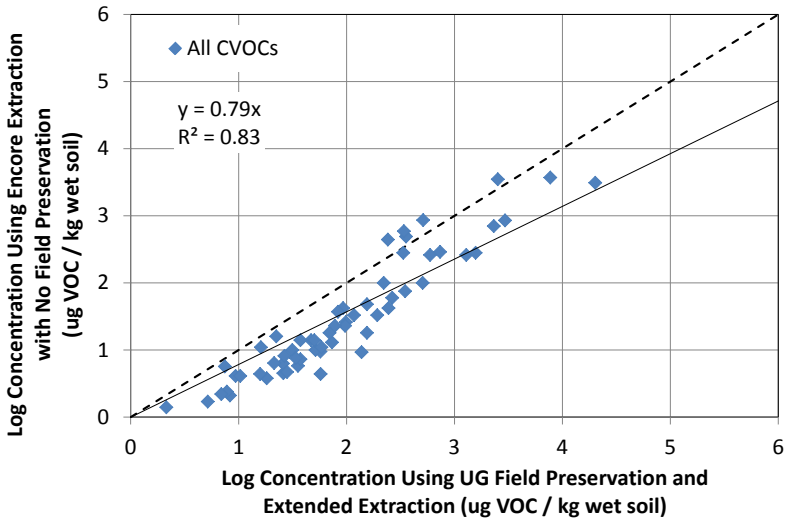


Figure 5.21. Comparison Between CVOC Concentration Data Collected with UG Method and Other Methods: Unpreserved Encore Samplers Analyzed at Commercial Laboratory. UG method (x-axis) involved collection using UG metal coring device, immediate field preservation in methanol, followed by extended "shake flask" extraction and analysis at UG laboratory. Solid line represents the best-fit regression line; dashed line represents 1:1 line through the origin.

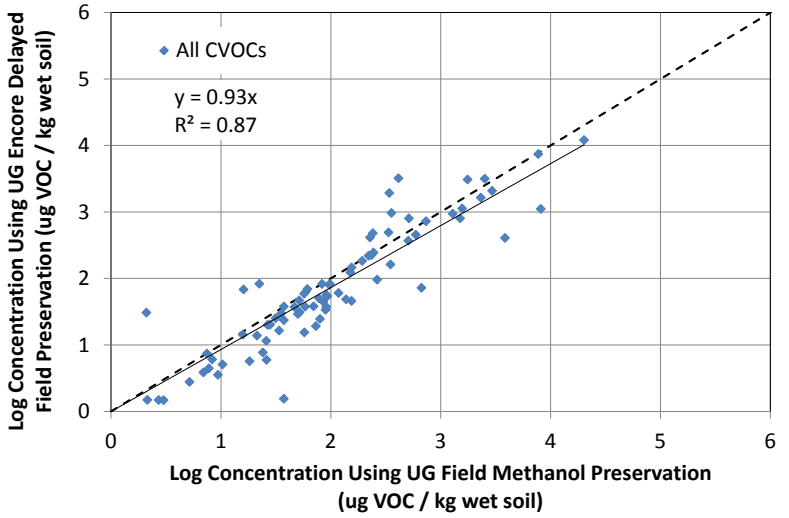


Figure 5.22. Comparison Between CVOC Concentration Data Collected with UG Method and Other Methods: Encore Samplers with Delayed Methanol Preservation. Y-axis represents samples collected using Encore samplers with the preservation step delayed until receipt at the UG laboratory (24 to 72 hours). UG method (x-axis) involved collection using UG metal coring device, immediate field preservation in methanol, followed by extended "shake flask" extraction and analysis at UG laboratory. Analyses of both sets of samples were completed at the UG laboratory. Solid line represents the best-fit regression line; dashed line represents 1:1 line through the origin.

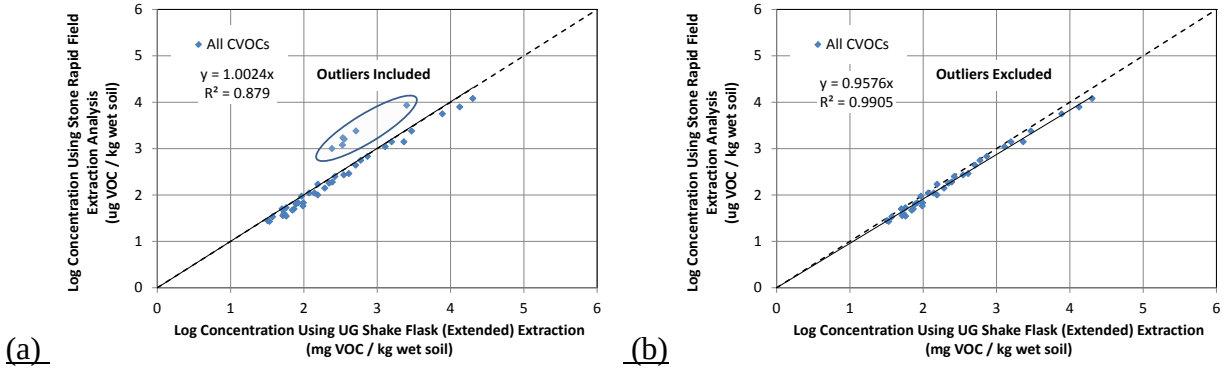


Figure 5.23. Comparison Between CVOC Concentration Data Collected with UG Method and Other Methods: Rapid Field Extraction. (a) all data; (b) outliers excluded. Y-axis represents samples analyzed at a commercial laboratory following rapid field extraction using methanol. UG method (x-axis) involved collection using UG metal coring device, immediate field preservation in methanol, followed by extended "shake flask" extraction and analysis at UG laboratory. Solid line represents the best-fit regression line; dashed line represents 1:1 line through the origin.

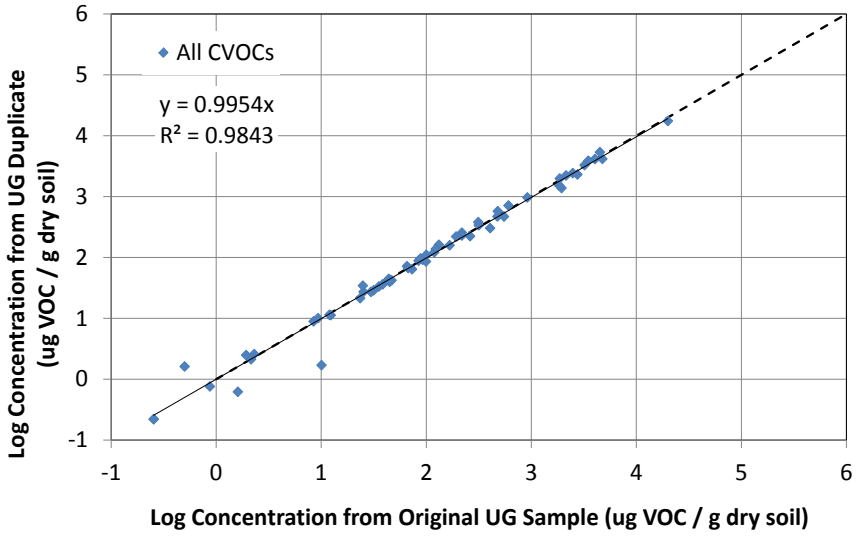


Figure 5.24. Comparison Between CVOC Concentration Data Collected with UG Method and Other Methods: Field Duplicates at Same Analytical Laboratory. Both datasets generated using UG method, which involved collection using UG metal coring device, immediate field preservation in methanol, followed by extended "shake flask" extraction and analysis at UG laboratory. Solid line represents the best-fit regression line; dashed line represents 1:1 line through the origin.

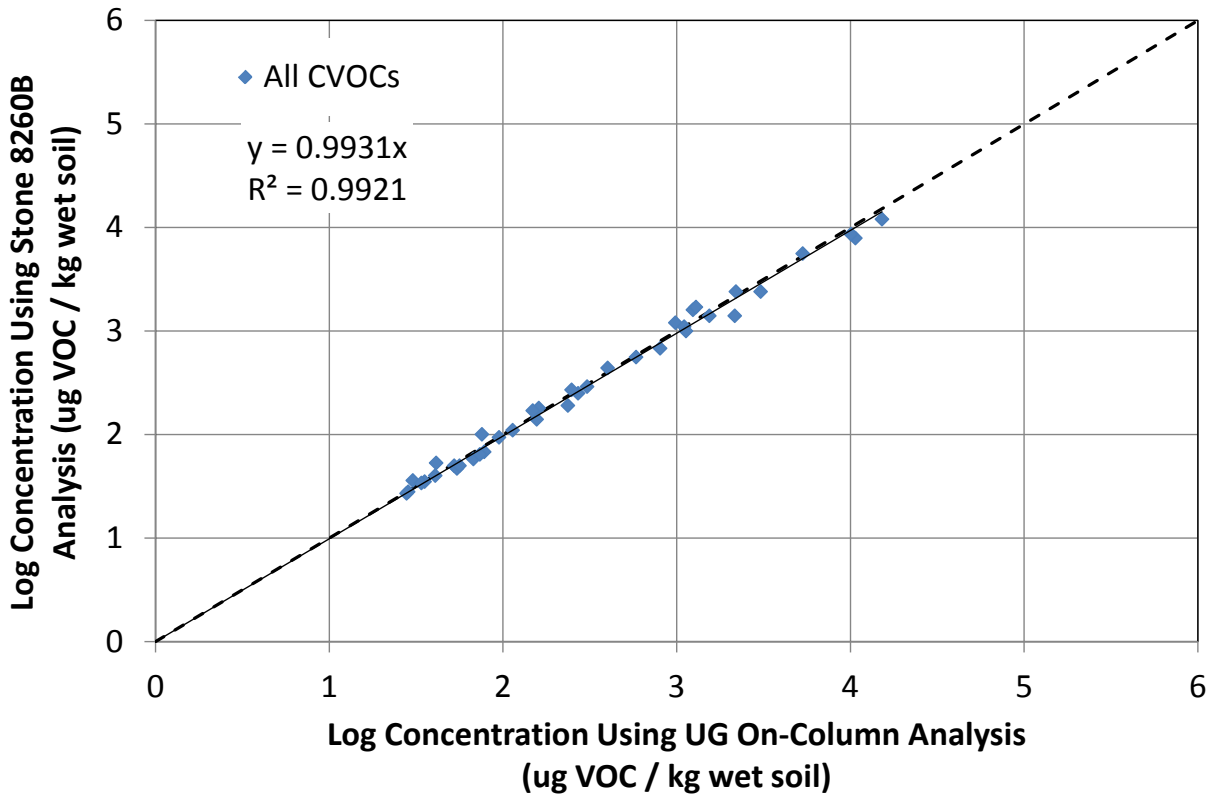


Figure 5.25. Comparison Between CVOC Concentration Data Collected with UG Method and Other Methods: Field Duplicates at Different Analytical Laboratories. Both datasets generated using similar methods involving sample collection using UG metal coring device and rapid field extraction in methanol. Analyses completed at either a commercial laboratory (y-axis) or UG laboratory (x-axis). Solid line represents the best-fit regression line; dashed line represents 1:1 line through the origin.

5.7 Modeling Results

The 1-D diffusion model was adapted and converted into a simple, Excel spreadsheet-based tool for estimating the source history at chlorinated solvent sites. This tool (named the ***ESTCP Source History Tool*** described in detail in the User's Manual included as **Appendix P** of this report) uses the soil CVOC concentration profile vs. depth within a low permeability soil layer to estimate the concentration vs. time in the overlying transmissive zone. The goal was to determine if the results from this simple modeling approach could reflect changes in source strength over time and space.

The basic approach for applying the software tool ("Toolkit") for this project is summarized below:

- The input data for the source history model, which include site specific concentration data and hydrogeologic parameters, were either measured directly or estimated based on site documentation. For parameters whose values encompassed a range (e.g., f_{oc}), the median value was typically used.
- Within each site, source histories were estimated at each location where soil cores were collected, and then these location-specific source histories were compared to assess whether the modeling results reflected effects of plume arrival (via downgradient advective transport over time). This approach was chosen over the alternative of constructing a 2-D model that would explicitly track advective transport. The primary motivation for this choice was avoiding an overly complicated software interface that would require additional input parameters and assumptions, and add additional uncertainty in the analysis.
- At each location, source histories were generated for each relevant parent compound (e.g., PCE and/or TCE, 1,1,1-TCA, 1,2-DCA) for the site.
- At relevant locations, a separate source history was estimated using the sum of the parent compound and any degradation products of that parent compound measured in the soil with the resulting source history expressed as the parent compound concentration. This second estimate incorporated the influence of degradation within the transmissive zone. The primary limitation of this approach is that diffusion within the lower permeability layer is modeled using a bulk diffusion coefficient (i.e., the model is unable to differentiate between the compound-specific diffusion coefficients when multiple compounds are present) and also neglects sorption differences between compounds.
- Degradation in the lower permeability zones was assumed to be low (half-life = 1000 years) based on the previously-described lines of evidence that supported this assumption. Note that for the scenarios tested as part of this project, the model output (i.e., source history estimates) were not particularly sensitive to this parameter, with little change observed once half-life values exceeded approximately 10 years.
- Vertical advection within the clay layer was assumed to be negligible in these modeling runs.
- The modeling runs were constrained slightly by user knowledge of site conditions regarding, such as periods of operation.

- Modeling runs were considered complete when a reasonable fit between the simulated and measured soil CVOC concentration data profiles were obtained. Minimization of the root mean square (RMS) error between these two datasets was used as the optimization metric. Note that the RMS error is a useful metric for optimizing at an individual location, but it is not suitable for comparing simulations obtained at different locations.

As described in the subsequent sections, source history modeling was completed using soil core data from the two distinct source areas at NAS Jacksonville OU3. In addition, a literature review was completed to identify several additional soil concentration profiles in low permeability zones to use for source history modeling.

5.7.1 Former Building 106 Source Area

Source histories were generated for both PCE separately and PCE plus its degradation products at four distinct coring locations (plus the duplicate core collected at location OU3-5). A summary of the input and output values for each location are presented in **Table 5.6a**. The location-specific results are also presented as **Figure 5.26** through **Figure 5.29,** and summarized in **Table 5.7**. Complete results are included in **Appendix Q**.

The modeling demonstrated that the locations at the Building 106 source area were characterized by relatively constant source histories, i.e., source loading that changed gradually over time. These source histories resulted from generally strong fits between simulated and measured soil concentration data based on visual inspection (**Figure 5.30**). These soil profiles exhibited decreasing concentration with depth into the low K zone, which is a distinguishing characteristic of continued loading over these low k zones by a source strength at the interface that remains high relative to historical values. This constant source history trend held regardless of whether the parent compound (PCE) or parent compound plus degradation products were modeled.

It is important to highlight that the location-specific starting dates for contaminant loading (i.e., time zero for the source history estimate) matched expectations regarding plume arrival. As summarized in **Figure 5.31**, the date of arrival increased moving downgradient, from 1962 at the near source location OU3-3 to 1992 at the far downgradient location OU3-6. The date for OU3-3 (1962) coincides with the start of the presumed DNAPL release period based on the dry cleaning operations at the site (1962-1990). OU3-3 is located just outside of the footprint of the former dry cleaner building, so it is possible that downgradient transport from a more localized release point a short distance upgradient from OU3-3 occurred. However, the results are consistent with a release (or releases) occurring sometime around the beginning of operations. The estimated concentration of PCE is high (71 mg/L) relative to the compound's aqueous solubility (150 to 200 mg/L), suggesting that non-aqueous phase liquid was released and has persisted such that high concentrations at the interface have been maintained at this location.

Plume arrival at OU3-4 (1971), OU3-5 (1976), and OU3-6 (1992) are consistent with the distances and estimated groundwater travel times for these downgradient locations. For example, OU3-4 is approximately 75 ft downgradient of OU3-3, such that the approximately 9 year travel time would be consistent with a contaminant travel velocity of approximately 8 ft/yr.

Assuming that the relevant retardation factor for contaminant transport is between 1.2 and 2.1, the resulting velocity range (10 – 18 ft/yr) is consistent with reported estimates of the groundwater seepage velocity within the shallow portion of the aquifer (2 – 70 ft/yr). The estimated arrival time at the two farther downgradient locations is shorter and more indicative of higher groundwater/contaminant velocities. For example, OU3-6 is approximately 430 ft downgradient of OU3-3, such that the estimated 30 year gap in the plume arrival time (i.e., 1962 to 1992) suggests a groundwater velocity of 17 - 30 ft/yr using the same range of retardation factors. However, the increased formation of cis-1,2-DCE (a less retarded compound than the parent PCE) at downgradient locations is consistent with higher contaminant velocities moving farther away from the source.

Relatively similar source history estimates were obtained using the two duplicate cores at location OU3-5 (**Figure 5.28a**, **Figure 5.29b**). A particularly strong match was obtained when PCE plus its degradation products were modeled, where the resulting initial concentration differed only slightly (30 mg/L vs. 32 mg/L).

As noted above, a constant source history trend was observed at each location for cases using the parent compound only as well as cases when parent compound plus degradation products were modeled. This is consistent with the assumption that the majority of degradation activity is occurring in the transmissive zones as opposed to in the low permeability zones. The soil concentration profiles for all metabolites decrease moving deeper into the low permeability zones. Had degradation in the low permeability zones been occurring to a significant degree, then it would have been difficult to obtain similar source histories with the parent compound alone vs. the parent compound plus its degradation products.

Instead, the source history patterns clearly show the impact of degradation moving downgradient from the source area (**Figure 5.31**). This is supported by the higher initial PCE concentration that was estimated at OU3-3 (71 mg/L total) relative to OU3-4 (43 mg/L), OU3-5 (23 mg/L), and OU3-6 (3 mg/L). This is the result of contaminant degradation as it is transported downgradient, causing stronger decline in PCE concentrations than would be expected from physical processes (e.g. dispersion) only, as evidenced by the decreasing percentage of mass represented by the parent compound. The pattern is consistent with the increased contribution of degradation products to the total CVOC concentration moving away from the source. **Collectively, these results suggest that while an appreciable decline in the source strength cannot be verified, significant attenuation along the plume flowpath has occurred. Consequently, monitored natural attenuation may not an appropriate site remedy if source control is a requirement, but attenuation processes are clearly helping to maintain plume stability and reduce risk.**

As a further evaluation of the representativeness of the source history estimates, a comparison was made to the available historical data from the site. Several monitoring locations in the area—primarily temporary piezometers—were sampled regularly during a several-year long period in early 2000s when interim remedial measures were being implemented. Three of these locations are within 20 ft or less of locations that were characterized as part of this project and screened in the aquifer above the interface with the clay layer (**Figure 5.32**). The predicted groundwater concentrations from these locations (i.e., the source history estimates) were then

compared to the actual historical records. As shown in **Figure 5.32**, there was a reasonable level of consistency between the predicted and actual datasets. The source history modeling indicated that the source loading (groundwater concentration) was constant at each location. The actual groundwater data exhibit some fluctuation but demonstrated no clear temporal trends, and the median concentration values were within a factor of 2 of the (constant) values predicted from source history modeling at all locations (**Table 5.8**). The finding that the piezometer-based monitoring data are slightly lower than the predicted values may reflect the fact that piezometers were screened above the interface with the clay layer (typically from 9 to 14 ft bgs). Note that there were a few other locations that were also monitored during this same time period, but these were too far from the locations characterized as part of this project to use as a basis for comparison. However, the data from two of these locations (MW-028 and PZ-1063) are included in **Figure 5.32** to illustrate how concentrations within the source zone decreased moving perpendicular to groundwater flow.

Table 5.8. Comparison of Actual and Predicted Groundwater Concentrations in the Former Building 106 Source Area

Location (Temporary Piezometer)	**Groundwater Concentration**	
	Actual (median over entire monitoring period)	**Predicted** (from nearest source history estimate)
PZ-1062	43 mg/L	71 mg/L
PZ-1066	29 mg/L	43 mg/L
PZ-1068	28 mg/L	32 mg/L

Notes: (1) Concentration is sum of constituents that were included in both datasets (PCE, TCE and cDCE); (2) Source history estimates from OU3-3, OU3-4, and OU3-5 were used to compare to data from PZ-1062, PZ-1066, and PZ-1068, respectively (see Figure 5.31); (3) Monitoring period was 2000-2004; (4) Source history modeling predicted constant source concentrations over time.

5.7.2 Building 780 Source Area

Source histories were generated for TCE, TCE plus its degradation products at three distinct coring locations. At the near source location (OU3-9) source histories were also completed for 1,2-DCA as well as 1,1,1-TCA and its degradation products. A summary of the input and output values for each location are presented in **Table 5.6b**. The location-specific results are also presented as **Figure 5.33** through **Figure 5.35,** and summarized in **Table 5.7**.

The modeling demonstrated that the locations at the Building 780 source area were characterized by declining source histories for TCE, i.e., source loading that changed gradually over time. At the near source location, OU3-9, a declining source history was also observed for 1,2-DCA, while a relatively constant source history was observed for 1,1-DCA. No 1,1,1-TCA (the parent compound for 1,1-DCA) was observed at OU3-9. Further, none of the chlorinated ethanes (1,1,1-TCA, 1,1-DCA, or 1,2-DCA) were observed at the other coring locations at this source area. Reasonable fits between simulated and measured soil concentration data were obtained at all locations, though there was a generally higher level of uncertainty when compared to the source history estimates from the other source area. In part, this is because of the greater extent of

heterogeneity at this site, as well as a more uneven spatial distribution of contaminants across the site.

With the exception of 1,1-DCA at OU3-9, soil profiles generally exhibited a maximum concentration at some distance (between 1 to 4 ft) into the low K clay unit, with lower concentrations measured near the interface (**Figure 5.36**). This pattern is a distinguishing characteristic of a declining source strength over time, such that concentrations near the near the low K interface have declined, changing the concentration gradient and causing diffusion out of the low K zone, with higher remnant concentrations occurring deeper into the low K zone and lower concentrations at the interface.. Note that at each location, these source history trends held regardless of whether the parent compound or parent compound plus degradation products were modeled.

For TCE, the starting dates for contaminant loading at each location (i.e., time zero for the source history estimate) were again consistent with expectations regarding plume arrival. As summarized in **Figure 5.37**, the date of arrival increased moving downgradient, from 1971 at the near source location OU3-9 to 1976 at the far downgradient location OU3-11. The date for OU3-9 (1971) falls at the beginning of the presumed release period based on the solvent use at this site (1970's through 1980's). OU3-9 is located at the upgradient (southwest) corner of Building 780 in an area where the highest concentrations were present based on previous investigations, thus it is within the suspected source area and time for transport from the actual release point is assumed to be negligible.

The arrival of the TCE plume at OU3-10 (1973) and OU3-11(1976) are consistent with the distances and groundwater travel times for these downgradient locations, though suggestive of relatively high groundwater/contaminant velocities. For example, OU3-10 is approximately 120 ft downgradient of OU3-9, such that the approximately 3 year travel time would be consistent with a contaminant travel velocity of approximately 40 ft/yr. Given the relevant range of retardation factors for contaminant transport (1.2 to 2.1), this would correspond to a groundwater velocity range (48 – 84 ft/yr), which is at the high end of the range of groundwater seepage velocities reported for the shallow aquifer (2 – 70 ft/yr). The estimated time between plume arrival at the farthest downgradient location (OU3-11) from OU3-9 is consistent with a slightly lower range of groundwater velocities (22 – 38 ft/yr). Again, it is important to note that the exact release point(s) at this source area are unknown, such that there is some uncertainty in these travel time estimates. All three locations that were characterized were relatively close to the building, such that releases from other building locations can complicate the interpretation of contaminant flowpaths. For example, the source history estimates are also consistent with a scenario where OU9-10 is more-or-less adjacent to the source. Regardless, the estimated velocity ranges appear to be consistent with known site characteristics.

As noted above, a declining source history trend was observed for TCE at each location when the parent compound was modeled, as well as the case when parent compound plus degradation products were modeled. This pattern is consistent with attenuation of the TCE source over time and reflects the impact of a likely transition from TCE to 1,1,1-TCA (i.e., as the primary chlorinated solvent used at the site) as well as degradation. Also, the soil concentration profiles

for cis-1,2-DCE were similar to that for TCE; both exhibited a maximum concentrations at similar depths within the low permeability zones at the three Building 780 locations. This is consistent with the assumption that the majority of degradation activity is occurring in the transmissive zones as opposed to in the low permeability zones. Had degradation in the low permeability zones been occurring to a significant degree, then it would have been difficult to obtain similar source histories with the parent compound alone vs. the parent compound plus its degradation products.

Along the presumed flowpath, the source history patterns for chlorinated ethenes suggest that degradation rates are higher at the source location (OU3-9) than at downgradient locations. For example, the concentrations of total chlorinated ethene concentration were very similar at both OU3-9 and OU3-10, but the relative contribution of cis-1,2-DCE was much higher at the upgradient (near source) location. These data are consistent with a decline in source strength at OU3-9 that has resulted from significant attenuation at this location. While the source history estimates at OU3-10 also support a declining trend at this location, the lower percentage of cis-1,2-DCE suggests that impact of degradation processes may have been less pronounced at this location. There is less evidence for increased degradation of contaminant mass as it is transported downgradient, with the possible exception of cis-1,2-DCE moving dowgradient from OU3-9 to OU3-10.

Location OU3-11 appeared to be a more unique case. The highest contaminant concentrations were encountered within a more transmissive layer located between two low permeability intervals. This could have resulted from penetration through the upper clay layer, which appeared to be thinner in this area. Consequently, source history modeling was performed on only the deeper clay layer to ensure that diffusion from one direction (downward) was being modeled. The concentrations in this deeper clay layer, as well as the shallower units at this location, were much lower than those at the upgradient locations, which may reflect attenuation (either declining source strength or degradation along the flowpath), although TCE remained the dominant CVOC at this location.

For 1,1,-DCA, the soil concentration profiles and resulting source history estimates supported a later starting date for contaminant loading. At OU3-9, this date was estimated to be 1988, which may reflect a shift from the use of TCE to 1,1,1-TCA as the latter become a more popular solvent nationwide during the 1980's. However, no 1,1,1-TCA was detected at this location.

For 1,2-DCA, a starting date of 1971 was supported based on the modeled source history. There is no record of this compound being used at the site and no evidence of widespread detections during previous investigations, which complicates the interpretation of the results.

Unlike TCE, appreciable levels of other suspected parent compounds 1,2-DCA and 1,1,1-TCA were not detected at the two downgradient coring locations. For both parent compounds, this lack of downgradient transport is consistent with other patterns related to attenuation seen at the source location (OU3-9). In the case of 1,2-DCA, a declining source history trend was supported by the soil data. This means that the source itself is being attenuated and contributing lower levels of contaminant mass over time that would be subject to downgradient transport. In the

case of 1,1, -DCA, the source history estimate suggested that the "source" strength at OU3-9 has remained relatively constant over time. As noted above, 1,1,1-TCA is no longer detectable at this source location, with the majority apparently degraded to 1,1-DCA. Therefore, the results from this location only provide information on the temporal history of 1,1-DCA as the source. This pattern would suggest that 1,1,1-TCA attenuation is occurring in the areas upgradient of OU3-9, but ultimately contributes to a constant 1,1-DCA loading at OU3-9.

Based on the relatively negligible concentrations of 1,1-DCA (a degradation product of 1,1,1-TCA) and chloroethane (a degradation product of both 1,1,1-TCA and 1,2-DCA) at OU3-10, significant degradation appears to have occurred along the flowpath (Note that the dechlorination of 1,2-DCA to ethene via an alternate pathway was not considered due to the lack of soil ethene data). Historical information available from previous site investigations does suggest that the spatial distribution of chlorinated ethane impacts are not uniform and hot spots may be relatively localized. This is consistent with data from this project that show no 1,1,1-TCA present and 1,2-DCA and 1,1-DCA present at only one location.

Of interest is that both TCE and 1,2-DCA exhibited declining source histories that appeared to reflect the effects of interim remedial measures at this source area. Specifically, some excavation of contaminants occurred as part of the initial site investigations in about 1990, or about 21 years prior to the date when cores were collected for this project. Later, soil vapor extraction and groundwater pump-and-treat systems were operating in this area starting in 1998 and extending through 2005. In each of the source history estimates for these compounds, a sharper "step" decline was noted starting between 1983 to 1996, with the later dates associated with farther downgradient locations. As a result, the source strength leveled off, generally at low levels (relative to those observed historically). There was no evidence of substantial concentration rebound. 1,1,-DCA did not reflect the influence of remediation, though it is important to note the source history for this compound provides little information about the parent compound 1,1,1-TCA (since 1,1,1-TCA was not detected in the soil samples).

The expected impact of these remedial efforts on source strength could vary depending on site characteristics. For excavation and soil vapor extraction, there is little indication from the soil concentration profiles that this was a vadose zone source, though the low concentrations within the shallower soil could also reflect vadose zone mass removal. Groundwater extraction could have removed significant mass assuming that the extraction wells were placed near source locations. The lack of evidence for rebound following suspension of remedial operations suggests that it was causing source reduction. Note that the lack of groundwater monitoring wells at this site greatly impacts ability to assess the impacts of these remedial measures, as well as the validity of the source history estimates.

Collectively, the results obtained at this source area suggest that significant source strength attenuation has occurred over time for TCE and 1,2-DCA. Potential contributing factors to this decline are active degradation process (particularly at the upgradient location) and interim remedial measures that were implemented at this site. 1,1,-DCA did not show a similar decline in source strength, but the lack of detection of the parent compound (1,1,1-TCA), combined with the lack of detection of any chlorinated ethanes at downgradient

locations, confirm that significant chlorinated ethane attenuation is occurring. Consequently, monitored natural attenuation may be an appropriate for remedy for this site because the source history estimates provide evidence that these attenuation processes are controlling the source(s).

Table 5.6.(a) Summary of Source History Modeling Input and Output Parameter Values for Former Building 106 Source Area

Parameter	Units	LOCATION									
		OU-3		OU3-4		OU3-5		OU3-5 (Duplicate)		OU3-6	
		PCE	PCE + Degradation Products	PCE	PCE + Degradation Products	PCE	PCE + Degradation Products	PCE	PCE + Degradation Products	PCE	PCE + Degradation Products
Top of low k zone	ft bgs	16	16	16.5	16.5	15	15	15	15	15.5	15.5
Thickness of low k zone	ft	6.3	6.5	6.5	6.5	9.9	9.9	9.9	9.9	9.4	9.4
Low k zone description	-	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Porosity	v/v	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Transport type	-	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only
Diffusion coefficient	m^2/sec	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10	8.2E-10
Apparent Tortuosity Factor Exponent		1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
Bulk density	L/kg	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
f_{oc}	-	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
R[1]	-	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Half-life[2]	yr	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
t_1 (year of core collection)	Date	2011	2011	2011	2011	2011	2011	2011	2011	2011	2011
t_0 (year of contaminant arrival)	Date	1962	1962	1971	1971	1976	1976	1976	1976	1992	1990
Initial GW concentration[3]	mg/L	71	78	43	50	23	32	18	30	3.1	13
Source History Style	-	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**	**Constant**

Notes: (1) Calculated retardation factor for parent compound; (2) Half-life for parent compound in low k zone; (3) Groundwater concentration in transmissive zone adjacent to low k zone at t_o.

Table 5.6. (b) Summary of Source History Modeling Input and Output Parameter Values for Building 780 Source Area

Parameter	Units	LOCATION						
		OU3-9				OU3-10		OU3-11
		TCE	TCE + Degradation Products	1,1,1-TCA + Degradation Products[4]	1,2-DCA	TCE	TCE + Degradation Products	TCE + Degradation Products
Top of low k zone	ft bgs	19.2	19.2	19.2	19.2	20	20	29
Thickness of low k zone	ft	5.9	5.9	5.9	5.9	9.0	9.0	5.5
Low k zone description	-	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Porosity	v/v	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Transport type	-	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only	Diffusion only
Diffusion coefficient	m^2/sec	9.1E-10	1.1E-09 (for cis-DCE)	1.05E-09	9.9E-10	9.1E-10	9.1E-10	1.1E-977
Apparent Tortuosity Factor Exponent		1	1	1	1	1	1	1
Bulk density	L/kg	1.5	1.5	1.5	1.5	1.5	1.5	1.5
f_{oc}	-	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
R[1]	-	1.7	1.7	1.2	1.1	1.7	1.7	1.7
Half-life[2]	yr	1000	1000	1000	1000	1000	1000	1000
t_1 (year of core collection)	Date	2011	2011	2011	2011	2011	2011	2011
t_0 (year of contaminant arrival)	Date	1971	1971	1992	1971	1973	1973	1976
Initial GW concentration[3]	mg/L	30	160	0.9	34	50	50	1.4
Source History Style	-	**Decreasing (Step/ Exponential)**	**Decreasing (Step/ Exponential)**	**Constant**	**Decreasing (Exponential)**	**Decreasing (Step/ Exponential)**	**Decreasing (Step/ Exponential)**	**Decreasing (Exponential)**

Notes: (1) Calculated retardation factor for parent compound; (2) Half-life for parent compound in low k zone; (3) Groundwater concentration in transmissive zone adjacent to low k zone at t_o.; (4) No source history for estimated for 1,1,1-TCA alone because the compound was no longer detected at OU3-9.

Table 5.7. Summary of Source History Trends for Former Building 106 and Building 780 Source Areas

Location	Compound(s)	Trend/Style of Source History	Median RPD (non-directional)	RMS Error (mg/L)	Ratio of RMS Error to Max Measured Concentration
Former Building 106 Source Area					
OU3-3	PCE	Constant	12%	2.9	5.3%
	PCE + Degradation Products	Constant	21%	2.3	4.7%
OU3-4	PCE	Constant	39%	7.5	19%
	PCE + Degradation Products	Constant	34%	7.9	17%
OU3-5	PCE	Constant	97%	1.2	5.3%
	PCE + Degradation Products	Constant	44%	1.7	5.5%
OU3-5-Duplicate	PCE	Constant	170%	3.2	18%
	PCE + Degradation Products	Constant	123%	1.9	6.5%
OU3-6	PCE	Constant	200%	0.45	14%
	PCE + Degradation Products	Constant	200%	0.68	5.1%
Building 780 Source Area					
OU3-9	TCE	Decreasing (Step/Exponential)	20%	1.27	30%
	TCE + Degradation Products	Decreasing (Step/Exponential)	7%	5.49	20%
	1,1,1-TCA + Degradation Products	Constant (for 1,1-DCA)	33%	0.075	8.3%
	1,2-DCA	Decreasing (Exponential)	15%	0.99	23%
OU3-10	TCE	Decreasing (Step/Exponential)	86%	3.25	30%
	TCE + Degradation Products	Decreasing (Step/Exponential)	28%	3.5	28%
OU3-11	TCE + Degradation Products	Decreasing (Exponential)	21%	0.036	16%

Notes: (1) For cases where degradation products were included, the concentration of each degradation product was converted to equivalent parent compound concentration on a molar basis; (2) RMS error = relative means square error; (3) Max measured concentration is the maximum measured soil concentration after converting to equivalent porewater concentration (mg/L).

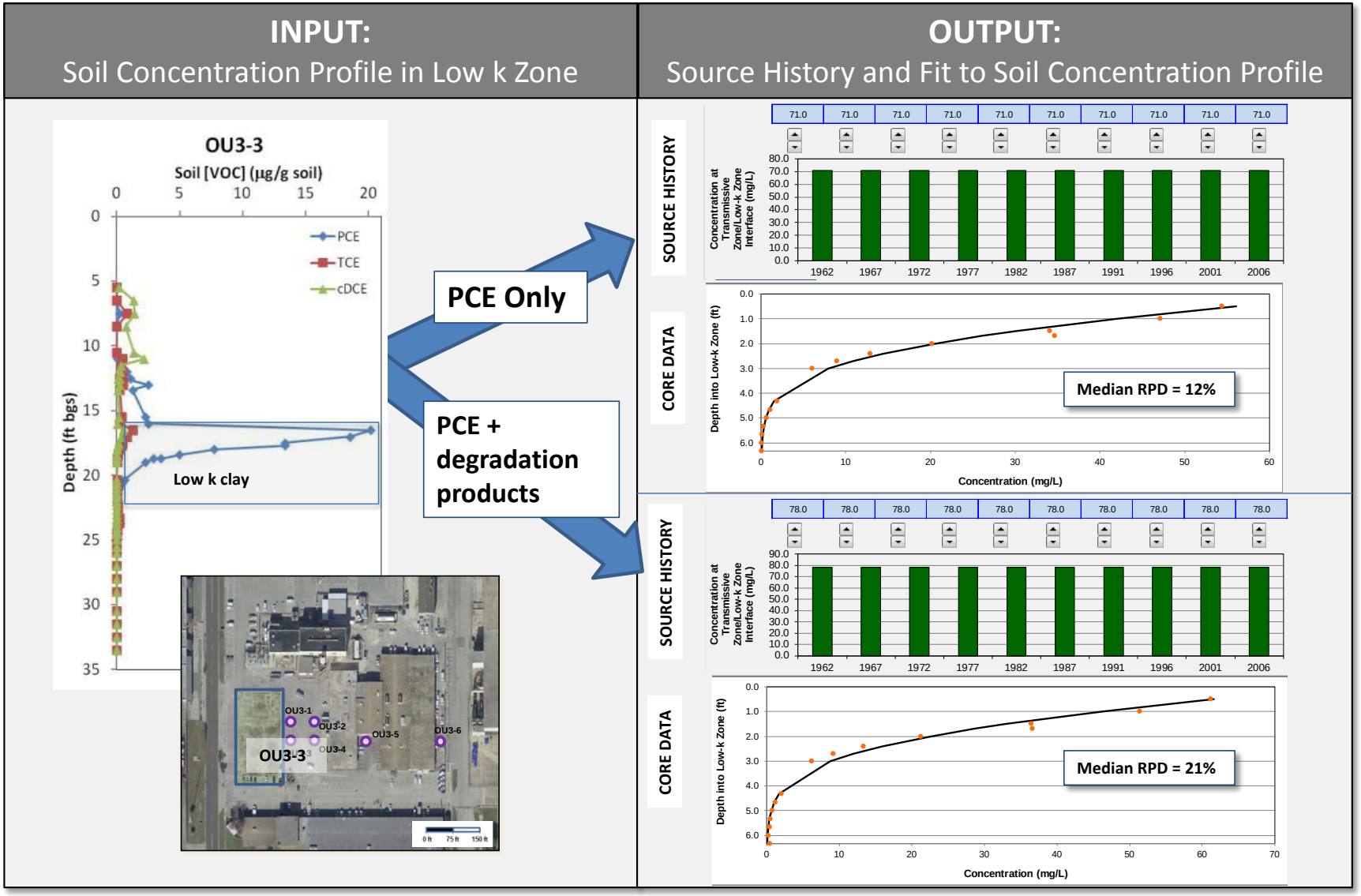


Figure 5.26. Source History Modeling Results for Location OU3-3 at Former Building 106 Source Area: Chlorinated Ethenes.

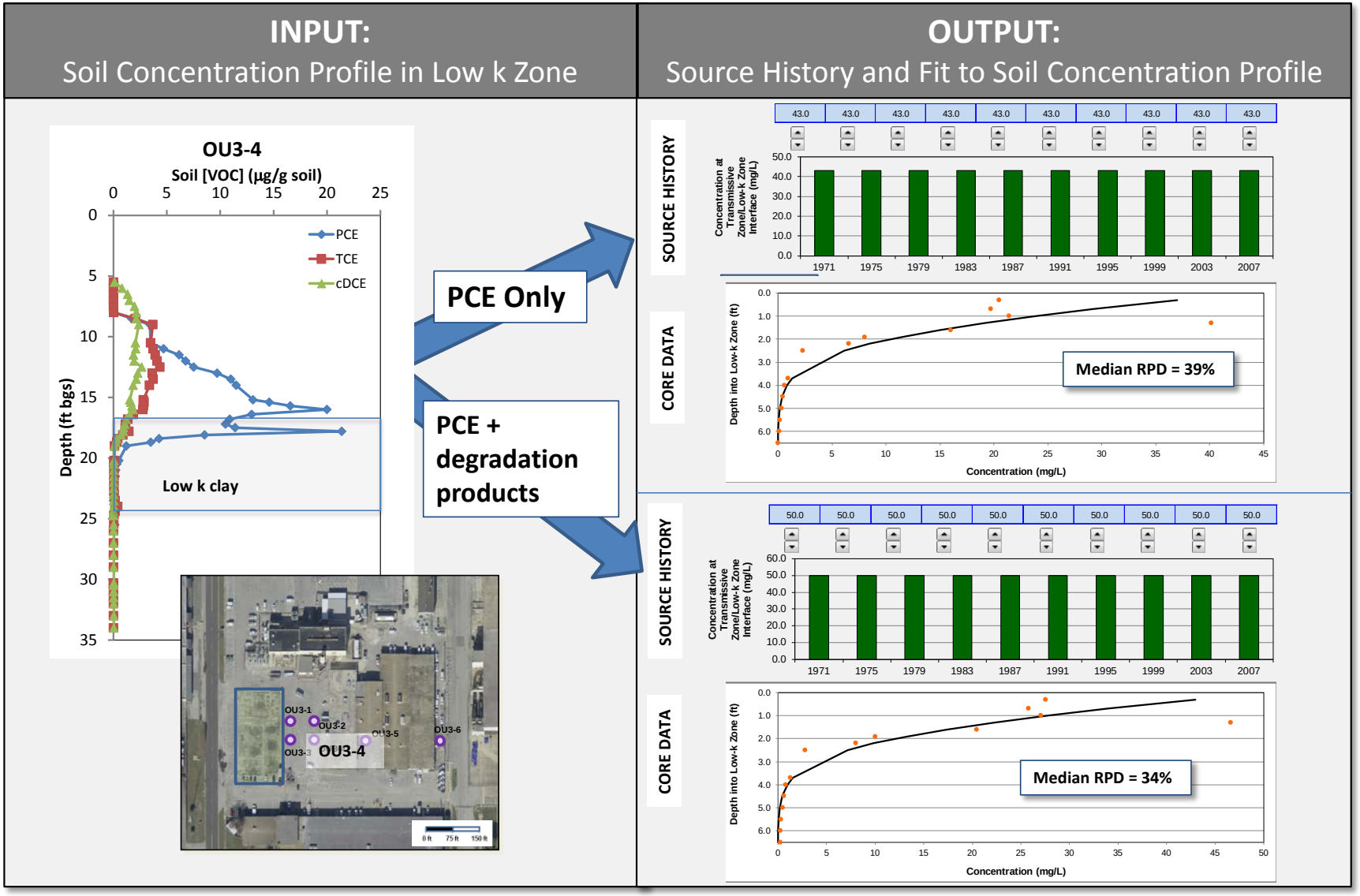


Figure 5.27. Source History Modeling Results for Location OU3-4 at Former Building 106 Source Area: Chlorinated Ethenes.

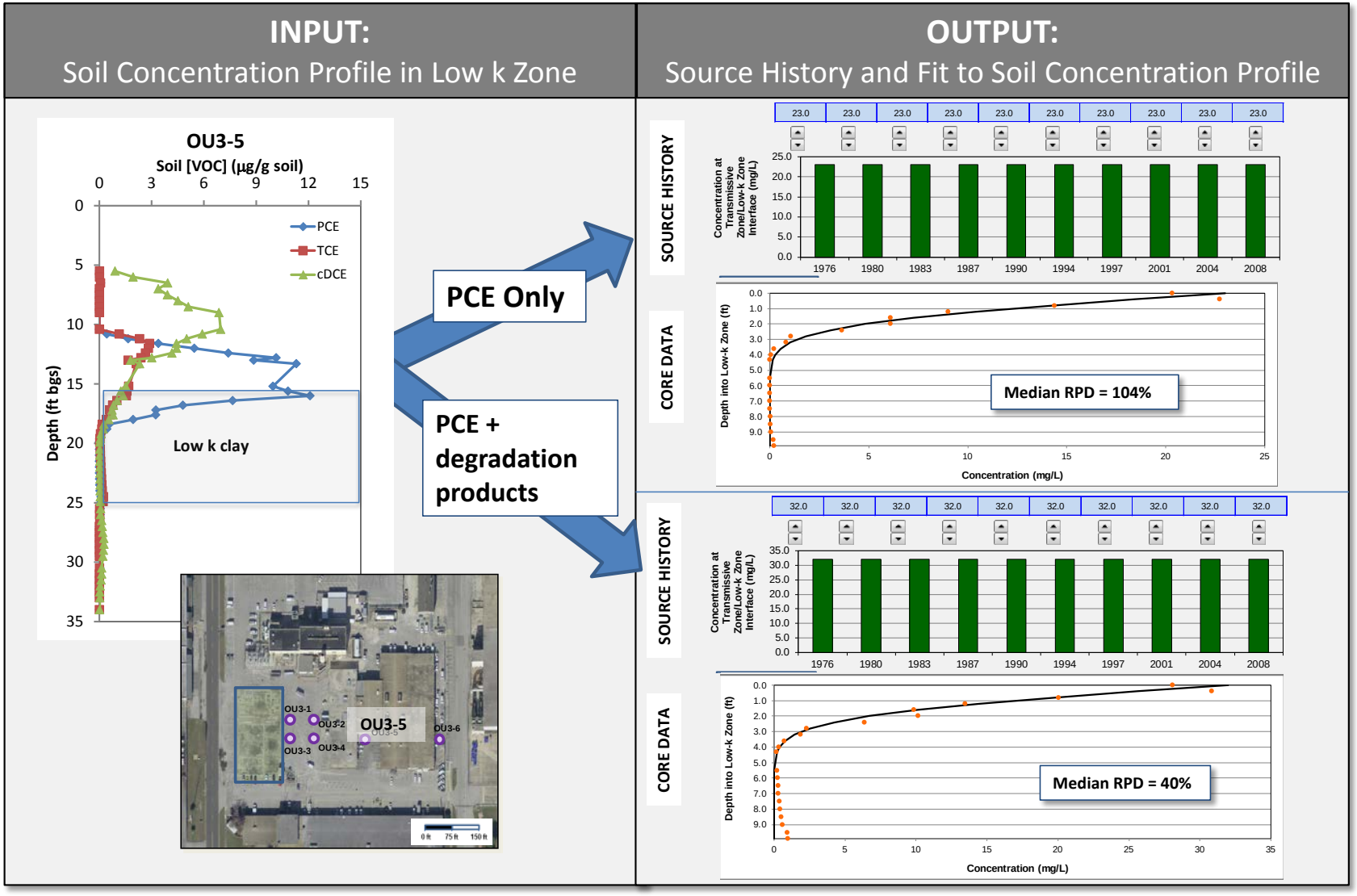


Figure 5.28a. Source History Modeling Results for Location OU3-5 at Former Building 106 Source Area: Chlorinated Ethenes.

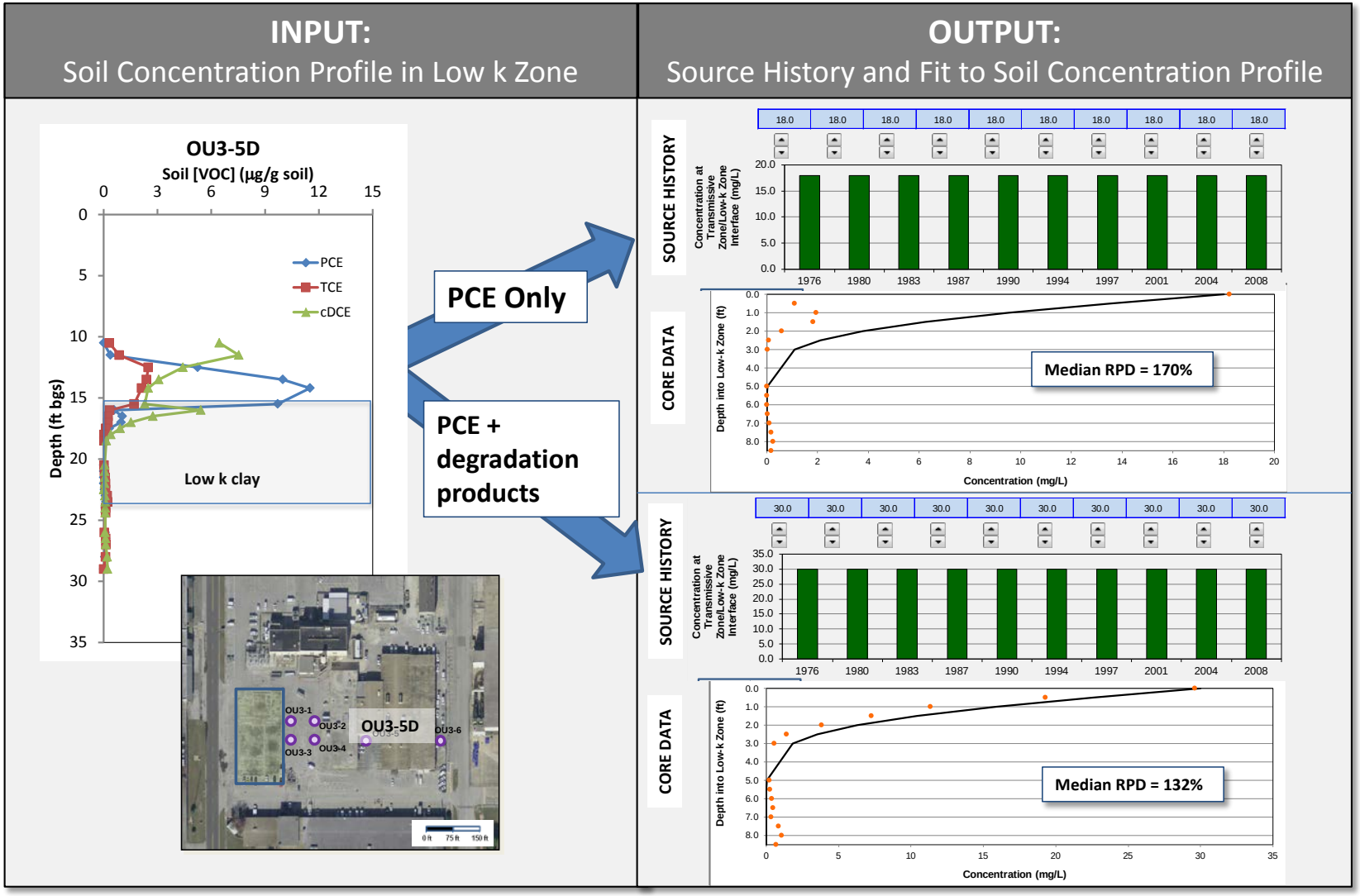


Figure 5.28b. Source History Modeling Results for Location OU3-5D at Former Building 106 Source Area: Chlorinated Ethenes. Data are from a duplicate core collected approximately 1 m from the coring location for OU3-5 (see Figure 5.28a).

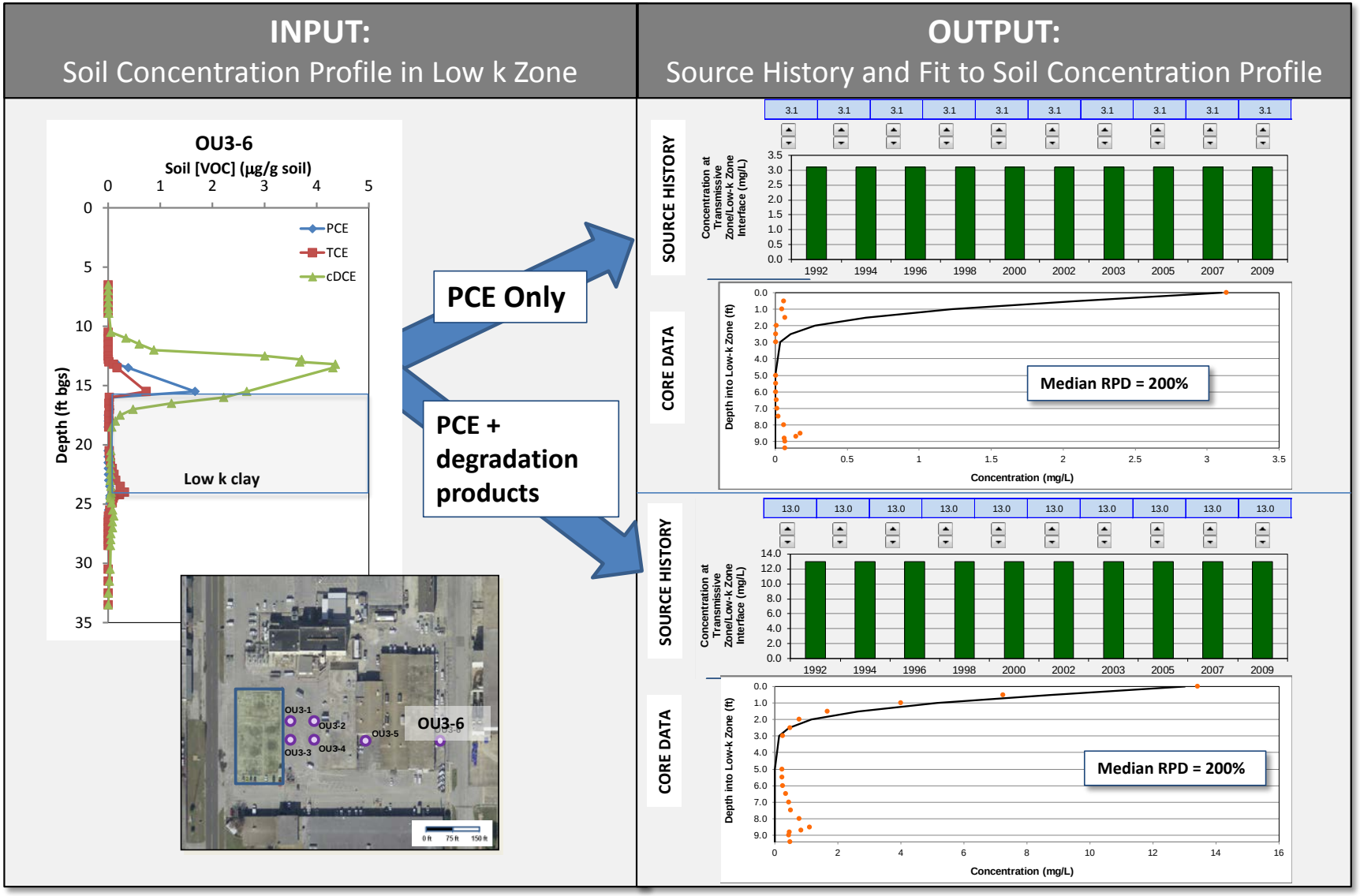


Figure 5.29. Source History Modeling Results for Location OU3-6 at Former Building 106 Source Area: Chlorinated Ethenes.

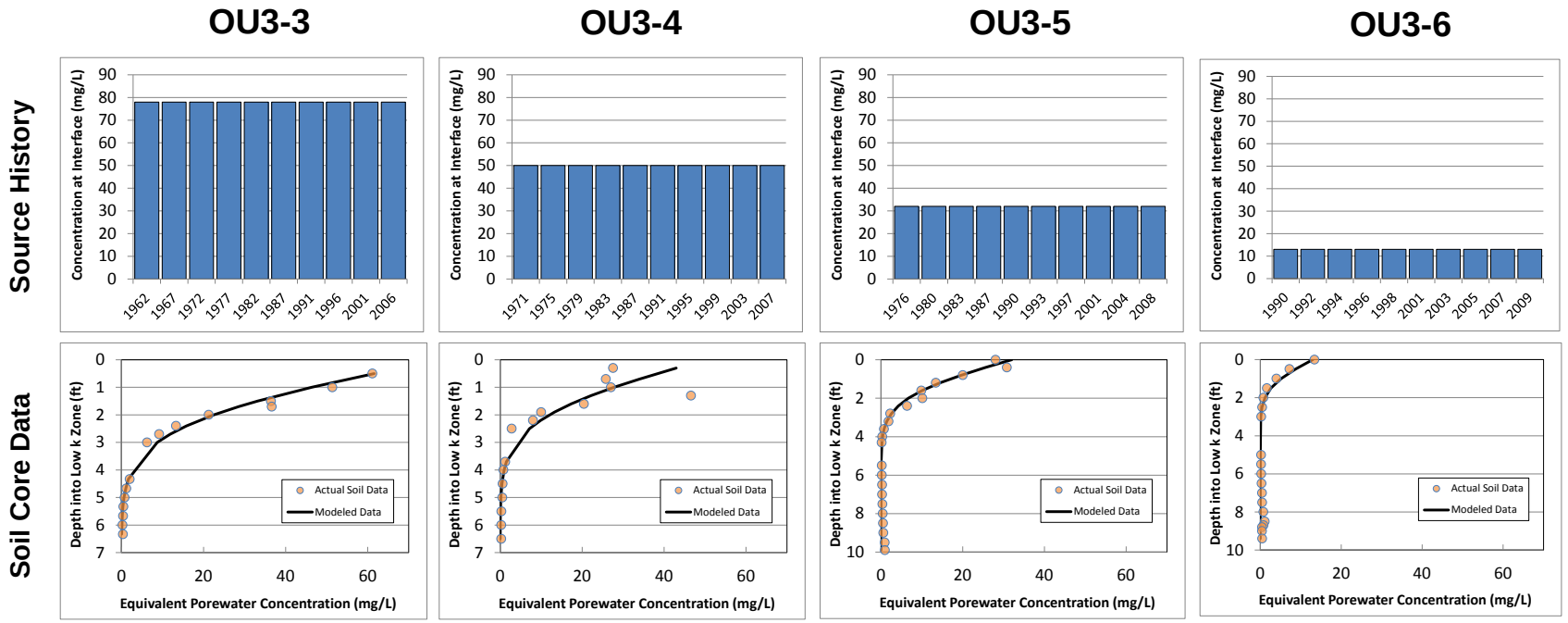


Figure 5.30. Low-k Soil Core Data and Source History Modeling Results at Former Building 106 Source Area. Concentrations reflect total chlorinated ethenes in the low-k zone (soil data) and transmissive zone (source history)

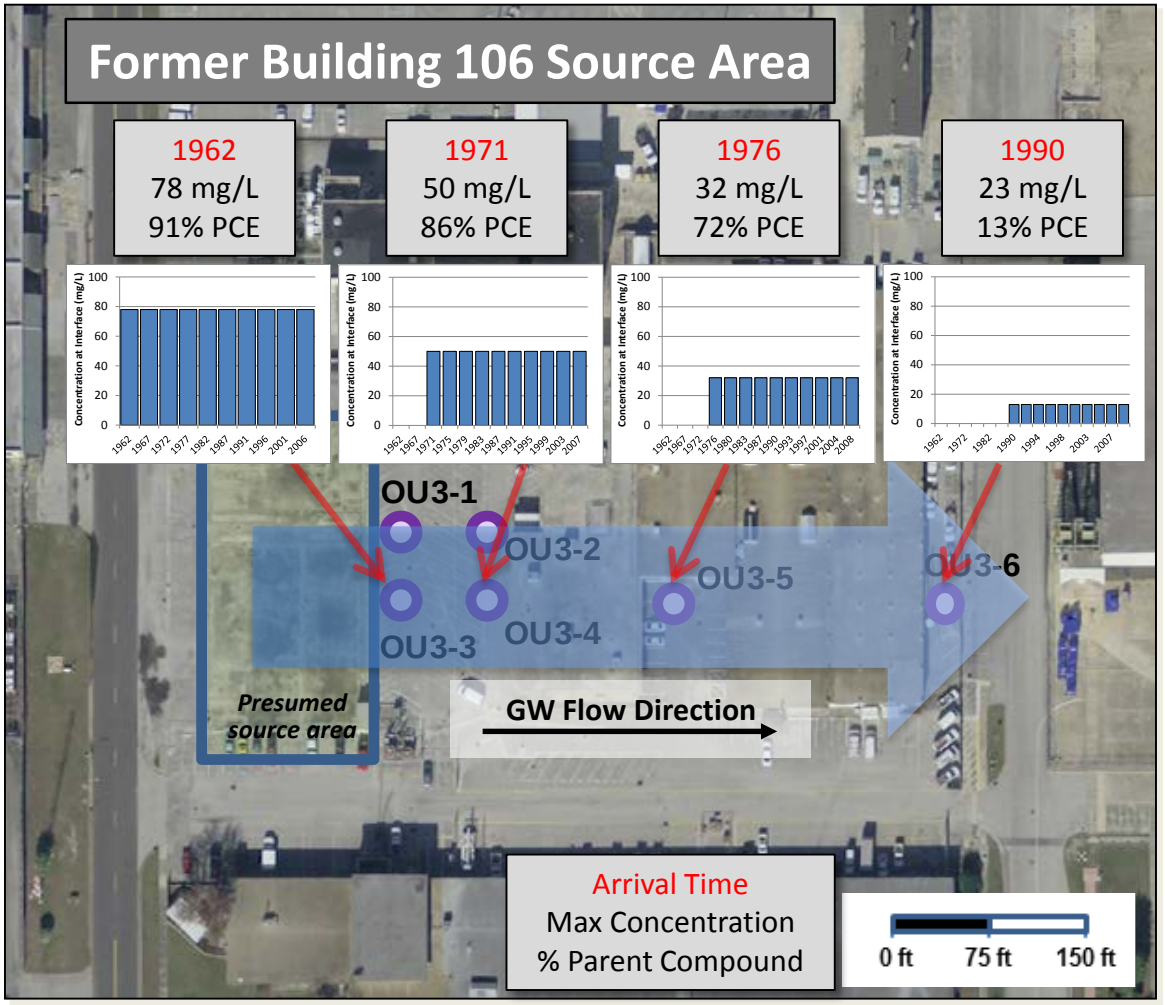


Figure 5.31. Overview of Source History Modeling Results at Former Building 106 Source Area. Dates reflect plumes arrival, concentrations reflect total chlorinated ethenes in the transmissive zone, and percentages reflect contribution of parent compound (PCE) to total chlorinated ethene concentration.

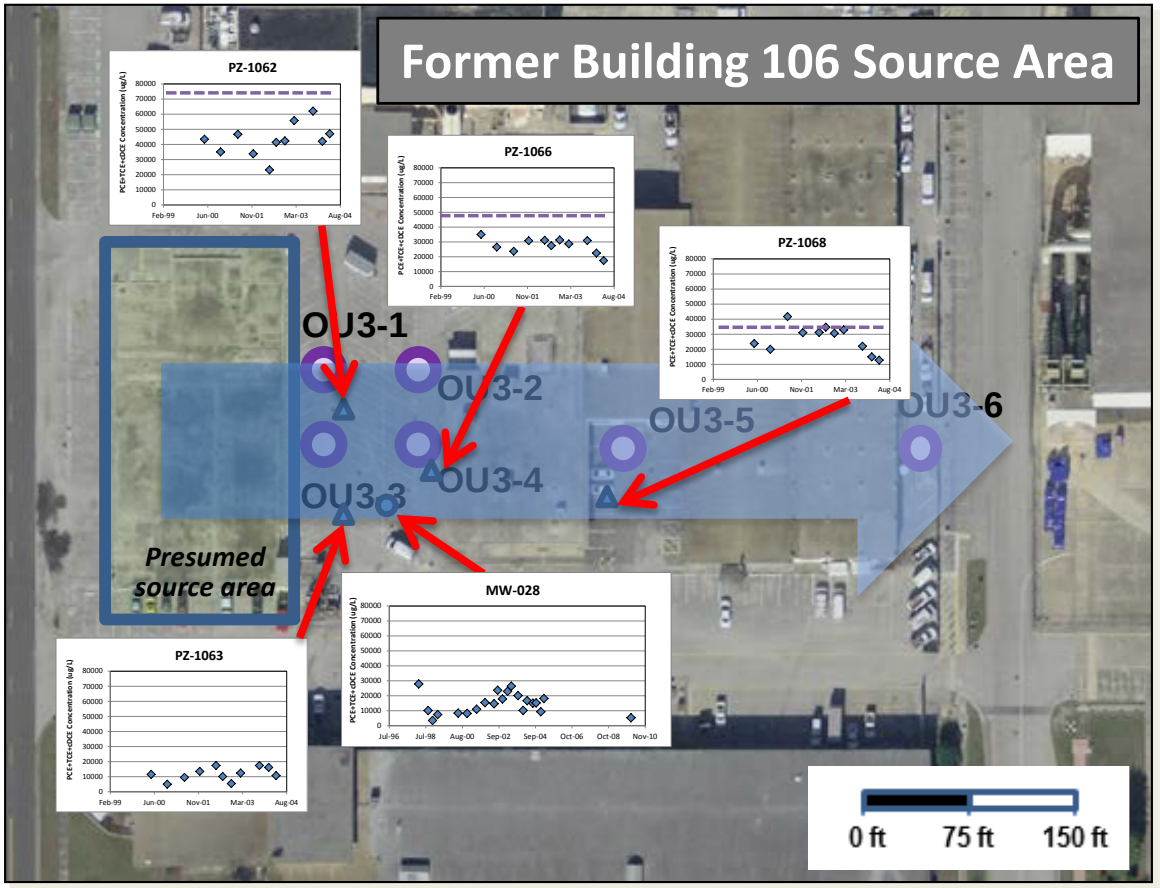


Figure 5.32. Comparison of Source History Modeling Results at Former Building 106 Source Area Relative to Historic Data. Plots show historic concentration record from monitoring points in the area, primarily temporary piezometers that were monitored during the 2000 to 2004 as part of interim remedial measures. The dashed purple lines overlaid on the plots show the predicted groundwater concentrations based on the nearest source history estimates generated as part of this project. Data for PZ-1063 and MW-028 are included to illustrate that concentrations were generally moving perpendicular to the direction of groundwater flow; source history estimates were not overlaid on the plots for these locations because they are at least 30 ft from the nearest location where a source history estimate was generated.

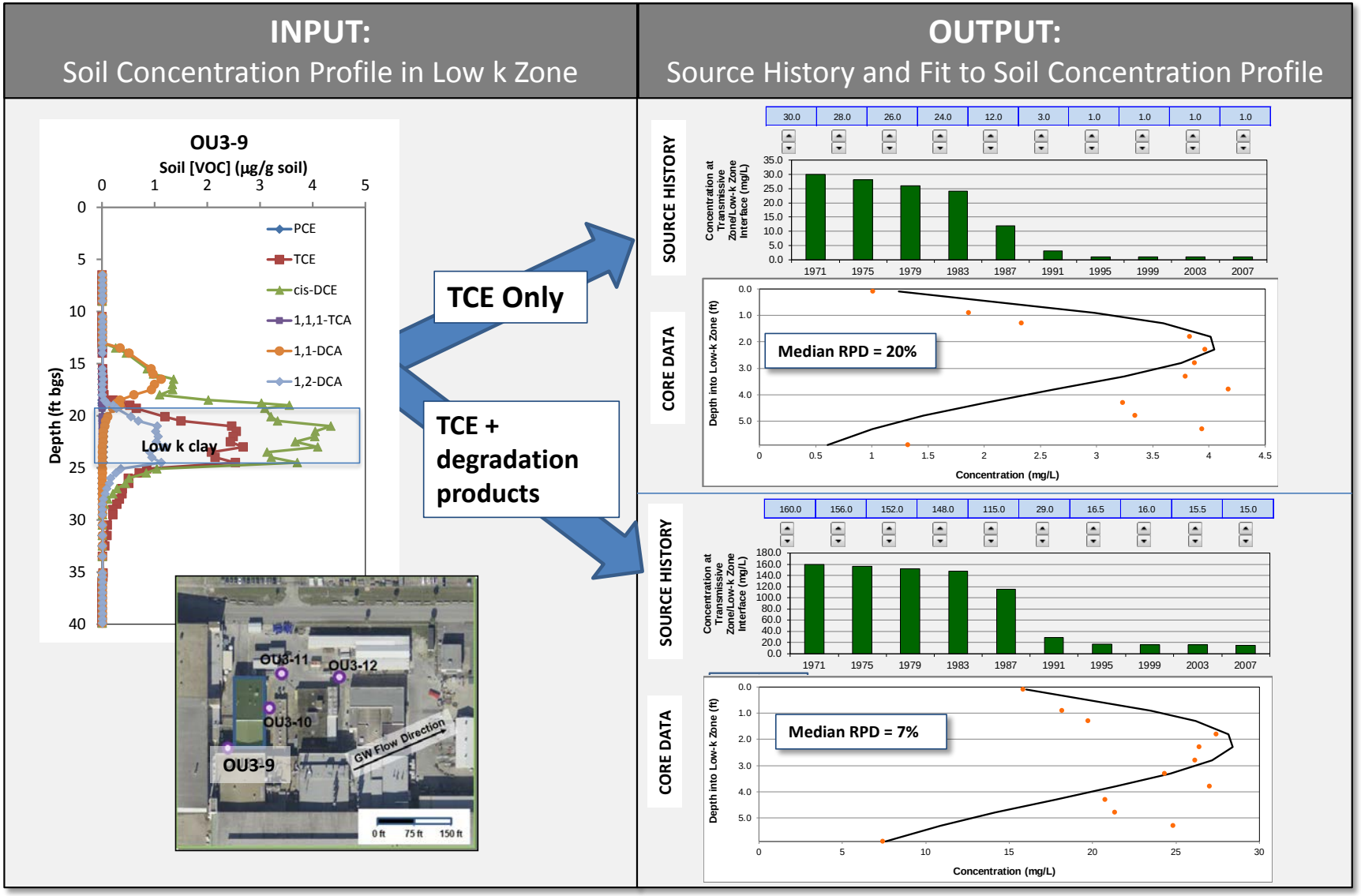


Figure 5.33a. Source History Modeling Results for Location OU3-9 at Building 780 Source Area: Chlorinated Ethenes.

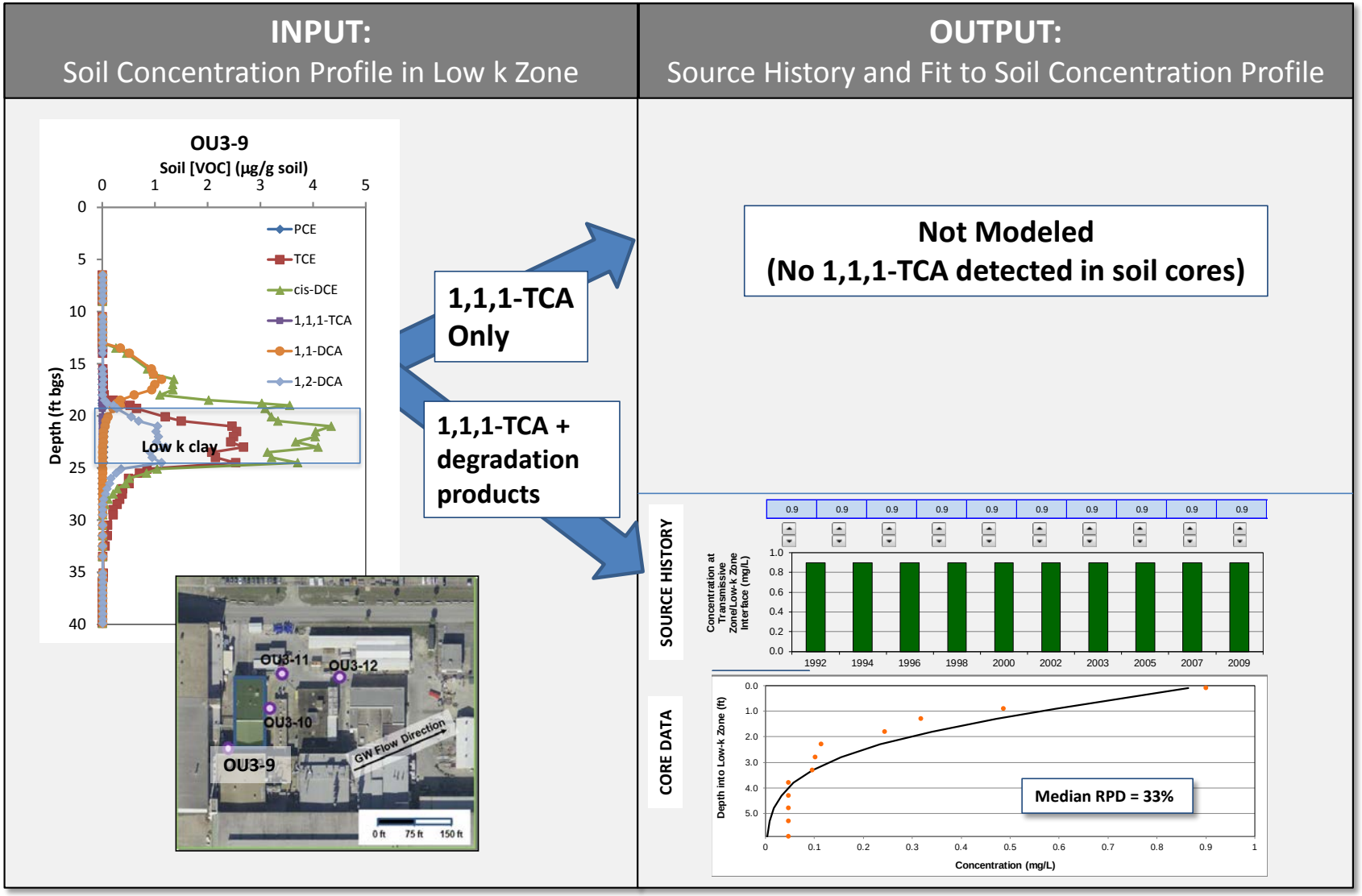


Figure 5.33b. Source History Modeling Results for Location OU3-9 at Building 780 Source Area: Chlorinated Ethanes (1,1,1-TCA)

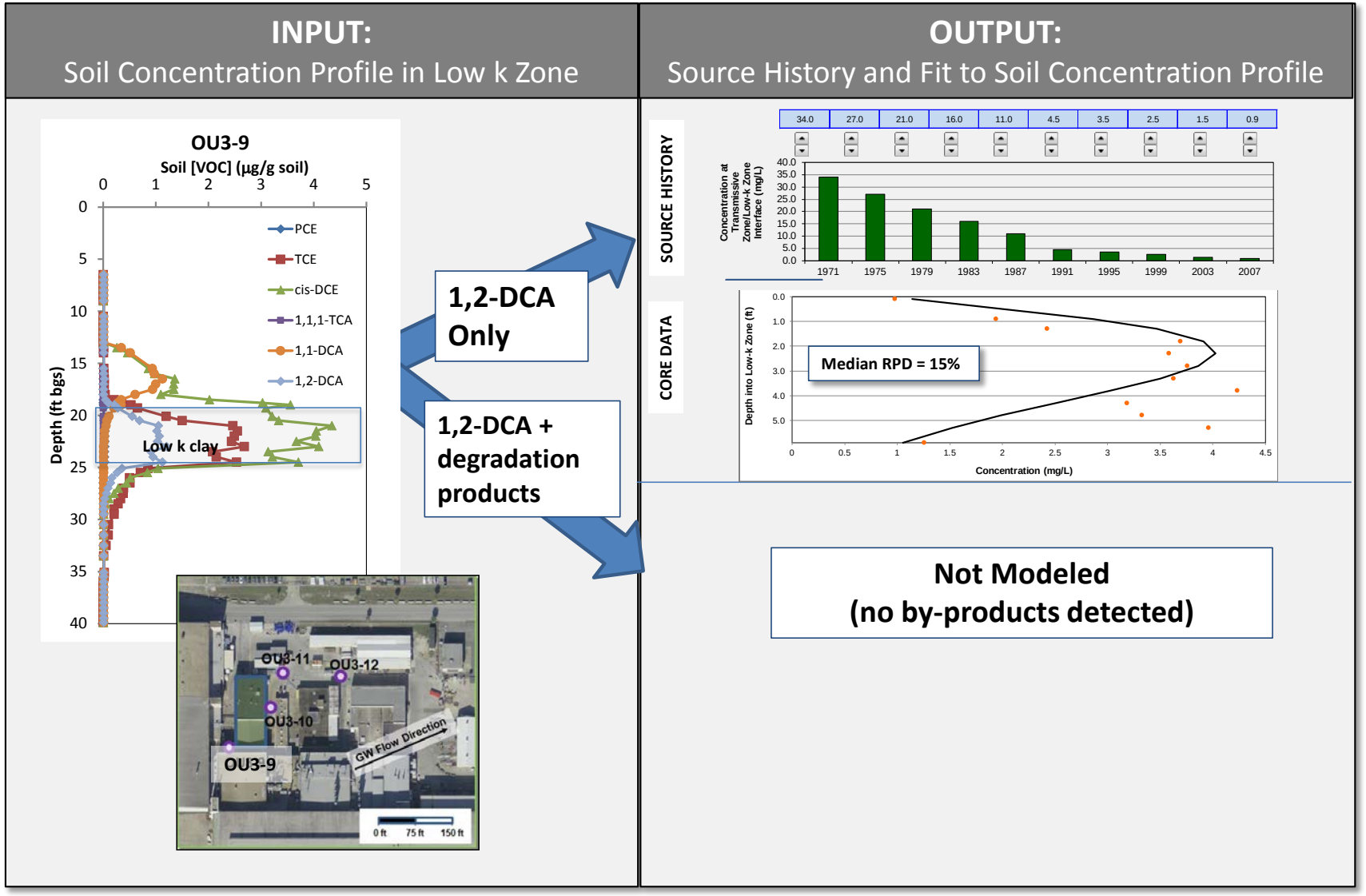


Figure 5.33c. Source History Modeling Results for Location OU3-9 at Building 780 Source Area: Chlorinated Ethanes (1,2-DCA)

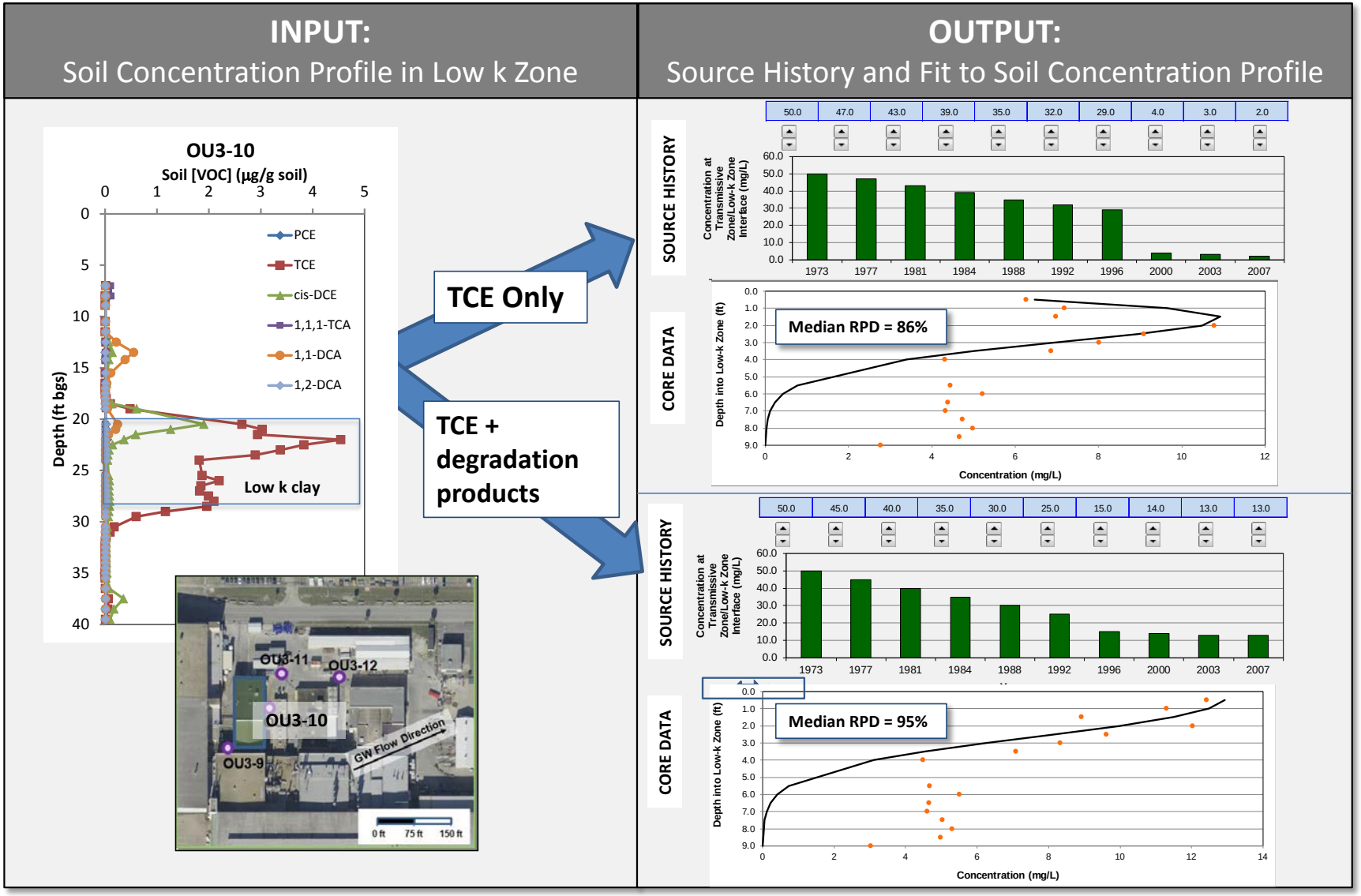


Figure 5.34. Source History Modeling Results for Location OU3-10 at Building 780 Source Area: Chlorinated Ethenes.

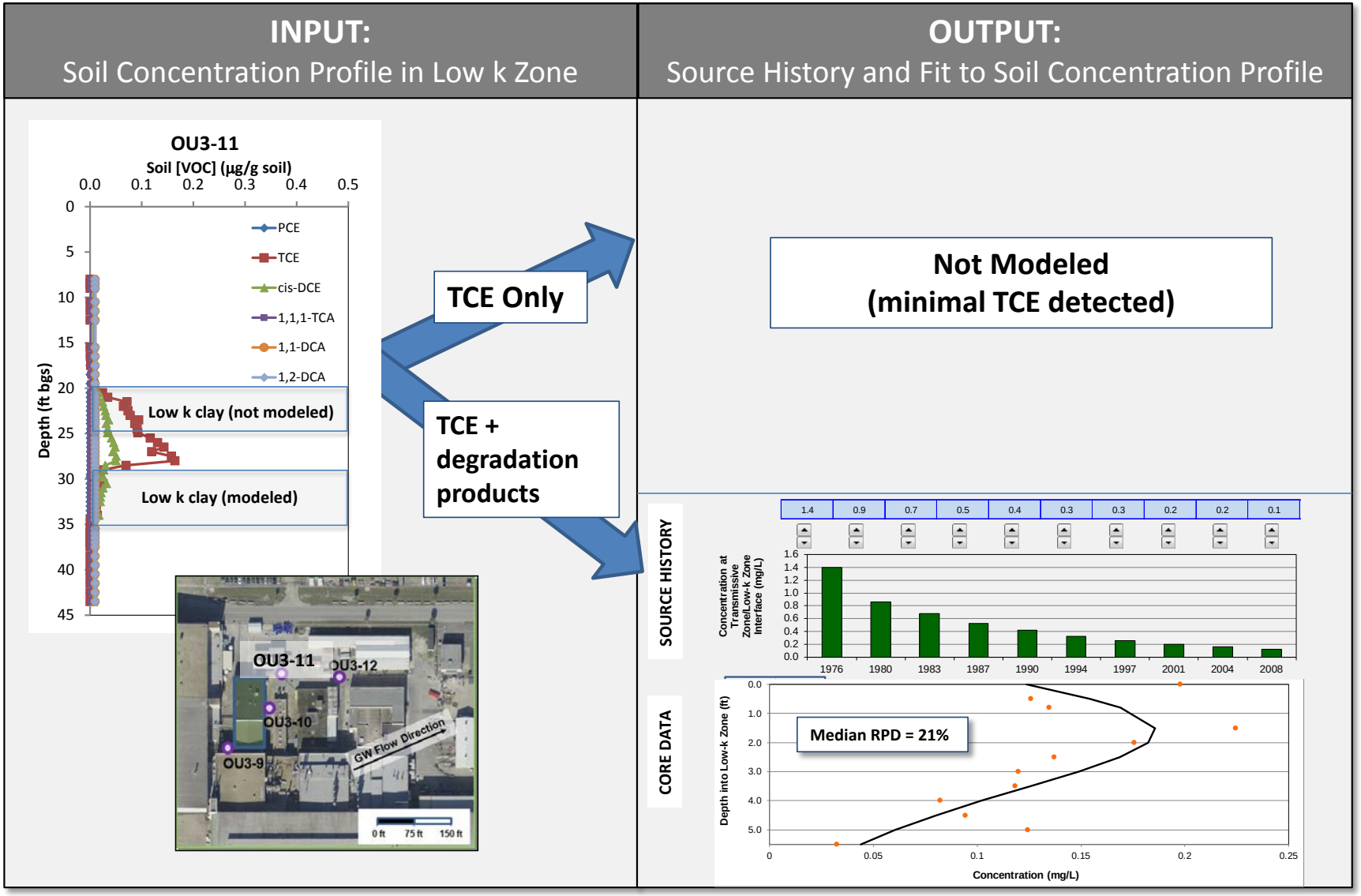


Figure 5.35. Source History Modeling Results for Location OU3-11 at Building 780 Source Area: Chlorinated Ethenes.

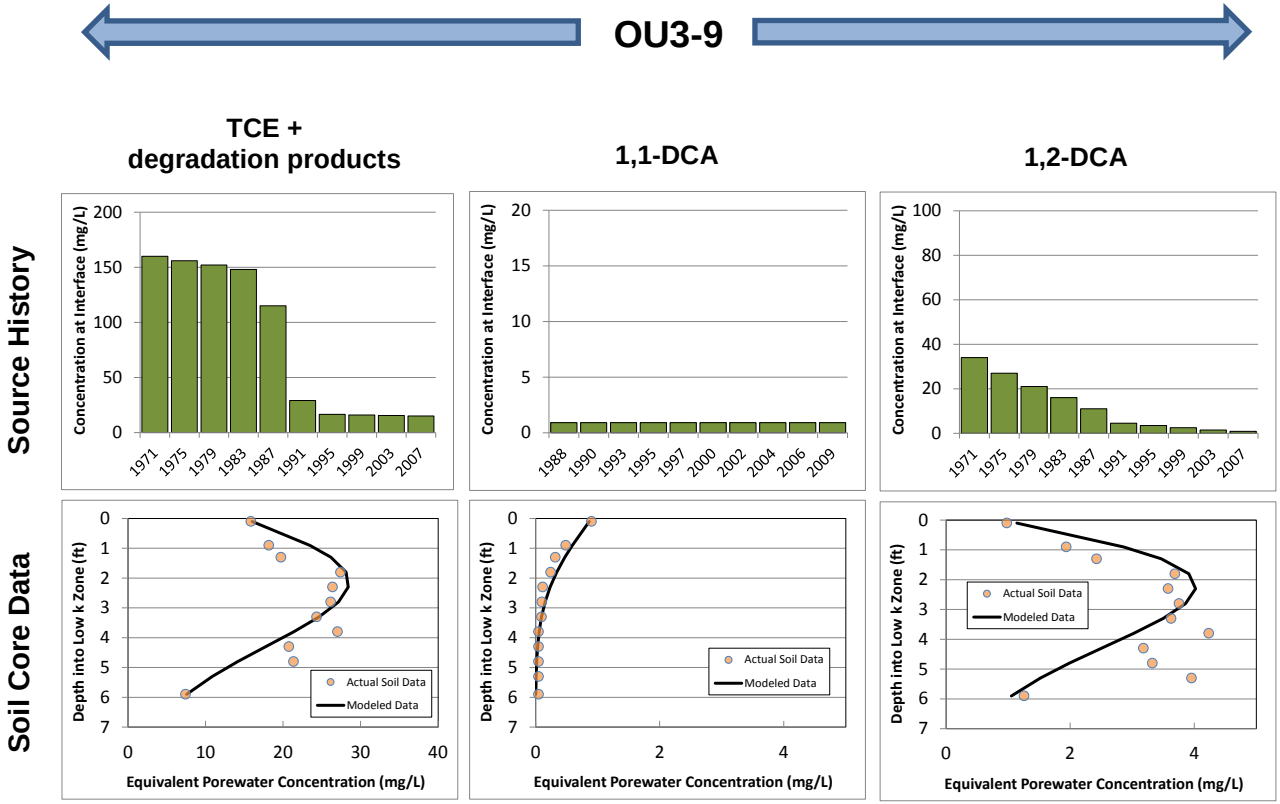


Figure 5.36. Low-k Soil Core Data and Source History Modeling Results at Location OU3-9 at Building 780 Source Area. Concentrations reflect total chlorinated ethenes or chlorinated ethenes in the low-k zone (soil data) and transmissive zone (source history).

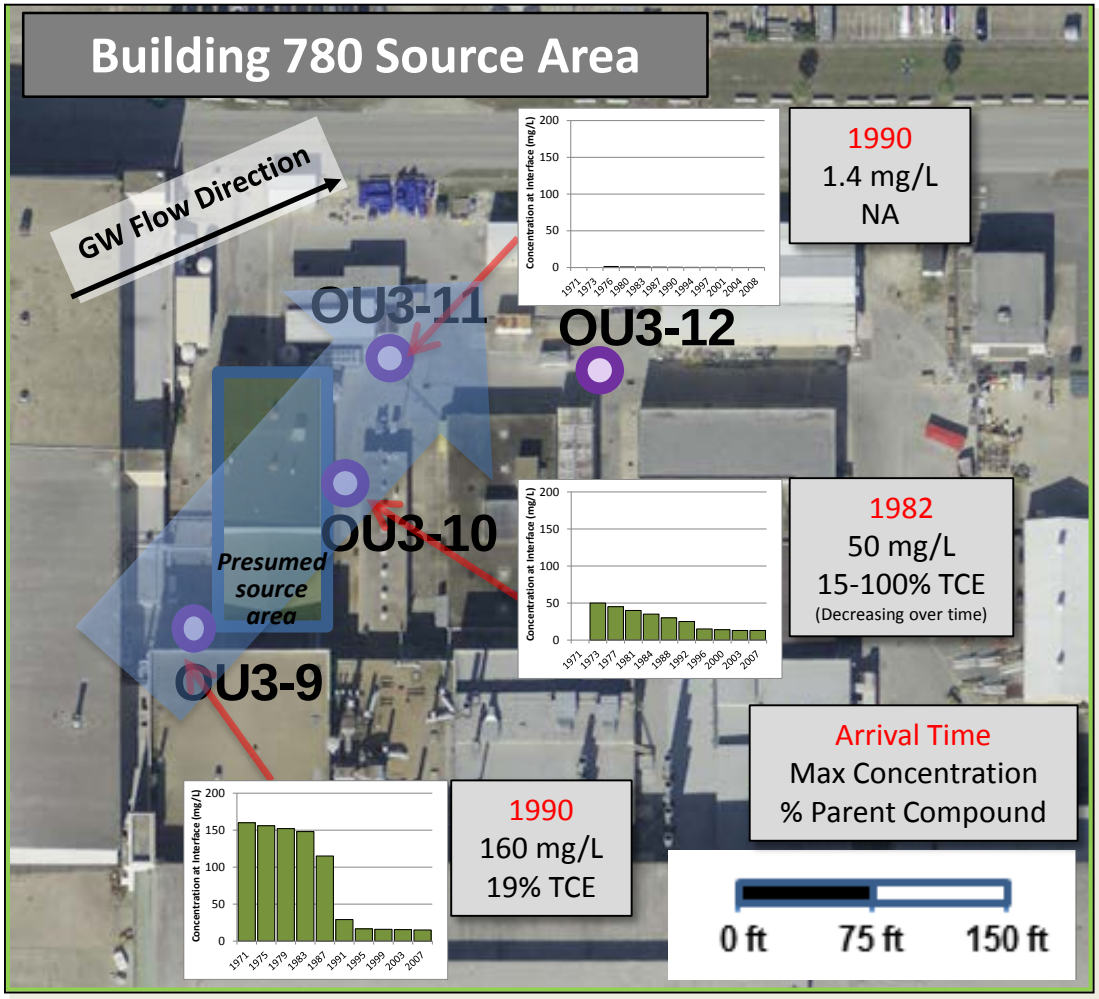


Figure 5.37. Overview of Source History Modeling Results at Building 780 Source Area. Dates reflect plumes arrival, concentrations reflect total chlorinated ethenes in the transmissive zone, and percentages reflect contribution of parent compound (TCE) to total chlorinated ethene concentration.

Table 5.9. Summary of Sensitivity Analysis for Select Locations at Former Building 106 and Building 780 Source Areas: Impact on Source History Trends

Parameter	Value Prior to Adjustment	Adjustment	Source History Trend Before Adjustment	Source History Trend After Adjustment	Comments
Former Building 106 Source Area: OU3-3					
Porosity	0.38	+10%	Constant	Same	Necessitates lowering concentrations for source history estimate (or increasing tortuosity or selecting later release date)
		-10%		Same	Necessitates increasing concentrations for source history estimate (or decreasing tortuosity or selecting earlier release date)
Tortuosity Factor Exponent	1.33	+10%		Same	Necessitates increasing concentrations for source history estimate (or increasing porosity or selecting earlier release date)
		-10%		Same	Necessitates decreasing concentrations for source history estimate (or decreasing porosity or selecting later release date)
Fraction Organic Carbon	0.0018	+10%		Same	Necessitates decreasing concentrations for source history estimate
		-10%		Same	Necessitates increasing concentrations for source history estimate
Half-Life in Low k zone	1000 years	+10%		Same	No impact
		-10%		Same	No impact (requires values < 50 yr to influence soil profile)
Estimated Release Date	1962	+ 5 years		Same	Necessitates decreasing tortuosity
		- 5 years		Same	Necessitates increasing tortuosity
Building 780 Source Area: OU3-9					
Porosity	0.38	+10%	Declining (Step)	Same	Necessitates lowering concentrations for source history estimate
		-10%		Same	Necessitates increasing concentrations for source history estimate
Tortuosity Factor Exponent	1.00	+10%		Same	Necessitates selecting earlier release date
		-10%		Same	Necessitates selecting later release date
Fraction Organic Carbon	0.0018	+10%		Same	Necessitates lowering concentrations for source history estimate
		-10%		Same	Necessitates increasing concentrations for source history estimate
Half-Life in Low k zone	1000 years	+10%		Same	No impact
		-10%		Same	No impact (requires values =< 10 yr to change shape of soil profile)
Estimated Release Date	1971	+5 years		Same	Necessitates decreasing tortuosity
		-5 years		Same	Necessitates increasing tortuosity

Table 5.10. Summary of Sensitivity Analysis for Select Locations at Former Building 106 and Building 780 Source Areas: Impact on Fit to Soil Data

Parameter	Value Prior to Adjustment	Adjustment	Style of Soil Profile Before Adjustment	Style of Soil Profile After Adjustment	Comments
Former Building 106 Source Area: OU3-3					
Porosity	0.38	+50%	Decreasing VOC concentration w/ depth (characteristic of constant source)	Same	Moderate influence throughout depth profile; Of parameters tested, results are most sensitive to porosity
		-50%		Same	
Tortuosity Factor Exponent	1.33	+50%		Same	Low to moderate influence; consistent throughout depth profile
		-50%		Same	
Fraction Organic Carbon	0.0018	+50%		Same	Generally low influence though more pronounced closer to k interface
		-50%		Same	
Half-Life in Low k zone	1000 years	+50%, +1000		Same	Results are not sensitive to degradation, even at lower limit (10 year half-life)
		-50%, 99%		Same	
All Parameters (i.e., 4 listed above)	NA	+50%		Same	Moderate influence throughout depth profile, but very similar pattern as porosity; all runs exhibit same general style
		-50%		Same	
Building 780 Source Area: OU3-9					
Porosity	0.38	+50%	VOC concentration increases w/ depth to maximum, then decreases (characteristic of declining source)		Moderate influence throughout depth profile; Of parameters tested, results are most sensitive to porosity
		-50%			
Tortuosity Factor Exponent	1.33	+50%			Low to moderate influence that increases with depth
		-50%			
Fraction Organic Carbon	0.0018	+50%			Generally low influence, though more pronounced closer to depth where peak concentration is predicted
		-50%			
Half-Life in Low k zone	1000 years	+50%			Results are not sensitive to degradation; marginal influence at lower limit (10 year half-life)
		-50%			
All Parameters (i.e., 4 listed above)	NA	+50%			Moderate influence throughout depth profile, but very similar pattern as porosity; all runs exhibit same general style
		-50%			

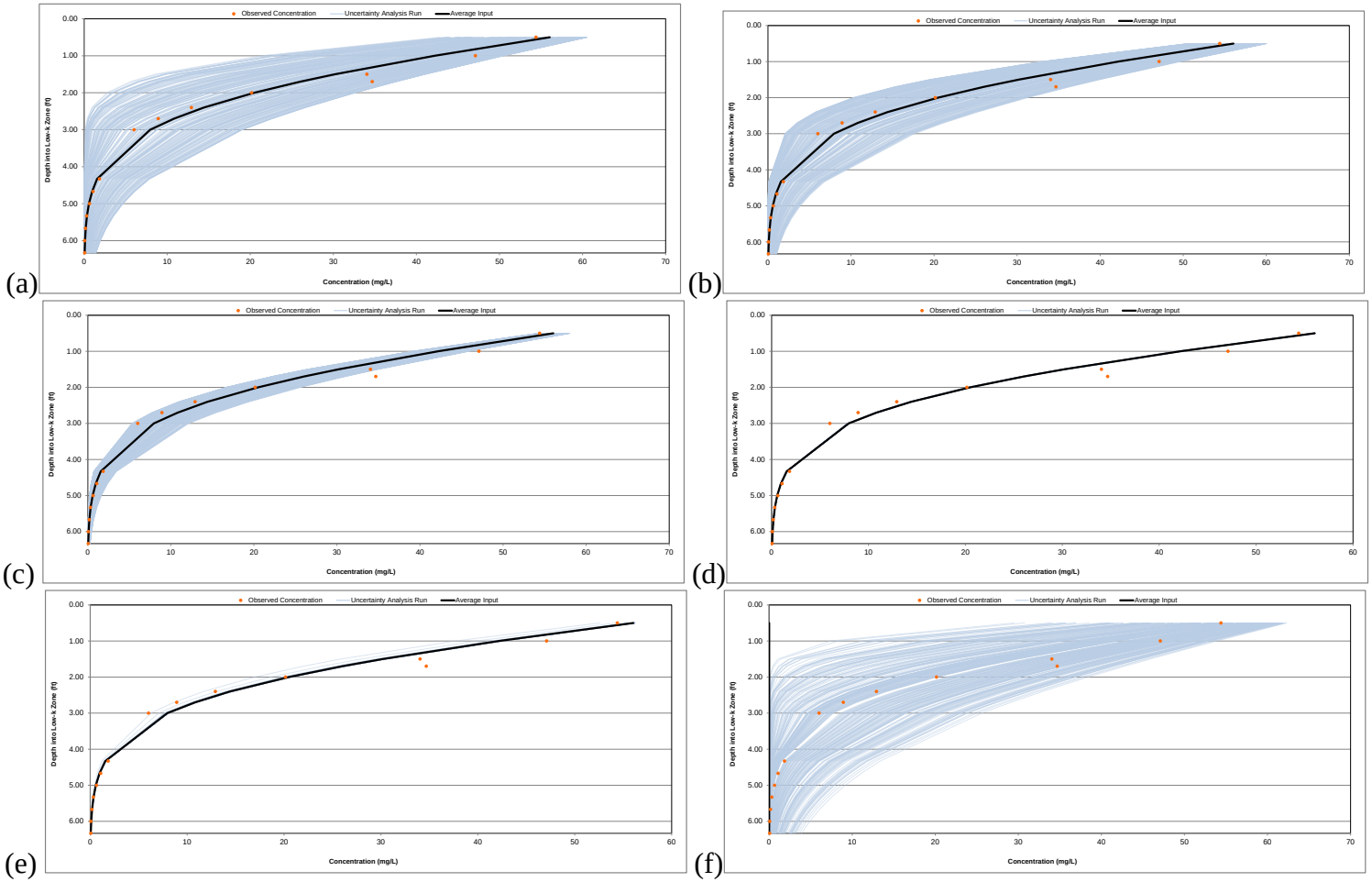


Figure 5.38. **Monte Carlo Sensitivity Analysis for Various Input Parameters for Source History Model at Location OU3-3.** The following input parameters were adjusted using a lower limit of 50% and an upper limit of 150% (except where otherwise noted) to show the impact of these adjustments on the fit of the soil VOC concentration data vs. depth: (a) porosity; (b) apparent tortuosity factor exponent; (c) fraction of organic carbon; (d) constituent half-life in low k zone (lower limit 50%, upper limit 150%) (e) constituent half-life in Low K zone (lower limit 1%, upper Limit 1000%) (f) all four parameters.

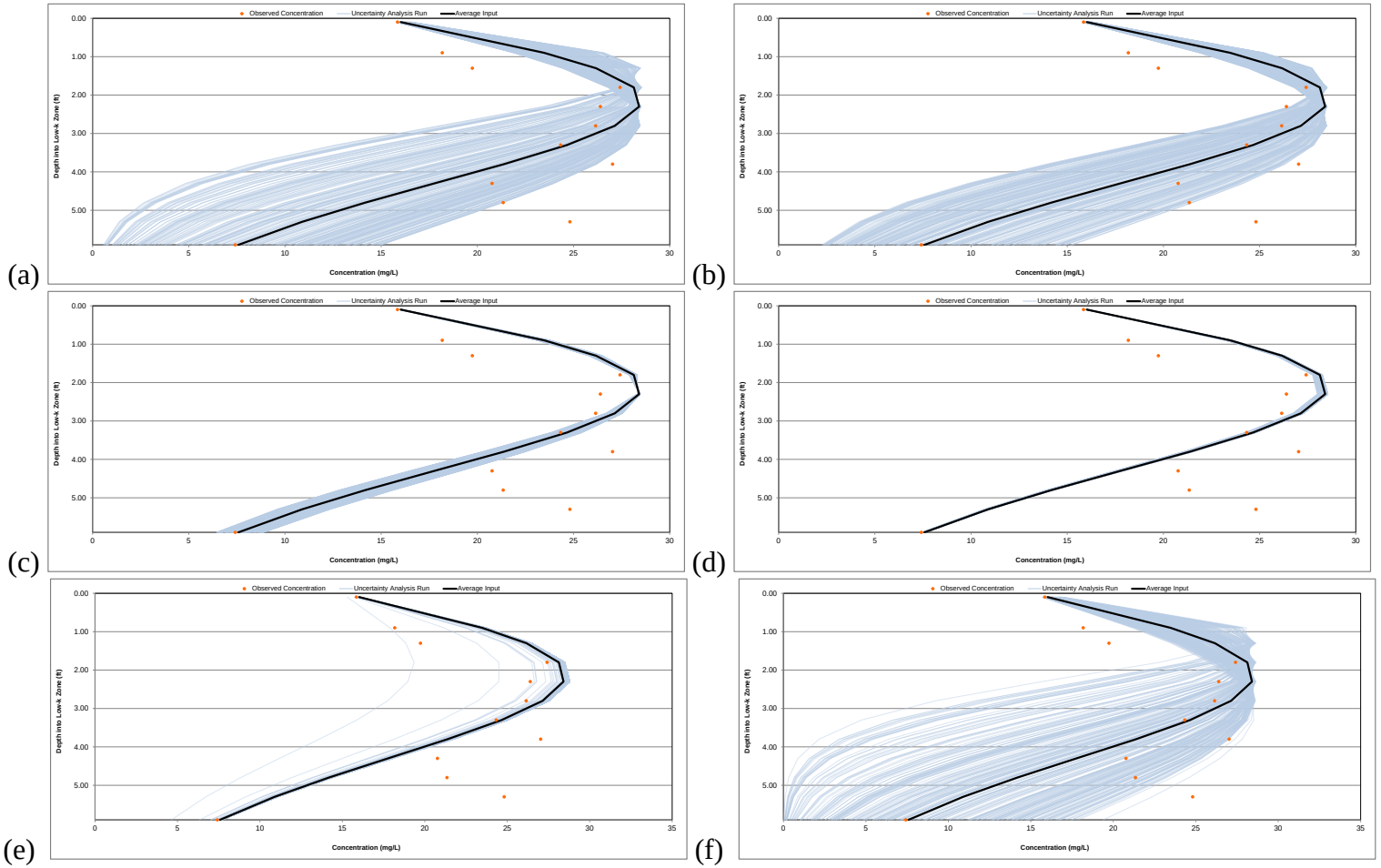


Figure 5.39. **Monte Carlo Sensitivity Analysis for Various Input Parameters for Source History Model at Location OU3-9**. The following input parameters were adjusted using a lower limit of 50% and an upper limit of 150% (except where otherwise noted) to show the impact of these adjustments on the fit of the soil VOC concentration data vs. depth: (a) porosity; (b) apparent tortuosity factor exponent; (c) fraction of organic carbon; (d) constituent half-life in low k zone (lower limit 50%, upper limit 150%) (e) constituent half-life in Low K zone (lower limit 1%, upper Limit 1000%) (f) all four parameters.

5.7.3 Sensitivity Analysis

To support the performance objectives, a comprehensive sensitivity analysis was performed using the datasets from one location at each of the two source areas. The goal was to determine:

1. The impact of small changes (i.e., +/- 10%) to several important parameters on the trend generated using the source history model. This was accomplished by manually adjusting each parameter individually and then regenerating a source history estimate. This estimate was then compared to the original estimate to see if the same source history trend was obtained before and after the adjustment (either visually or with Mann-Kendall non-parametric test, if necessary)
2. The impact of larger changes to these same parameters on the style of the fit to the soil data. This was accomplished using the Monte Carlo sensitivity analysis that is a built-in component of the spreadsheet model. Parameters were adjusted individually by +/- 50%, and then 500 realizations of the soil vs. depth VOC profile were generated. The goal was to visually inspect the baseline and adjusted data to determine if the same style was obtained before and after the adjustments. In other words, adjusting a parameter by 50% should not change a source history estimate that is consistent with a constant source (i.e., soil VOC profiles that decreased uniformly with depth) to a source history that is consistent with a declining source (i.e., soil VOC profile with a "shark-fin" shape where the maximum VOC concentration is well below the interface).

The results of this sensitivity analyses are summarized in **Table 5.9** (trend analysis) and **Table 5.10** (Monte Carlo analysis) for two locations (one at each source area). Graphical displays of the Monte Carlo simulations are shown in **Figure 5.38** (location OU3-3) and **Figure 5.39** (location OU3-9).

Essentially, there are no changes to the source history trends that result from small changes (+/- 10%) to the input parameters (**Table 5.9**). These changes may shift the soil VOC profile slightly, but do not significantly change the shapes of these profiles. As a result, there is no need to use a different source history trend to match the data that result from a small adjustment to a single parameter. Instead, improvements to the fit of the soil data can be achieved by slightly modifying other parameters to compensate. For example, **Table 5.9** highlights that a slightly higher porosity value can be compensated for by decreasing the concentration associated with the source history estimate. The main point is that the source history *trend* at a particular site is not—in and of itself—particularly sensitive to these parameters.

The Monte Carlo simulations provided another way of evaluating sensitivity by showing the impact of larger changes (+/- 50%) to one or more of these same parameters on the fits to the soil data. For the locations from both of the source areas, the style of the data remained the same regardless of the parameter changes. Of the parameters tested, porosity had the most significant influence. This is because the porosity has a direct effect on the conversion of soil concentrations to equivalent porewater concentrations, but also because it impacts transport calculations (as part of the retardation factor). The results also proved moderately sensitive to

tortuosity (in the form of the apparent tortuosity factor exponent), particularly the depth of penetration.

Neither the fraction of organic carbon nor the degradation half-life in the low k zone had significant impacts on the results for these compounds. Larger changes in both of these parameters would be required to see any meaningful influence on the fits to the soil data. In particular, the results were not sensitive to the half-life until values fell below approximately 10 yr. When degradation occurs at this magnitude (or greater), the result is lower concentrations throughout the soil profile and more limited penetration into the low k layer. The relatively limited impact of a more broad range of half-lives on the modeling results are shown in **Figures 5.38e** and **5.39e**. Similarly, **Figures 5.38g** and **5.39g** show the sensitivity of the modeling results when the fraction of organic carbon was allowed to vary within a range of 0 (no sorption) to the maximum value for all samples from OU3. Even over this range, there are no changes to the "style" of the source history results.

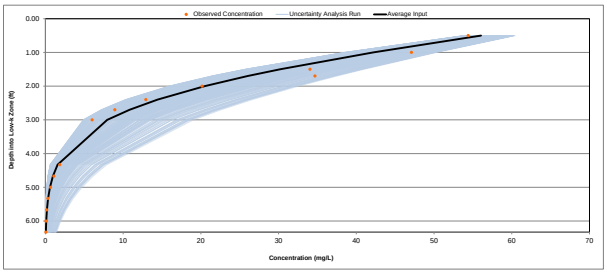


Figure 5.38g. Monte Carlo Sensitivity Analysis for Various Input Parameters for Source History Model at Location OU3-3. Fraction of organic carbon adjusted using a lower limit of 0% (i.e., no sorption) and an upper limit of 160% (i.e., the maximum value for all samples analyzed from OU3).

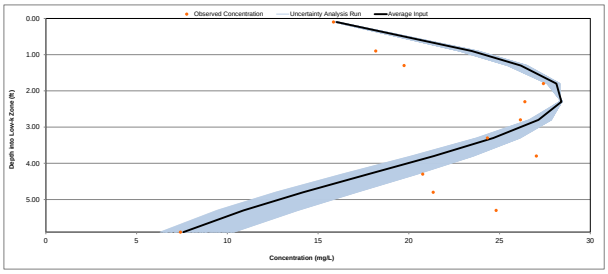


Figure 5.39g. Monte Carlo Sensitivity Analysis for Various Input Parameters for Source History Model at Location OU3-9. Fraction of organic carbon adjusted using a lower limit of 0% (i.e., no sorption) and an upper limit of 160% (i.e., the maximum value for all samples analyzed from OU3).

5.7.4 Other Sites

A review was completed to identify additional sites where high-resolution soil concentration datasets in low permeability zones were available for source history modeling using the project-generated Toolkit. Project team members were involved in the investigations of several of these sites, and there are multiple locations at each site that are suitable for modeling.

For most of the sites that were part of this evaluation, an estimate of the source history had already been generated using numerical modeling approaches. The objective of the evaluation described here was to compare whether these estimates are reasonably consistent with those generated with the Toolkit. For sites where there is no existing source history estimate, the objective was simply to evaluate whether the Toolkit-generated estimate was consistent with known site conditions.

At each site included, a source history estimate was generated at one or more locations using the Toolkit by: i) approximating the soil concentration vs. depth information (often estimated from figures in publications); ii) entering known or estimated values for the remaining input parameters (e.g., porosity, retardation factor); and iii) attempting to fit the data. While there is some error introduced by this approach (e.g., not all input parameters were known), we feel that it provides a reasonable representation of the datasets and is thus suitable for this type of evaluation. A summary of all modeling results for these sites is included in **Table 5.11**.

Connecticut Site (Source Area). Investigations of this industrial site are described in Parker et al. (2004). At the time of the investigations, a persistent zone of TCE DNAPL was present at the top of a clayey silt low permeability layer. High-resolution soil core data was collected from a number of locations within a source area that was isolated using a sheet pile enclosure. TCE was the primary contaminant; degradation was generally negligible throughout the site.

Five locations were included in this evaluation. All but one (WCP-14) had an analogous "source history" estimates included in Parker et al. (2004). Note that Parker et al. (2004) included several potential source history estimates for each location based on assumptions for the various input parameters. This typically included a range of vertical groundwater velocities (0 to 3 cm/yr) and release dates (35 to 45 years prior to core collection) to demonstrate sensitivity. For the purposes of the evaluation presented here, only one estimate (essentially the best fit) is used to compare to the Toolkit-generated results.

Modeling using the project Toolkit was able to consistently match the source history estimates provided in Parker et al (2004). Examples for locations WCP-70, WCP-71, and WCP-87 are shown in **Figure 5.40** (remaining locations are shown in **Appendix R**).

Strong fits between measured and model-predicted soil data were obtained in all cases using the site-specific values for input parameters. In general, significant improvements could be not be obtained by varying these parameters. As a result, the source history estimates generated by the Toolkit were identical or at least very similar to those these presented in Parker et al. (2004). This included constant source histories for WCP-70 and WCP-71 (with TCE at solubility levels), and declining source histories for WCP-15 and WCP-87. Primary differences included:

- At WCP-87, increasing the input value for the groundwater velocity from 1.5 cm/yr to 2.1 cm/yr slightly improved the source history estimate (based on the RMS error for each case).
- At both WCP-87 and WCP-15, the Toolkit used a more gradual decline in the source strength to produce a better fit than the step-decline in source strength that was presented in Parker et al (2004) for these locations. At WCP-15, this resulted in a less rounded shape for the shallow portion of the soil concentration vs. depth curve.
- The worst fit was obtained for WCP-14, primarily due to the wide range of measured soil values in the upper 2 ft of the low-k zone. The highest concentration points at WCP-14, which were influenced by the known presence of DNAPL at the interface, could not be fit using a source history with TCE at solubility levels. In other words, the soil

concentrations at many of these shallower depths suggested equivalent porewater concentrations that were much higher than solubility, and thus could not be incorporated into the model. However, the presence of DNAPL during soil core collection is an obvious indicator that a constant source history is appropriate, and that style provided the best fit at WCP-14.

The results from this site demonstrate that the ability to incorporate a vertical advection into the 1-D model is a valuable component of the Toolkit.

Connecticut Site (Downgradient Plume). Investigations of the downgradient plume of the same Connecticut site described above are presented in Chapman and Parker (2005). The locations included in this portion of the study were along a transect several hundred meters downgradient of the source area that was enclosed by a sheet pile wall. Because the source that was feeding these locations was essentially "removed" at a known point in time, this area is distinctly different than the source area described above.

It is important to note that for this type of area that is spatially distant from the defined source, the Toolkit generates a concentration vs. time estimate at the specific location where the soil core data were collected. This makes it slightly different than a concentration vs. time estimate that would reflect behavior at the source itself (which would require a 2-D approach). Regardless, we use the term "source" history to refer to the estimates generated by the Toolkit.

Three locations were included in this evaluation, and an example of the modeling results for location ML-10 are shown in **Figure 5.40** (remaining locations are shown in **Appendix R**). Reasonable fits were obtained when modeling the soil data with the site-specific values for the various input parameters. The source history estimates for the three locations that were modeled were all characterized by declining source strength over time. Because these locations are all downgradient of the source area, this decline is likely attributable to a combination of DNAPL depletion and mixing with cleaner groundwater moving downgradient. For all cases, the source strength during the most recent timepoint was set to zero to reflect isolation of the upgradient source (after accounting for the approximately 2-yr travel time). This boundary conditions generally improved the source history estimates generated by the Toolkit.

While the source history trends generated using the Toolkit are generally consistent with the site data and information presented in Chapman and Parker (2005), there are some items to highlight:

- A source history estimate is presented in Chapman and Parker (2005) for only ML-10. This estimate used an initial concentration of TCE solubility followed by a stepped declining source strength. As noted above, the estimate shown in the paper reflects the concentration within the source itself, while the Toolkit-generated estimate in Figure 5.39 is the concentration history at the ML-10 coring location. The best fit prediction using the Toolkit used a smoother declining trend but is not markedly different than a step decline.
- There was considerable scatter in the measured soil data from these locations; large changes in concentration across small changes in depth were common. As such, it was more important to capture the overall trend in the data rather than minimizing the RMS

error. Some of these abrubt changes may reflect real heterogeneities that are difficult to account for during this type of modeling because it relies on a single representative values for certain parameters (e.g., fraction of organic carbon). Regardless, the data variability increases the uncertainty of the source history estimates. However, it emphasizes that the overall trend should be the focus of these modeling efforts, not the accuracy of particular period-to-period changes in concentration.

- In general, improvements in the data fits could be obtained by increasing the vertical groundwater velocity so that it fell in the 3 to 6 cm/yr range. This is slightly higher than the range of values presented in Chapman and Parker (2005) for the site (0 to 3 cm/yr). However, it was difficult to account for the maximum depth of penetration in the measured soil data without increasing the contribution of downgradient vertical advection. This was particularly evident at ML-11, where the shape and depth of the soil VOC "peak" suggested significant penetration into the clay. It should be noted that ML-11 was not fully evaluated in Chapman and Parker (2005) because its location (near the plume boundary) contributed to uncertainty about representative boundary conditions.
- The soil VOC profile for ML-4 was characterized by peak concentration that occurred over a relatively narrow depth interval. This was consistent with a relatively short period when high concentrations were present in the overlying aquifer, followed by a rapid decline. The sharpness of the soil VOC profile (both above and below the peak concentration) thus provided guidance on estimating the rate of change of concentration in the overlying aquifer.

Dover AFB: A portion of this facility was part of a multi-year research investigation described extensively in the literature (e.g., Ball et al., 1997a; Ball et al., 1997b; Liu and Ball, 1998; Liu and Ball, 1999; Mackay et al., 2000; Liu and Ball, 2002). To better understand the impacts of back diffusion on remediation timeframes, two parallel sheetpiled areas were constructed and subjected to several rounds of high-resolution characterization (including coring). The sheetpiles provided hydraulic isolation of the subsurface soils within these areas, which were contaminated with PCE and TCE emanating from a source area located approximately 450 m upgradient. Releases were believed to have occurred in the 1960s. The site geology is characterized by a sandy aquifer overlying two distinct low-k layers, consisting of: i) an upper layer of orange silty clay loam (OSCL) measuring between 0.5 and 1.0 m thick; and ii) a bottom layer of dark gray silt loam (DGSL). For the purposes of this evaluation, only the upper low-k layer was included.

Four locations were included in this evaluation, all of which were located within the cell where pulsed pumping was conducted for a short period. A core from one location (PPC-11) was collected prior to pumping and thus represents conditions immediately after hydraulic isolation. A core from a second location (PPC-13) was collected immediately after the termination of pumping and thus represents conditions after extended flushing of the treatment cell. Cores from the remaining two locations (PPC-16 and PPC-19) were collected approximately 8 and 16 months after the end of pumping, respectively.

Two locations (PPC-11 and PPC-13) had analogous "source history" estimates specifically included in Liu and Ball (1999). Results for these two locations are shown in **Figure 5.41**

(remaining locations are shown in **Appendix R**). At PPC-11 and PPC-13, the source history estimates for both PCE and TCE matched strongly those presented in Liu and Ball (1999).

- PPC-11 was characterized by relatively low and constant PCE source loading that increased sharply in the period immediately prior to pumping. No significant improvement in fit was obtained using the "functional boundary condition" (i.e., the source concentration over time) predicted using the inverse model presented in Liu and Ball (1999). In contrast, the TCE source history estimate generated at this location using the Toolkit was characterized by a similar arrival time as PCE (approximately 1982) but the source strength had decreased during the most recent period. This pattern, which suggests that the peak TCE concentration has passed the treatment cell, is essentially the two-step boundary condition described in Liu and Ball (1999). The source history pattern predicted using inverse modeling in Liu and Ball (1999) was quite different but proved too difficult to simulate using the Toolkit due to the limited number of timesteps available in the Toolkit. While improvements in the fit may have been possible, the widely varying concentrations near the interface contribute to considerable uncertainty in the source history estimates, regardless of the methods used.
- PPC-13 was characterized by a two-step PCE concentration vs. time pattern that was similar to that predicted for PPC-11, where a constant PCE source strength shifted to a higher source strength near the start of the pumping period. However, because this core was collected after approximately 2 years of pumping, the source history estimate also included a sharp decline to reflect the hydraulic isolation of the treatment cell in late 1994. Liu and Ball (1999) does not include a two-step source history but instead presents a bi-model source history estimate based on the inverse modeling solution. An attempt was made to match this bio-model source history using the Toolkit, but given that there are only 10 timesteps available in the Toolkit model, there was some difficulty in recreating the non-linear curve. This resulted in a poorer fit at the shallow depths where high soil concentrations were measured and a higher RMS error than the estimate presented in Figure 5.39. For TCE, the same two-step source history pattern used for PPC-11 generated a strong fit for PPC-13, once a zero-source strength boundary condition was imposed on the final timestep to represent hydraulic isolation.

Source history estimates were also generated using the Toolkit for locations PPC-16 and PPC-19 (including separate estimates for both PCE and TCE). Strong fits could be obtained using the source history patterns established for PPC-11 or PPC-13. Essentially, these are all two-step concentration vs. time patterns with either decreasing (TCE) or increasing (PCE) at some point before the date when the treatment area was hydraulically isolated. While all these source history patterns provided a good match for the soil data, the primary limitation was accounting for the rapid changes between the pumping period (19 months) and the no-flow period (15 months). The Toolkit requires 10 evenly-spaced timesteps, with a minimal value that is dictated by the release/arrival date. Cores from PPC-16 and PPC-19 were collected at the end of the no-flow period, but a single concentration value had to be used for the last timestep, even though boundary conditions had changed more than once during this period.

In summary, the Toolkit provided reasonable fits at this site using relatively simple "two-step" source history estimates. It is not well-equipped to predict bi-modal patterns such as those presented in the literature for the Dover AFB locations. However, there is some question as to whether these more complex source history estimates are any more representative than the simpler ones; identifying which is more accurate would require site knowledge that is not available. As the Liu and Ball point out (1999), the fact that good fits can be obtained with either two-step concentration vs. time patterns or bimodal concentration vs. time patterns demonstrate the non-uniqueness of these solutions. Identifying the overall pattern (increasing vs. decreasing source strength) should remain the priority.

Note that vertical advection and degradation were not considered for these simulations given their perceived minimal impact, consistent with the observations in Liu and Ball (2002). Also, a combined source history for total chlorinated ethenes (PCE plus TCE) was not generated. This is because TCE concentrations were several orders of magnitude higher than PCE, such that the combined source history would not have been different than the TCE source history.

Ontario Site: Investigations of this former manufacturing facility are described in Parker et al. (2003). Site activities contributed to TCE being released during an unknown period of time. TCE DNAPL was subsequently identified in monitoring wells, and high-resolution soil core data used to delineate the source zone also identified areas with high concentrations that were consistent with the presence of DNAPL. Positive indicators of DNAPL were generally encountered within a transition zone overlying a clay till aquitard. TCE was the primary contaminant; degradation was generally negligible throughout the site.

One location was included in this evaluation (AC-6). In this case, the soil core was collected in 1998 adjacent to a monitoring well where DNAPL was present; however, no DNAPL was visible in the core (based on Sudan IV dying). No analogous "source history" estimate was included in Parker et al. (2003).

Modeling of the low-k zone (the clay till) below transition zone using the project Toolkit provided a reasonable match with the soil data using a combination of site-specific values and default values for the various input parameters (**Figure 5.42**). Consistent with the presence of DNAPL and a decreasing TCE concentration moving into the clay, a constant source was predicted using this approach. The best fits were obtained when the release date was set as late as possible. Given that site-specific information on TCE releases was not available, a date of 1975 was selected based on patterns of usage at similar sites. It is important to note that later release dates improved the fit only marginally (e.g., RMS error decreases from 267 mg/L to 261 mg/L if the release date is set at 1980) while earlier release dates negatively impact the fit.

However, it is clear that (regardless of the release date) the model underpredicts soil concentrations at shallow depths and overpredicts at deeper depths. Slight improvements can be obtained for the deeper intervals if tortuosity or degradation is increased. A more reasonable correction would be to increase sorption because this improves the fit across both the shallow interavls and (to a lesser extent) deeper intervals. By increasing the f_{oc} value from 0.0009 (cited in Parker et al. (2003)) to 0.0022, the RMS error decreases from 271 mg/L to 92 mg/L. This also

reduces the porewater concentration at the interface to a level more consistent with TCE solubility (approximately 1100 mg/L).

Florida Site: This site was an operational metal fabricating and cleaning facility where TCE releases occurred in the period between approximately 1964 and 1976. Extensive high-resolution characterization efforts described in Parker et al. (2003) were used successfully to delineate the high concentration areas. The presence of TCE DNAPL was confirmed in selected boreholes, with the DNAPL confined to a relatively narrow interval near the interface with a distinct (< 1 m thick) clay layer. DNAPL had apparently been able to penetrate through a thinner (< 0.5 m thick) clay layer present at shallower depths throughout the site.

One location was included in this evaluation (PM-18). In this case, the soil core was collected in 1999. The presence of a thin layer of DNAPL in the sandy soil above the clay interval was confirmed by visual inspection following Sudan IV dying. No analogous "source history" estimate was included in Parker et al. (2003).

Modeling of the low-k zone using the project Toolkit provided a strong match with the soil data using a combination of site-specific values and default values for the input parameters (**Figure 5.42**). Consistent with the presence of DNAPL, a constant source with TCE at approximately 500 mg/L was predicted using this approach. The best match was obtained by using the earliest known release date—1964—as a boundary condition. Using the default tortuosity factor (1.1) for silts/clay provided a strong fit. The finding that a constant concentration that is well below TCE solubility (approximately 1100 mg/L) provides the most optimal fit is not wholly inconsistent with the known presence of DNAPL in the overlying aquifer. As described in Parker et al. (2003), DNAPL appeared to be confined to very narrow zones within the sandy soils, such that loading into the low-k zone may have been dampened. Alternatively, the f_{oc} value assumed for the low-k zone may be too high; improved fits can be obtained by decreasing the impact of sorption. However, the f_{oc} value used for modeling was based on the average of 22 field samples, increasing confidence in its representativeness.

Table 5.11. Summary of Source History Trends for Other Sites with High-Resolution Data in Low Permeability Zones

Location	Compound(s)	Trend/Style of Source History Using Project Toolkit	Consistent with Existing Source History Estimates and/or Site Info?	Median RPD (non-directional)	RMS Error (mg/L)	Ratio of RMS Error to Max Measured Concentration
Connecticut Site (Source Area) *(described in Parker et al., 2004)*						
WCP-14	TCE	Constant	Yes Difficulty in fitting soil concentrations above solubility	51%	509	17%
WCP-15	TCE	Constant with late gradual decline	Yes Toolkit used more gradual late decline (instead of step decline)	34%	97	11%
WCP-70	TCE	Constant	Yes	49%	119	10%
WCP-71	TCE	Constant	Yes	17%	64	6%
WCP-87	TCE	Constant, then gradual decline	Yes Toolkit used higher velocity and more gradual late decline (instead of step decline)	23%	54	12%
Connecticut Site (Downgradient Area) *(described in Chapman and Parker, 2005)*						
ML-4	TCE	Decreasing (exponential)	Yes Toolkit used higher velocity and estimate is representative of plume arrival	21%	3.8	16%
ML-10	TCE	Decreasing (exponential)	Yes Toolkit used higher velocity and more gradual decline (instead of step decline); estimate is representative of plume arrival	78%	17	27%
ML-11	TCE	Decreasing, then leveling off at low level	Yes Toolkit used higher velocity and estimate is representative of plume arrival	20%	2	16%

Notes: (1) RMS error = relative means square error; (2) Max measured concentration is the maximum measured soil concentration after converting to equivalent porewater concentration (mg/L).

Table 5.11. Summary of Source History Trends for Other Sites with High-Resolution Data in Low Permeability Zones *(continued)*

Location	Compound	Trend/Style of Source History Using Project Toolkit	Consistent with Existing Source History Estimates and/or Site Info?	Median RPD (non-directional)	RMS Error (mg/L)	Ratio of RMS Error to Max Measured Concentration
Dover AFB *(described in Liu and Ball, 1999; Liu and Ball, 2002; several other articles)*						
PPC-11	PCE	Step increase (constant, then late increase)	Yes Toolkit used similar two-step source histories	20%	0.0044	8%
	TCE	Step decrease (constant, then late decrease)		15%	0.34	13%
PPC-13	PCE	Step increase/decrease (constant, then late increase, then late decrease)	Yes Toolkit used similar source history (but with slightly higher concentrations) and reflected late decline in concentration due to hydraulic isolation	13%	0.0032	8%
	TCE	Step decreases (constant, then two late decreases)		14%	0.25	12%
PPC-16	PCE	Step increase/decrease (constant, then late increase, then late decrease)	Yes Toolkit used similar source history (but with slightly higher concentrations) and reflected late decline in concentration due to hydraulic isolation	14%	0.0027	10%
	TCE	Step decreases (constant, then two late decreases)		37%	0.42	25%
PPC-19	PCE	Step increase/decrease (constant, then late increase, then late decrease)	Yes Toolkit used similar source history (but with slightly higher concentrations) and reflected late decline in concentration due to hydraulic isolation	24%	0.0043	13%
	TCE	Step decreases (constant, then two late decreases)		16%	0.30	18%

Notes: (1) RMS error = relative means square error; (2) Max measured concentration is the maximum measured soil concentration after converting to equivalent porewater concentration (mg/L).

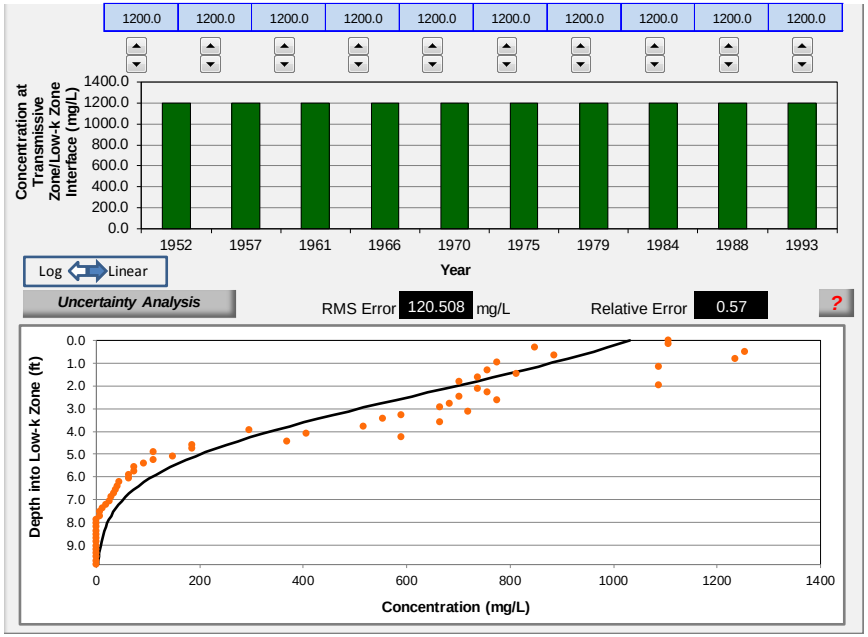
Table 5.11. Summary of Source History Trends for Other Sites with High-Resolution Data in Low Permeability Zones *(continued)*

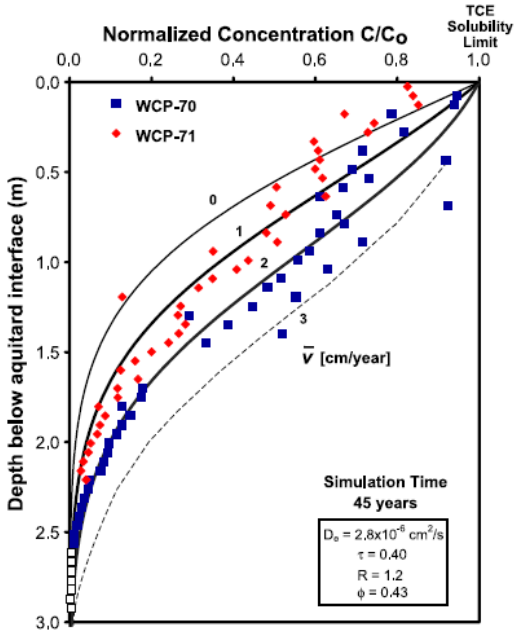
Location	Compound	Trend/Style of Source History Using Project Toolkit	Consistent with Existing Source History Estimates and/or Site Info?	Median RPD (non-directional)	RMS Error (mg/L)	Ratio of RMS Error to Max Measured Concentration
Ontario Site *(described in Parker et al., 2003)*						
AC-6	TCE	Constant	Yes Consistent with presence of DNAPL	20%	267	18%
Florida Site *(described in Parker et al., 2003)*						
PM-18	TCE	Decreasing (Exponential)	Yes but concentrations are lower than expected from presence of DNAPL	84%	77	17%

Notes: (1) RMS error = relative means square error; (2) Max measured concentration is the maximum measured soil concentration after converting to equivalent porewater concentration (mg/L).

WCP-70 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(vertical groundwater velocity = 2.3 cm/yr)

Fit to Soil Data in Parker et al (2004) Using Constant Source History (1200 mg/L for 45 years)



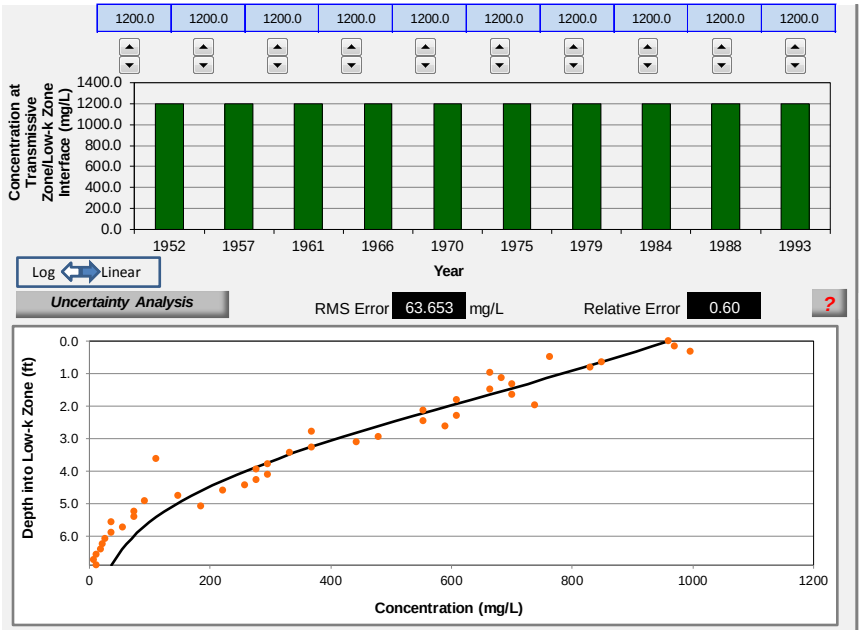


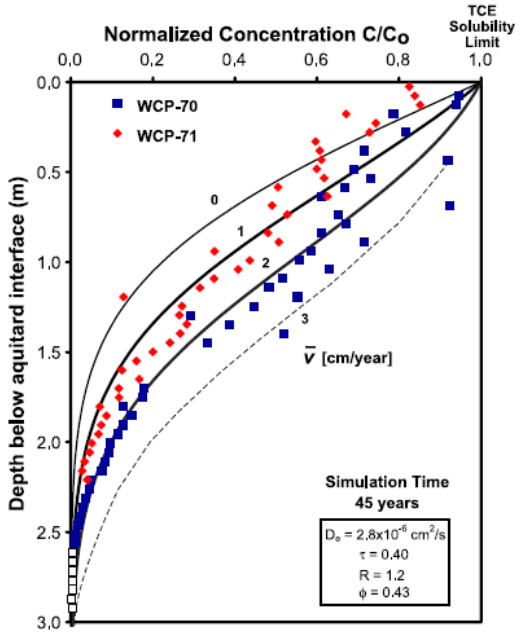
KEY FINDING: *Strong match achieved for WCP-70 using same constant source history and input parameters described in Parker et al (2004). No significant improvement in fit could be achieved by changing source history or input parameters.*

Figure 5.40. **(a) Source History Estimate for location WCP-70 at Connecticut Site (Source Area).** Site described in Parker et al. (2004). Right panel displays results for both locations WCP-70 and WCP-71, with four lines showing model predictions using range of vertical groundwater velocities (0 to 3 cm/yr).

WCP-71 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(vertical groundwater velocity = 1.9 cm/yr)

Fit to Soil Data in Parker et al (2004) Using Constant Source History (1200 mg/L for 45 years)

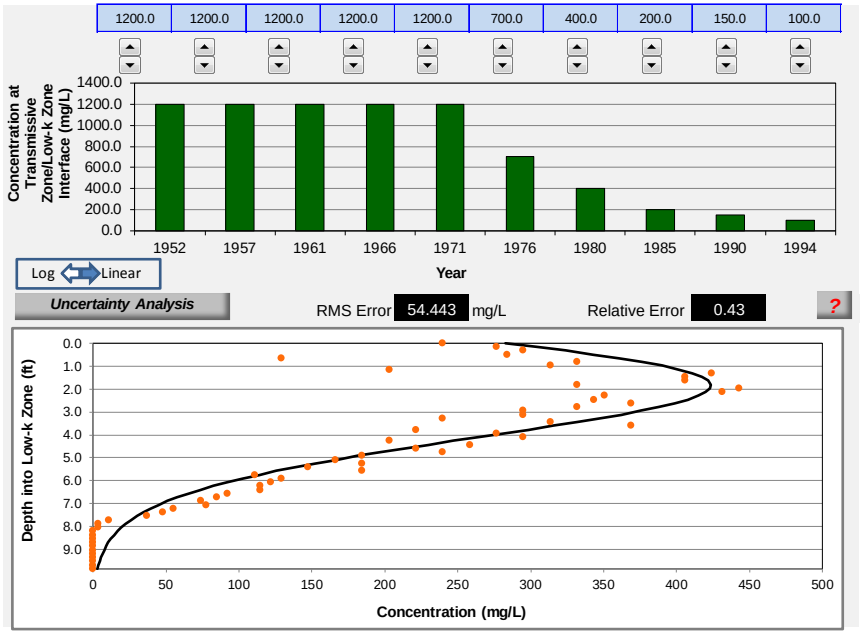




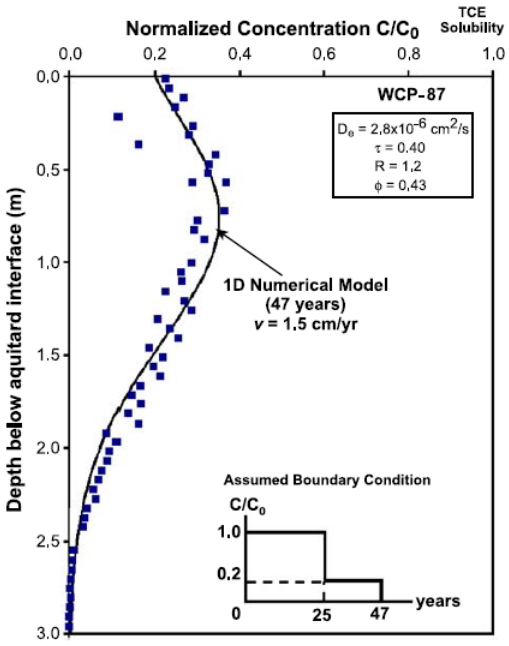
KEY FINDING: *Strong match achieved for WCP-71 using same constant source history and input parameters described in Parker et al (2004). No significant improvement in fit could be achieved by changing source history or input parameters.*

Figure 5.40. **(b) Source History Estimate for location WCP-71 at Connecticut Site (Source Area).** Site described in Parker et al. (2004). Right panel displays results for both locations WCP-70 and WCP-71, with four lines showing model predictions using range of vertical groundwater velocities (0 to 3 cm/yr).

WCP-87 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(vertical groundwater velocity = 2.1 cm/yr)



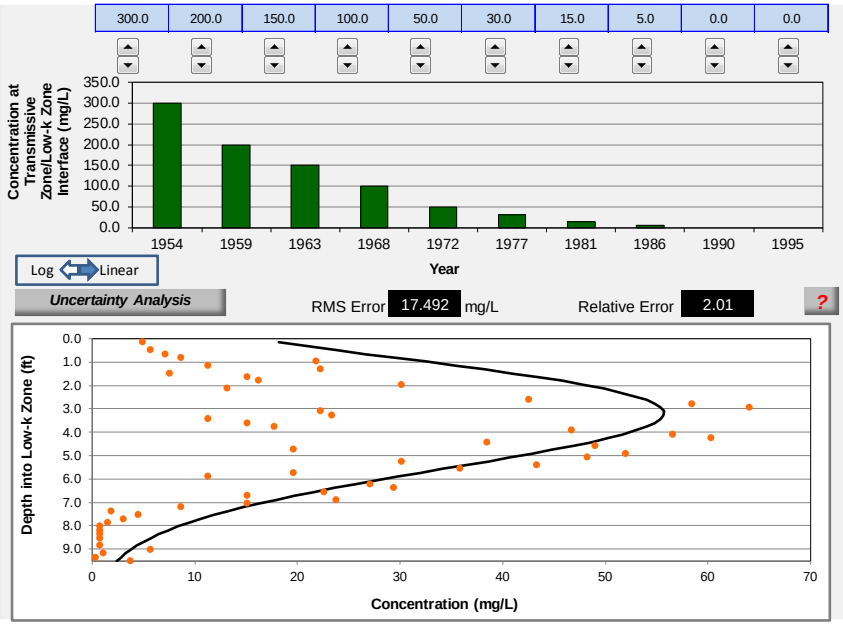
Fit to Soil Data in Parker et al (2004) Using Step-Decline Source History (shown in inset)



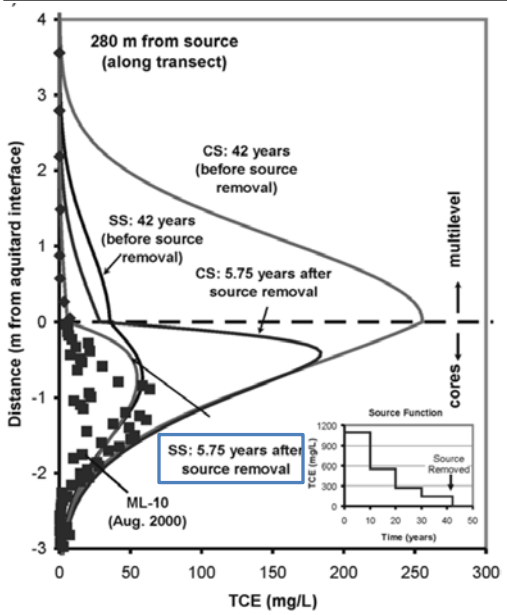
KEY FINDING: *Strong match achieved for WCP-87 using decreasing-style source history and input parameters described in Parker et al (2004). Slight improvement in fit was achieved by using higher gradual vertical groundwater velocity and more gradual decline in source strength as opposed to step decline used in Parker et al (2004).*

Figure 5.40. **(c) Source History Estimate for location WCP-87 at Connecticut Site (Source Area).** Site described in Parker et al. (2004).

ML-10 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(vertical groundwater velocity = 2.9 cm/yr)



Fit to Soil Data in Chapman and Parker (2005) Using Stepped-Declining (SS) Source History (shown in inset)

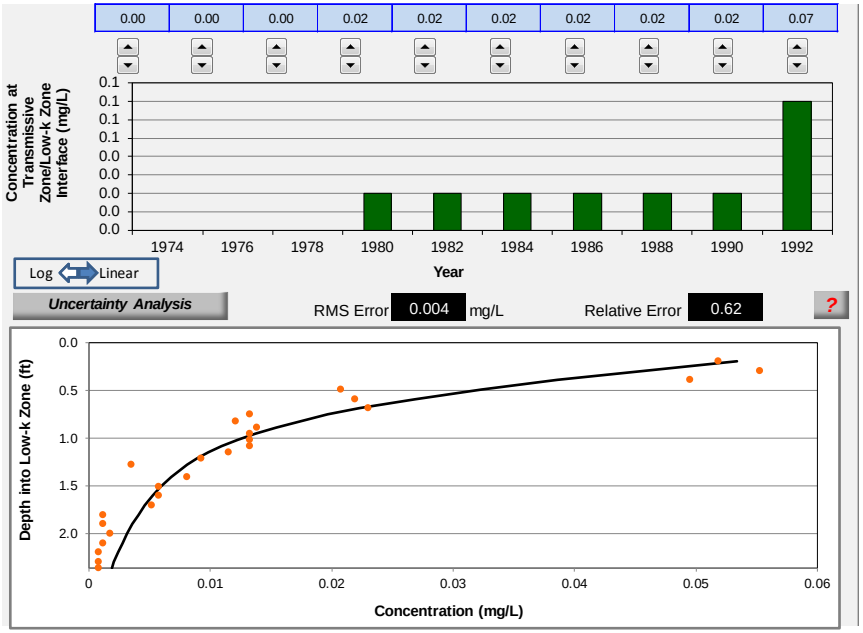


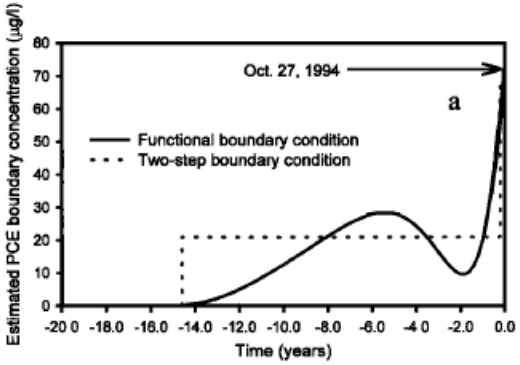
KEY FINDING: *Reasonable match achieved for ML-10 using decreasing-style source history and input parameters described in Chapman and Parker (2005). Source history generated by Toolkit is specific to the location where the core was collected. Source history presented in Chapman and Parker (2005) reflects concentrations in the upgradient source area (see curve "SS: 5.75 years after source removal"). Slight improvement in fit was achieved by using more gradual decline in source strength as opposed to stepped declining source used in Chapman and Parker (2005), as well as slightly higher vertical groundwater velocity.*

Figure 5.40. **(d) Source History Estimate for location ML-10 at Connecticut Site (Downgradient Area)**. Site described in Chapman and Parker (2005).

PPC-11 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(PCE)

Fit to Soil Data in Liu and Ball (1999) Using Two-Step Boundary Condition



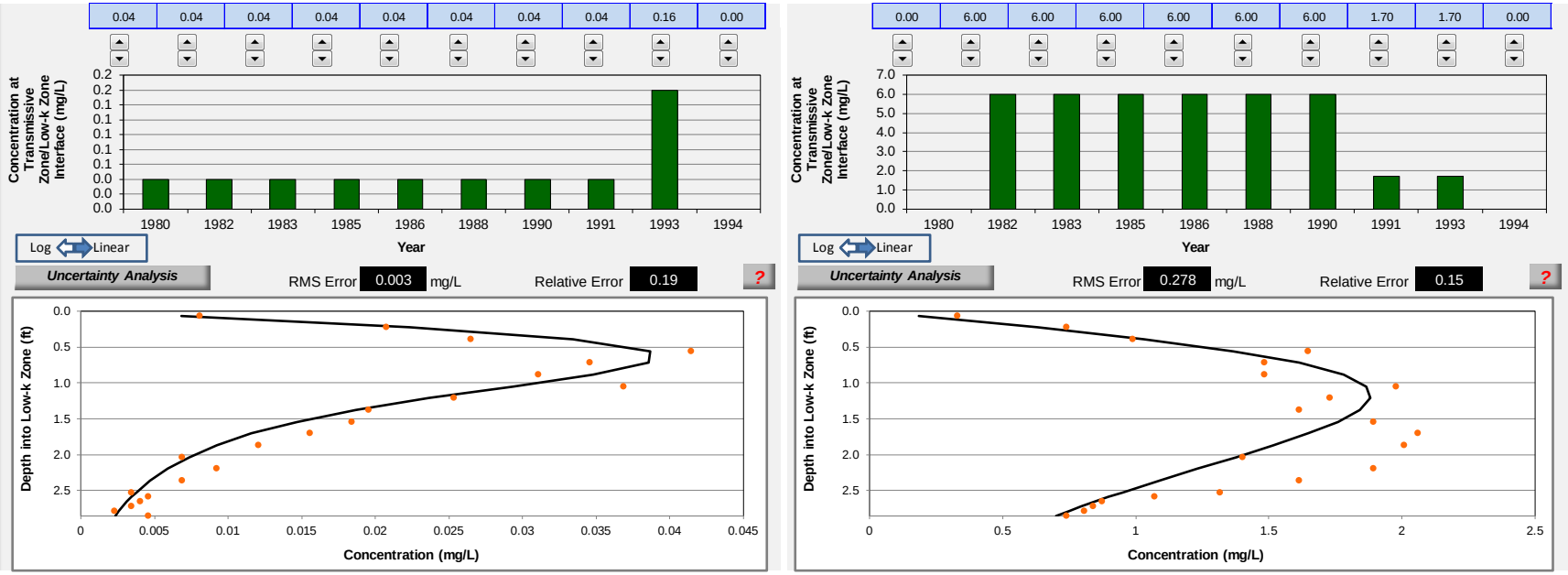


KEY FINDING: *Strong match achieved for PPC-11 using same two-step source history and input parameters described in Liu and Ball (1999). No significant improvement in fit could be achieved by changing source history (including "functional boundary condition" curve) or input parameters.*

Figure 5.41. (a) Source History Estimate for PCE at location PPC-11 at Dover AFB Site. Site described in Liu and Ball (1999, 2002). Source history estimate for TCE at same location is shown in Appendix R.

PPC-13 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(PCE)

PPC-13 Source History Estimate and Fit to Soil Data Using Project Specific Toolkit
(TCE)



KEY FINDING: *Strong match achieved for PPC-13 using same two-step source history and input parameters described in Liu and Ball (1999). No significant improvement in fit could be achieved by changing source history (including "functional boundary condition" curve) or input parameters.*

Figure 5.41. **(b) Source History Estimate for PCE for location PPC-13 at Dover AFB Site; (c) Source History Estimate for TCE for location PPC-13 at Dover AFB Site.** Both sites described in Liu and Ball (1999, 2002).

PM-18 Source History Estimate and Fit to Soil Data

AC-6 Source History Estimate and Fit to Soil Data

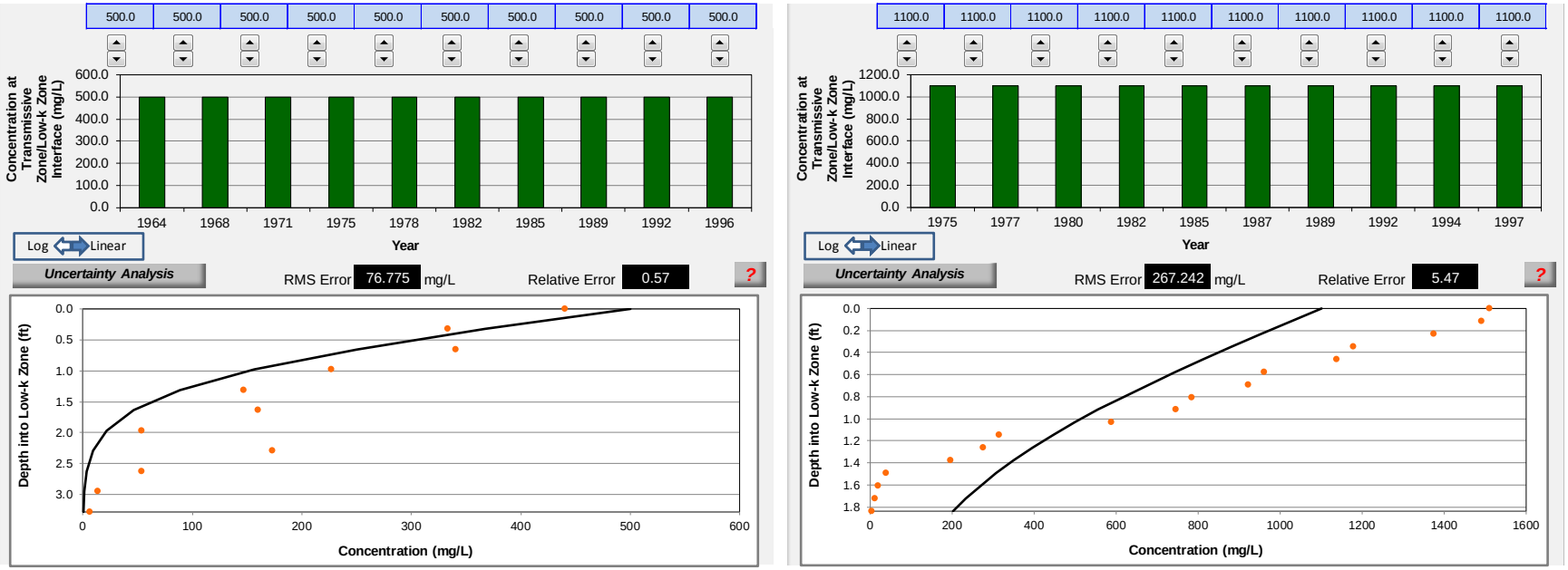


Figure 5.42. (a) Source History Estimate for location PM-18 at Florida Site; (b) Source History Estimate for location AC-6 at Ontario Site. Both sites described in Parker (2003).

6.0 PERFORMANCE ASSESSMENT

A summary of the performance objectives for this demonstration, along with an overview of technology performance, was presented in Section 3. This section includes a detailed assessment of technology performance based on the quantitative data presented in Section 5. Following completion of the sampling and analysis program, the data were reviewed to determine whether the success criteria for each performance objective have been met. The evaluation of each individual performance objective is discussed below, with references to relevant supporting results in Section 5.

6.1 Reconstruct Source Histories - Accuracy

Success Criteria Achieved? **PARTIALLY**

This performance objective was developed as a way to demonstrate the level of confidence that the source history model ("Toolkit") was providing representative results. The assessment was based on the fit of the modeled soil concentration vs. the measured field data for soil concentration. This was used because the source history results (C vs. time data) cannot be compared to real site data in the absence of extended temporal monitoring records. Instead the comparison between the soil results (C vs. depth data) was used as a surrogate for assessing accuracy or "goodness of fit".

Using the soil cores collected as part of this project, seventeen different source history estimates were generated for the locations investigated using the project Toolkit. This included separate source histories for different parent compounds, as well as additional source histories for parent compounds alone and parent compounds plus degradation products. Only 7 of the 17 soil concentration profiles (measured and simulated) associated with these source histories met the criterion (median RPD $\leq$ 30%) (**Table 5.7**). This means that the performance objective was not met. The range of median RPD values was 10 to 200%. In addition to the 7 that met the 30% limit, an additional 4 estimates had a median RPD of < 66% (i.e., measured and simulated values differed by a factor of 2).

Based on a visual inspection of the data comparisons, it was clear that they passed a simple "eyeball test". For all of the cases, the simulated and measured soil data often appeared very similar in style throughout the entire low permeability interval (see **Figures 5.26 - 5.29** and **Figures 5.32 – 5.34**). In particular, the shape of the curve was always captured, and concentrations near the interface and at the depth of maximum concentration were successfully representative. The poorer visual fits typically occurred deeper into the low permeability layers, where concentrations approached zero.

The results of the RPD-based evaluation were not consistent with the visual inspection of the fits, in part because RPD is a limited metric in this case and in part because of the strictness of the criterion. Selecting a criterion that mandated that all of the source histories had to exhibit an RPD of $\leq$ 30% was unlikely to meet with success. This rigid criterion did not account for outliers. Even more importantly, it did not account for the inadequacies of RPD as a goodness of

fit metric. This is particularly true when the concentration values approach zero, where even small absolute differences in concentration can result in very high RPD values. This is what occurred at deeper penetration depths into the low permeability layers, where the fits did appear poorer in many cases, but the actual magnitude of the differences (frequently much less than 1 mg/L) was relatively small.

To overcome these limitations, a secondary metric was developed to aid in the evaluation of this performance objective. The RMS error, which was generated during modeling runs to optimize the results, was well suited for these purposes. The RMS error represents the average error for the datasets, i.e., the average concentration difference between the measured and simulated data over the entire low permeability interval. This makes it a better representation of the error associated with a source history estimate, primarily because it is a single value that accounts for errors throughout the entire interval. Outliers will still impact the error calculation, but the error will be better distributed. The limitation in using the RMS error is that its magnitude is dependent on the magnitude of the datasets being compared, which limits its comparative value across datasets. However, simple normalization procedures can be used to improve its utility. For this project, the RMS error associated with each source history estimate was simply normalized by the maximum soil-based concentration measured throughout the entire depth interval at that location. To be consistent with the RPD-based metric, a limit of 0.3 (i.e., 30%) was set as the criterion for the RMS-based ratio, with success based on at least 75% of the ratios being below this criterion.

For the 17 source history estimates, the RMS error was generally low (0 to 8 mg/L, expressed as equivalent porewater concentration after converting soil concentration data). At any given location, the RMS value was generally an order of magnitude smaller than the maximum measured concentration. When the ratio of RMS error to maximum concentration was calculated, the value for 17 of 17 source history estimates were equal to or below the 30% limit (**Table 5.7**). Consequently, the secondary criterion for this performance was successfully achieved. Using this more representative metric confirmed that the modeling results demonstrated reasonable accuracy, which matches the expectations based on simple "eyeball tests".

Additional source history modeling was completed for cores collected from several other sites that were not part of this demonstration project. For the 18 source history estimates generated using the Toolkit from these other sites, 12 of 18 met the criterion that the median RPD is ≤ 30%. Further, 18 of 18 estimates met the criterion that the ratio of RMS error to maximum measured concentration is ≤ 30% (**Table 5.11**).

Note that an additional illustration of how the basic source history pattern can be accurately assigned to capture the style of the data is presented in **Figure 6.1**. This involved a comparison of the soil concentration profiles resulting from an initial assumption of source strength that declined over time vs. source strength that remained constant over time. Using project data from location OU3-3, it is clear that the selection of one type of source history was more appropriate than the alternative (using both visual inspection and the RMS error).

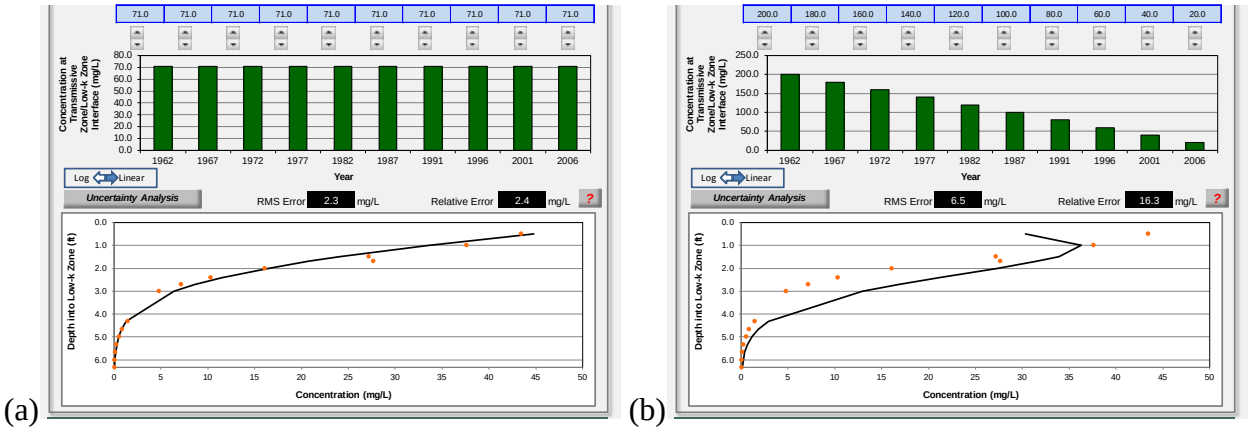


Figure 6.1. Example of How Source History Assumptions Impact the Style of the Data (Using Source History Tool). (a) Assumption of constant source concentration over time (RMS error = 2.3 mg/L); (b) Assumption of a declining source concentration over time (RMS error = 6.5 mg/L) showing that the style of the modeled soil VOC profile vs. time is clearly different than the field-measured profile. Screenshots of the source history spreadsheet tool are used to show the results for both cases. For both cases, the results show the best possible fit that could be obtained using the pattern selected for the source history. For the case where a declining source concentration over time was assumed, linear decay was a better fit than exponential or other decay patterns. The aqueous solubility of PCE (200 mg/L) was used as the upper limit for the initial source concentration. Soil data are from location OU3-3.

6.2 Reconstruct Source Histories - Precision

Success Criteria Achieved? **YES**

To demonstrate that the source history method can generate precise and reproducible results, duplicate cores were collected at locations spaced approximately 1 m apart (OU3-5 within the Former Building 106 source area). Sub-samples were analyzed to establish the soil concentration profiles with the low permeability intervals, and then source history estimates were generated for each soil core profile. The goal was to achieve an RPD between paired data points for the two source histories (i.e., modeled source concentration at single time point vs. source concentration at same time point using duplicate datasets) that was less than 30% for at least 70% of the paired data points. A second objective relied on established the same trend for both source histories using a non-parametric statistical test (Mann-Kendall).

Both of the sub-objectives were successfully achieved. The source histories from the duplicates cores collected at OU3-5 exhibit the same constant trend over time (**Figure 5.14c**, **Figure 5.28b**). The initial concentrations at the two locations were slightly different (30 vs. 32 mg/L) but both remained unchanged from the initial to final timepoints. As a result, a constant RPD of 7% was achieved for all 10 of 10 datapoints. This easily met the goal of 70% of the points achieving an RPD of less than 30%.

The success criterion for the second sub-objective was also met. Specifically, the Mann-Kendall non-parametric test confirmed both source histories exhibited stable trends that were statistically significant. Due to the uniformity of the two source histories, the trend analyses yielded identical Mann-Kendall tests statistics (0), Coefficient of Variation (0), and Confidence Factor (45.6%). Note that this type of non-parameteric test is well-suited for datasets that are not expected to be normally distributed, and the Mann-Kendall method in particularly is widely used in analyzing environmental data.

The results from these duplicate cores support the assumption that both the high-resolution soil concentration profiles, as well as the source histories generated from these profiles, are reproducible. It is natural to expect some differences at certain sites due to spatial subsurface heterogeneities. At NAS Jacksonville, the similarity between the duplicate datasets suggests that there was little to no evidence of heterogeneity at the scale associated with their respective locations (i.e., < 1 m apart).

6.3 Reconstruct Source Histories – Sensitivity

Success Criteria Achieved? **YES**

The purpose of this performance objective was to evaluate the impact of small and large changes to various input parameters on the modeling results. While the number of input parameters is relatively limited, several may be unfamiliar to end-users of the spreadsheet tool (e.g., tortuosity). The tool provides guidance for cases when site-specific values are not available, but it is still valuable to demonstrate how uncertainty in these parameters may impact the results.

Both sub-objectives that were developed as part of this evaluation were met. Small changes in tested parameters (tortuosity, porosity, degradation rates/half-life, organic carbon, release date) did not necessitate changes to the source history trend to fit the adjusted data. Similarly, larger changes to these same parameters did not result in a shift in the "style" of the soil concentration vs. depth results (**Figure 5.36, Figure 5.37**). The latter evaluation relied on a Monte Carlo analysis that is a built-in component of the spreadsheet tool. This allows for a visually-compelling assessment of how sensitive the modeling results are to changes in the individual parameters. Of the parameters tested, porosity has the greatest impact, in part because it impacts concentration estimates (i.e., conversion of soil concentrations to equivalent porewater concentrations) and contaminant transport (i.e., as part of the retardation calculation). Contaminant half-life had little influence until relatively low values were selected (< 10 yr), supporting the use of conservative half-life values in the absence of site-specific evidence of degradation in low k zones.

Collectively, the results of this evaluation confirmed that the modeling results (source history *trend* and the style of the soil VOC profile) at a particular site are not particularly sensitive to these input parameters.

6.4 Comparison of Data Collection Methods

Success Criteria Achieved? **PARTIALLY**

The purpose of this performance objective was to confirm the high level of data quality obtained using the sampling and analysis procedures that were part of this project (i.e., the UG methods). Several sub-objectives were developed as part of this evaluation. Two of the three sub-objectives were successfully achieved.

For the split samples analyzed by different laboratories, the goal was that at least 70% of the sample pairs exhibited an RPD of 30% or less. Twenty seven samples were including in this evaluation, resulting in 39 compound detections. For this set of 39 data pairs, 37 exhibited an RPD of less than 30%, meaning that the success criterion was achieved (**Table J.3**). The two that were above this limit represented marginal exceedences (30.03% and 42.6%). The median non-directional RPD of this dataset was 11.8%. A strong correlation was also obtained following linear regression of the split sample datasets (slope = 0.99, R^2 = 0.99) (**Figure 5.25**). These results confirm that there was a high level of precision between data generated at the UG laboratory and data generated at a standard commercial laboratory.

A total of 26 co-located soil samples were collected and analyzed using two different methods: (1) baseline method, consisting of Encore sample collection without preservation in the field, followed by sample analysis at a commercial laboratory; and (2) the UG method, consisting of a metal soil sample with methanol preservation in the field, followed by extended shake-flask extraction and analysis at the UG laboratory. The goal was to demonstrate limited variability between the two datasets (R^2>0.9 based on linear regression). Linear regression of the datasets generated an R^2 of 0.83, which was slightly lower than the objective of 0.9 (**Figure 5.21**). It was clear based on the slope of the regression line (0.79) that the baseline method resulted in significant losses as a result of eliminating the field preservation step. This loss of volatiles was expected, but it appeared to also contribute to overall variability in the dataset comparison, as evidenced by the R^2 value. These results provide a quantitative basis for the importance of preservation in reducing variability and limiting volatile losses. Because the split sampling results demonstrated the differences between lab analyses were minimal, it is clear that sample handling differences are a primary contributor to bias and variability in the data.

A final sub-objective was designed to show that the UG laboratories met standard acceptance criteria for precision. In this case, a limit of no more than 10% RSD between duplicate samples was chosen as the success criterion. Twenty-two field duplicates were collected and analyzed at the UG laboratory, with a resulting median RSD of 7% (covering 60 analyte detections) (see **Table J.4** in **Appendix J)**). Therefore, the success criterion of a median RSD of 10% was achieved. For further evidence, the RSD of 95% of the sample pairs fell below this this limit. The duplicate datasets also demonstrated strong correlation following linear regression (**Figure 5.25**)

6.5 Ease of Use

Success Criteria Achieved? **PARTIALLY**

Success criteria for this objective were primarily evaluated qualitatively. As part of a larger objective to evaluate the time required to complete these methods, a specific criterion that was chosen involved completing all work at a site within a single mobilization. Due to project restrictions, the field work at NAS Jacksonville was completed in two separate mobilizations. In other words, screening-level characterization data (MIP, Waterloo$^{APS\ TM}$, Geoprobe HPT) were completed as part of an initial mobilization, and the coring was completed as part of a second mobilization. The reasons for this were logistical and not technical in nature:

a. The two source areas that were investigated are part of the same site (OU3 at NAS Jacksonville). This meant that the entire program was longer, and it was more logical to complete each characterization phase (e.g., Waterloo profiling) at both source areas before moving on to the next phase (e.g., soil coring).
b. Extra work was done in support of another project involving this PI group (SERDP ER-1740), specifically the inclusion of another screening-level characterization method (MIP).

As a result, multiple screening-level methods were used during the initial mobilization (including both MIP and Waterloo$^{APS\ TM}$). This made it too difficult to perform the soil coring during the same mobilization. Instead, the work was completed in two separate, shorter field programs.
Note that the all work related to this characterization approach was completed at two different source areas was completed in approximately 3 weeks, or approximately 1.5 weeks per source area. For high-resolution characterization using multiple methods, this is a reasonable length. If these requirements had not existed and only a single site was being investigated, then we are certain that the field program could have been completed in a single mobilization. Therefore, the success criterion for this sub-objective would have been met under normal circumstances.

The bulk of the success criteria for this objective were met. Specifically, field personnel found the field characterization approach straightforward to implement. This included personnel who were relatively unfamiliar with specific methods. All were able to familiarize themselves rapidly and are confident that they could implement them again in future projects. Stone Environmental Inc. served as a technology specialist for the project, and they supplied and operate the Waterloo$^{APS\ TM}$, MIP, and Geoprobe HPT systems. However, a local contractor supplied the direct-push rig to used drive the tools and collect data. This drilling contractor had extensive experience with MIP but no experience in using some of the other data collection system. Regardless, he had no problems successfully executed the work plan under the supervision of GSI/UG/Stone field personnel.

Collectively, the project demonstrated that the field characterization methods are easy to implement and can be completed in a timely manner.

6.6 Selection of Appropriate Locations

Success Criteria Achieved? **YES**

Success criteria for this objective were evaluated qualitatively. Of particular importance was evaluating whether site documentation was sufficient to select an appropriate test area at each site. At NAS Jacksonville, this was confirmed. While groundwater monitoring data was limited, extensive mapping of the sites with MIP had already been completed, and these data were useful in understanding site conditions and selecting locations for further investigation. For the purposes of this project, collecting additional characterization data was deemed unnecessary. Exact coring locations were based on screening-level characterization data that was a specific component of this project. This step is recommended for most sites, although there was an option to omit it at NAS Jacksonville OU3 given the availability of MIP data. However, the existing MIP data were approximately 5 years old, and relying on these data could have resulted in some problems, including difficulty in calibrating model data (e.g., MIP provides no groundwater data) and potential inconsistencies between tool operating procedures.

The data generated for this project were consistent with existing site data, though the former (particularly the coring data) were purposely more quantitative.

The collection of soil concentration profiles at multiple locations per site also proved valuable in understanding source history and attenuation patterns. In particular, the selection of points along a downgradient flowpath provided confirmatory information about contaminant fate and transport (without having to rely on 2-D modeling). Without multiple points per site, information may have been lost or subject to misinterpretation.

7.0 COST ASSESSMENT

A key objective of this project was to track costs associated with this technology demonstration in order to provide a basis for estimating costs of a full-scale implementation of the technology. Full-scale implementation costs were then incorporated into various scenarios and then compared to various alternatives. Specifically, an outcome-based cost comparison was made, using the data generated during this project to determine the viability of MNA vs. more aggressive remedial options, and then determining the net cost difference between the various outcomes.

7.1 Cost Model

As part of the demonstration, the cost of implementing the field program was carefully tracked and this cost data was used to estimate the cost that would be associated with implementing this methodology at a generic site. These are summarized in **Table 7.1**. Only those elements that are unique to this technology were included as part of the cost assessment and comparison. Other costs that are standard to characterization methods were tracked but were not included in the cost assessment, along with costs that were incurred during this demonstration with the objective of obtaining a more comprehensive dataset than would be expected during a standard implementation.

7.1.1 Technology-Specific Cost Elements

The following descriptions focus on the cost elements that are specifically associated with the source history characterization approach. There are other cost elements associated with the various scenarios that were part of the scenario-based cost model, but these are not discussed separately here.

*Review of Existing Data and Preliminary Selection of Locations***:** The approach developed as part of this project focuses on characterization of one or more locations at a chlorinated solvent site. In order to select generally favorable locations, a review of existing site data (to the extent that it is available) by experienced personnel is required prior to completing additional site work. The level of review is similar to that for conventional characterization efforts at a site, such that there are no unique requirements for the review proposed as part of the current project. Typical reviews would involve approximately 100 hour of labor and cost $10,000 to $20,000 depending on personnel used (likely a mixture of entry-level and mid-level engineer and/or geologist) and associated labor rates.

Table 7.1. Cost Model for Field Demonstration

Cost Element	Tracked Data
Review of Existing Data and Selection of Locations	Costs are standard for site characterization but were tracked to demonstrate effort associated with typical application of this method • Personnel required and associated labor
Screening-Level Characterization (profiling)	Detailed stratigraphic pre-characterization is recommended • Unit costs for characterization per ft (including time for oversight, mobilization) Other costs are standard for baseline characterization
Soil Sampling and Analysis	High-resolution soil sampling is required • Unit costs for sampling per ft (including time for oversight) • Unit costs for analysis per sample
Well Installation	Multi-level wells are optional (to track temporal trends in groundwater for comparison to model predictions) but were ultimately not used for this demonstration; no cost tracking
Data Review and Source History Reconstruction (Modeling)	Trained personnel for compiling and evaluating data • Personnel required and associated labor Use of publicly-available free software tool and guidance document
Material Cost	No unique requirements anticipated; no cost tracking
Long-Term Monitoring	No unique requirements beyond option for additional monitoring wells; no additional cost tracking
Operations and Maintenance Costs	No unique requirements anticipated; no cost tracking
Waste Disposal and Decommissioning	No unique requirements; no cost tracking

Screening-Level Characterization: The field demonstration included a comprehensive pre-characterization that incorporates Waterloo$^{APS\ TM}$ with groundwater sampling and analysis. In addition, MIP and HPT were completed at a number of locations to provide companion high-resolution characterization datasets as a basis for methods comparison (partially in support of SERDP ER-1740). Regardless of the type of characterization method that is selection, this step is important in fully understanding stratigraphic conditions at the test site, identifying locations for soil sub-sampling, and calibrating quantitative relationships between soil and groundwater concentrations. For the purposes of the cost comparison, Waterloo$^{APS\ TM}$ was used to provide a significant source zone characterization and detailed spatial information (particularly vertical) for permeability and target contaminants. For the demonstration, costs for labor (geologist/engineer for oversight) and implementation (subcontractor mobilization, day rate, sample analysis) were tracked and reported as total cost and included in the cost per vertical foot estimates that incorporated all steps in the characterization process (amortized over the number of locations characterized). The scale of the characterization efforts that are part of this project were similar to what would be proposed for full-scale implementation at other sites. As a result, there are no issues of scale.

Note that for this phase of the project, a higher number of personnel than would otherwise be used for a standard screening-level characterization, in part to orient various project team members to the site. Only those costs associated with a standard screening-level characterization were included for the scenario-based cost comparison.

Soil Sampling and Analysis: The proposed approach for focuses on detailed soil sub-sampling, a task that is typically included as part of initial characterization efforts at impacted sites. However, the number of soil samples collected per location is higher than what would be typically collected during conventional soil characterization.

In terms of analytical requirements, the analyte list for this project included VOCs and organic carbon. The latter is infrequently included in analytical programs but is important for understanding sorption effects in low permeability zones. In addition, the project-specific analyte list included several parameters (carbon isotopes, biomarkers, geochemical indicators) that would not necessarily be part of a conventional application of this approach. These were added to provide more complete forensic information about contaminant degradation and were important for project objectives, but could be omitted from more general applications. As such, they were not included in the scenario-based cost comparison. Both the VOC analyses and organic carbon analyses were performed at the University of Guelph using slightly modified techniques to improve extraction and detection limits. Note that the University of Guelph operates in a manner similar to a commercial laboratory, charging on a per sample unit rate that depends on the analyses performed and the total number of samples anticipated. This facilitates cost tracking as well as cost comparisons to third-party commercial laboratories. In the end, the overall analytical unit costs for this project were similar to commercial labs.

The cost assessment tracked soil sampling and analyses costs on a per foot basis using real project costs. Costs also included labor (geologist/engineers for collecting samples and oversight), drilling subcontractors, and sample analyses. There are no issues of scale anticipated with these unit costs since the scale for this project is relatively close to what would be proposed for full-scale implementation at other sites.

Because this high-resolution soil sampling was considered a standalone or extra step in the scenario-based cost comparison, there was no direct comparison to costs associated with more conventional soil sampling and analyses, using a commercial laboratory and fewer samples per location. However, an estimate of unit costs associated with the project-specific method (for the scenario envisioned) was approximately $400 per vertical foot, while a rough estimate of the costs associated conventional soil sampling and analysis would be $100 to $200 per vertical foot (depending on the number of analytes).

Similar to the screening-level characterization step, this phase of the project utilized a higher number of personnel than would otherwise be used for a more typical implementation of this method. Only those costs associated with a typical high-resolution soil sampling program were included for the scenario-based cost comp

Well Installation: Multi-level monitoring wells are an option for the proposed characterization approach because they provide data for tracking temporal trends in groundwater and for checking/calibrating model predictions on source history. Installation of multi-level wells immediately after soil sub-sampling is more cost-effective because it can utilize the open borehole and available personnel. The number of sampling ports (i.e., number of discrete sampling depths) can be tailored to generate long-term groundwater data that compliment the soil/groundwater data obtained.

For the current demonstration, wells were not installed due to the short-term nature of the project. Consequently, costs were not included as part of the comparison. However, costs associated with well installation for the purposes of long-term monitoring were included in the scenario-based cost comparison.

Data Review and Source History Reconstruction (Modeling): The field data obtained as part of this approach must be reviewed and processed in order to generate source history estimates for sites involved. In terms of labor hours, the level of review is similar to what would be required for conventional characterization efforts, and thus will not be tracked separately. However, the actual reconstruction of source history will require personnel that are able to use the spreadsheet tool ("Toolkit") that is one of the project deliverables. For the purposes of the cost assessment, real project costs were used, though it was assumed that this person did not need to undergo extra training (i.e., reading relevant sections of the guidance document and becoming familiar with how the model works). These trained personnel require several hours with the spreadsheet tool in order to generate the desired output data. As a result, the costs for this element were based on the labor required, and units reported on a per site basis. Note that both the guidance document and spreadsheet tool are intended to publically-available and thus free to all end-users, so there are no separate costs with their use beyond labor.

Material Cost: There are no additional material requirements for this characterization method. Therefore, there are no unique cost elements that were tracked.

*Long-Term Monitoring***:** Additional long-term monitoring requirements are a potential cost depending on the option to install monitoring wells as part of characterization efforts or to confirm assumed trends over longer periods. Wells were not installed as part of this project, and therefore long-term monitoring was not a relevant cost element for the standalone application of this approach (i.e., Scenario 1). However, it was included as part of Scenarios 2 and 3, which consider for longer project lifetimes.

Operations and Maintenance: Because there are no permanent installations that are associated with the proposed technology, there are no additional operations and maintenance costs. Therefore, costs were not tracked as a unique element.

Waste Disposal and Decommissioning: For the proposed technology, there were no additional costs associated with either waste disposal or decommissioning. These were not considered unique cost elements and, as a result, were not tracked separately.

7.1.2 Cost Scenarios

The cost elements described above were incorporated into several scenarios for comparing the costs associated with various uses of the source history approach.

- ***Scenario 1: Implementation of Source History approach as a standalone characterization method***. In this case, it was assumed that the source history method was used to improve the conceptual site model but was not necessarily included as part of remedy selection process. As such, there is no comparison to alternative outcomes (e.g., MNA vs. source remediation) and simply represents the costs associated with implementing the approach itself. This means it also represents a situation where the method was implemented but did not ultimately change the remedy selection.
- ***Scenario 2: Source History Leading to MNA vs. Source Treatment.*** In this case, the source history method was implemented and resulted in a strong line of evidence for source attenuation over time. Consequently, MNA was approved as a site remedy moving forward. The alternative outcome was that source treatment was required as an initial step. For the purposes of this cost assessment, in situ bioremediation was used as a representative in situ treatment technology, followed by MNA as a long-term management strategy.
- ***Scenario 3: Source History Leading to MNA vs. Pump-and-Treat.*** This case also involves the use of the source history method as a strong line of evidence that ultimately supports the selection of MNA as a long-term management strategy to ultimately achieve site closure. The alternative outcome was that pump-and-treat was required as part of the long-term management strategy for the site.

7.1.3 Assumptions

The various assumptions used to develop the cost model and generate cost estimates for the various scenarios are described below:

- Site characteristics for the generic site used in this assessment were assumed to be similar to those at the former Building 106 source area at NAS Jacksonville. This ensured that the cost tracking performed for the project would be useful and representative. Consequently, the site was assumed to be contaminated with chlorinated solvents to depths of approximately 35 ft bgs. A low permeability layer was present within the impacted zone, and a high percentage of the low to moderate degradation activity observed near the source. The size of the source area and near downgradient plume was assumed to be 0.5 acre. The total volume requiring treatment was assumed to be
- The source history characterization approach was assumed to include 6 locations for screening-level characterization (using Waterloo$^{APS\ TM}$) and 4 locations for high-resolution coring. These locations would be focused in the source area and near

downgradient plume. Soil subsampling occurred within a 35-ft interval at a frequency of approximately one sample every 0.7 ft (averaged over low and high permeability zones).

- For those Scenarios that involve comparison of outcomes (2 and 3), the costs associated with additional characterization efforts during the post-remedy selection period were not considered. For example, additional characterization may occur immediately prior to the start of in situ bioremediation to optimize the design. These costs can vary widely based on site-specific considerations and thus were not included in this cost assessment.
- MNA and pump-and-treat were tracked over a 30-year timeframe. This was based on normal expectations for site management rather than any assumptions about the actual remediation timeframe associated with these remedies. In part, this is because there are no specific remedial goals for the site used during this demonstration project at this time.
- Source treatment was assumed to reduce the remediation timeframe by 33% relative to MNA or pump-and-treat. This is based on the reduction of mass of approximately 90% following implementation of the treatment technology. This is a conservative estimate—in many cases, the impact of source treatment on remediation timeframe can be minimal (Newell and Adamson, 2005). Further, the majority of mass is assumed to be present in the lower permeability zones, such that it would be hard to target using conventional amendment delivery strategies.
- The treatment area for in situ bioremediation was assumed to focus on only the source (and not the downgradient plume). This area was estimated to be approximately 15,000 ft2 (150 x 100 ft) with a 20 ft treatment thickness and require 150 injection points installed using direct-push rig (using 10 ft center spacing). Two direct-push rigs working in parallel were assumed. The design was assumed to rely on a two injections of a slow-release substrate (two years apart), using an injection rate of 1 to 10 gpm to estimate the time required for injecting substrate and chase water (assuming manifold with ability to inject up to 10 wells at a time). Note that the labor requirements are based on an extended pumping period (45 days per event) due to the slow delivery rate assumed for the lower permeability layers There are other delivery strategies that could be used, which may result in slightly different cost estimates. However, the design used for this model resulted in a unit cost of $38 per cubic yard (based on a treatment volume of approximately 11,000 cubic yards), which is consistent with typical unit costs for in situ bioremediation as a source zone depletion technology (McDade et al., 2005). It is our experience that higher unit costs are appropriate for settings with significant portions of the contaminants present in low permeability zones.
- The treatment area for a groundwater extraction system (i.e., pump-and-treat) was assumed to be similar to that for the in situ bioremediation option. A design pumping rate of 2 gpm was selected based on a similar rate that was targeted as part of the interim remedy for the Building 780 site from the late 1990s through the mid 2000s. Due to the relatively low hydraulic gradient at the site, this pumping rate should be sufficient to capture the plume using 2 extraction wells (with only one operating at a time, with a second for backup). Ex situ treatment using GAC or air stripping was assumed, with discharge to the storm sewer system at no additional cost (due to the low rates). The capital costs ($245,000) and O&M costs (approximately $40,000 annually) were consistent with published values (EPA, 2001) for small-scale systems.

- Long-term monitoring involved bi-annual (twice yearly) monitoring of 8 wells for CVOCs. The monitoring period for MNA and pump-and-treat options were assumed to be 30 years, while the monitoring period for the in situ source treatment option was assumed to be 20 years.

7.2 Cost Analysis

This section provides a cost comparison for each of the three scenarios described above. The costs were compiled using a combination of the demonstration data, information from similar projects, vendor quotes, literature values, and the Remedial Action Cost Engineering and Requirements (RACER) software. Drillers and analytical laboratories that were part of the demonstration were used where applicable. The cost breakdown for each scenario is presented in **Table 7.2** and summarized below.

Scenario 1: For the case when the source history method was applied at a single site at a scale similar to that used for this project, the standalone costs were approximately $161,000, or $1150 per vertical foot (cored). Essentially, this represents the approximate costs that were associated with implementing the method at former Building 106 source area in a standard manner (i.e., if the costs of extra project-specific analyses and personnel were excluded). Note that this method includes $35,800 related to the project-specific report, a cost that could likely be reduced from a generic application since reporting would be included as part of the modeling-focused data analysis step. This would reduce the unit costs to approximately $950 per vertical foot. Regardless of whether or not the results are used to support MNA as a remedy, the information can prove valuable for developing and/or refining the conceptual site model.

Scenario 2: For the case when the source history method was implemented (at a single site at a scale similar to that used for this project) to support MNA, the total life-cycle cost was $651,000 (or $59/cy). Approximately 26% of this was associated with the supplemental source history characterization method, while the remaining cost was associated with long-term monitoring and reporting. The total life-cycle cost associated with the alternative source treatment option was estimated to be $849,000 (or $76/cy), with approximately 50% of this cost related to the treatment itself and the remaining cost attributable to long-term monitoring and reporting. Therefore, the source history approach resulted in a total cost that was 23% lower than the source treatment option.

The primary benefit of the in situ treatment option is that it could result in a shorter remediation timeframe (and thus allows the land or groundwater resources to return to beneficial uses more quickly). However, there is considerable uncertainty regarding the performance of in situ bioremediation at a site where much of the mass is present in low permeability zones. Amendment delivery within these zones is challenging, and even if effective, may not significantly reduce the remediation timeframe relative to MNA. The MNA-based option has the advantage of lower cost, but it is also significantly less material-intensive and energy-intensive (i.e., lower carbon footprint). Because there is a reduced labor requirement, it is also preferable from a health and safety perspective (i.e., lower risk of on-site accidents). Finally, the potential impacts on secondary water quality that are associated with in situ bioremediation are avoided with MNA.

Scenario 3: This scenario compared the case when the source history method was implemented (at a single site at a scale similar to that used for this project) to support MNA vs. a site where pump-and-treat was required as a source control measure. For the MNA option, the total life-cycle cost was again $651,000 (or $59/cy), with approximately 26% related to the supplemental source history characterization method. The total life-cycle cost associated with the alternative pump-and-treat option was estimated to be $2,570,000 (or $232/cy), with approximately 50% of this cost related to long-term (30 year) operations and maintenance of the system. Therefore, the source history approach resulted in a total cost that was 75% less than the pump-and-treat option.

The MNA-based option represents a significant cost savings and demonstrates the advantage of demonstrating that a source is attenuating (and thus more likely to result in a stable or shrinking plume). In many cases, pump-and-treat is unlikely to change the remediation endpoint relative to MNA, so the costs associated with pump-and-treat will naturally increase the total costs associated with site management. Even in cases where the source history method indicates that the source loading has been relatively constant over time (i.e., as indicated for the former Building 106 area), the method can be used to confirm significant attenuation along the plume flowpath. Additional benefits of the MNA-based approach were described for Scenario 2, many of which are related to sustainability and safety issues. A final consideration is that once a pump-and-treat system is operating, it can be difficult to shut off from a political perspective. Because the costs of pump-and-treat accrue at a higher rate than MNA, this can result in much higher lifecycle costs if the project extends beyond the 30-year timeframe that was assumed for this simple model.

Table 7.2. Summary of Results of Cost Modeling

COST ELEMENT	SCENARIO 1	SCENARIO 2		SCENARIO 3	
	Source History Characterization Only (Duration = 3 months)	Source History Characterization Followed by MNA (Duration = 30 years)	In Situ Source Treatment Followed by MNA (Duration = 15 years)	Characterization Followed by MNA (Duration = 30 years)	Pump-and-Treat as Sole Remedy (Duration = 30 years)
TASK 1. Review of Available Data and Location Selection	$8,650	$8,650	$0	$8,650	$0
TASK 2. Screening-Level Characterization	$35,100	$35,100	$0	$35,100	$0
TASK 3. High-Resolution Soil Coring and Sampling	$49,300	$49,300	$0	$49,300	$0
TASK 4. Modeling	$10,900	$20,400	$0	$20,400	$0
TASK 5. Other Characterization/Reporting in Support of Remedy Selection/Design	$0	$0	$0	$0	$0
TASK 6. Well Installation (monitoring wells, injection wells, extraction wells)	$0	$29,450	$29,450	$29,450	$33,950
TASK 7. Treatment System Design and Installation	$0	$0	$422,800	$0	$245,300
TASK 8. Treatment System Operations and Maintenance	$0	$0	$0	$0	$1,235,000
TASK 9. Long-Term Monitoring	$0	$387,000	$250,000	$387,000	$657,000
TASK 10. Closeout and Decomissioning	$0	$0	$0	$0	$30,000
TASK 11. Final Reporting	$35,800	$35,800	$35,800	$35,800	$35,800
CONTINGENCY (15%)	$20,963	$84,855	$110,708	$84,855	$335,558
TOTAL COST	$160,713	$650,555	$848,758	$650,555	$2,572,608
COST PER LOCATION (4)	$40,178	NA	NA	NA	NA
COST PER FT	$1,148	NA	NA	NA	NA
LIFE-CYCLE COST PER CUBIC YD TREATED	NA	$59	$76	$59	$232

Notes: (1) See Section 7.1.2 for description of scenarios; (2) See Appendix S for full list of all cost input and output data; (3) Costs per location and per foot include only those locations that were cored; (4) Treatment volume is approximately 30,000 cubic yards.

7.3 Cost Drivers

The total costs of implementing this technology are primarily associated with the level of characterization performed at a site. The goal should be to collect sufficient data to meet site-specific objectives (i.e., line of evidence for MNA, improve conceptual site model). The key cost drivers are the number of locations characterized per site, and the number of soil samples collected per location. These parameters were included in the following sensitivity analysis.

7.3.1 Sensitivity to Number of Locations Cored Per Site

The baseline scenario in the cost model used four locations for a relatively modest-sized source area where extensive characterization data were already available. At larger sites, additional investigation points may be necessary. Assuming all other inputs remained unchanged, the estimated costs associated with the number of cored locations are shown in **Figure 7.1**:

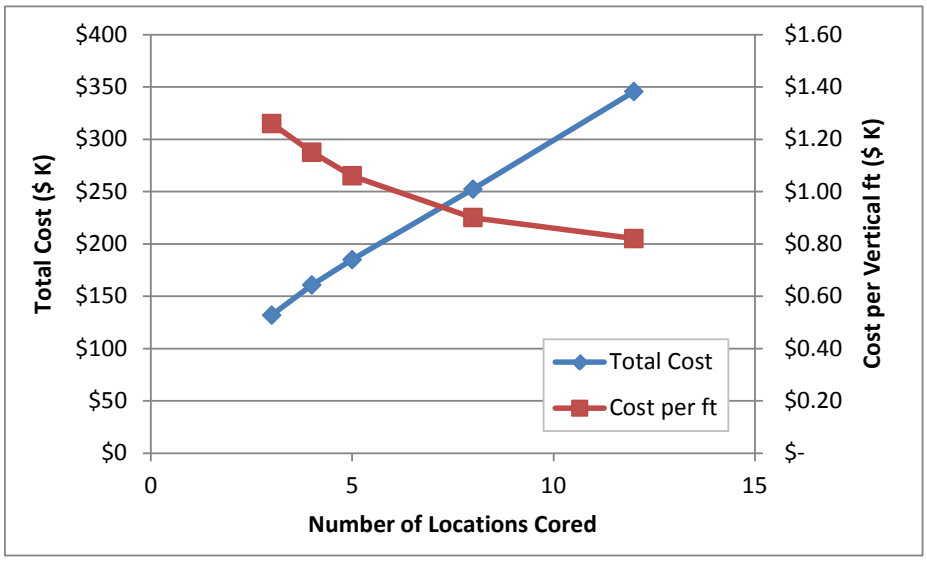


Figure 7.1. Sensitivity of Cost of Source History Characterization Approach to Number of Locations Cored

While total costs understandably increase if the number of locations is increased, there is an economy of scale that results in a decrease in the cost per vertical foot. Note that this sensitivity analysis assumed that there was also an increase in the number of locations where a screening-level characterization method was used (allowing for amortizing of mobilization fees). It also includes modeling and reporting costs, which increase modestly when additional locations are added to the characterization program.

7.3.2 Sensitivity to Number of Soil Samples Characterized Per Site

The baseline scenario in the cost model assumed that 50 soil samples were collected and analyzed per location, over a vertical interval of 35 ft. In addition, duplicates were collected at a

frequency of 1 per 10 samples. This represents 1 sample per 0.7 ft of characterized soil (not including duplicates). For an interval containing low k and high k intervals of similar thickness, this is approximately equivalent to a 1-ft sampling frequency within the high k interval(s) and a 0.5-ft sampling frequency within the low k interval(s). Higher sampling frequencies may be desirable, especially in heterogeneous formations, and the sensitivity of the cost estimates to this parameter is shown in **Figure 7.2**:

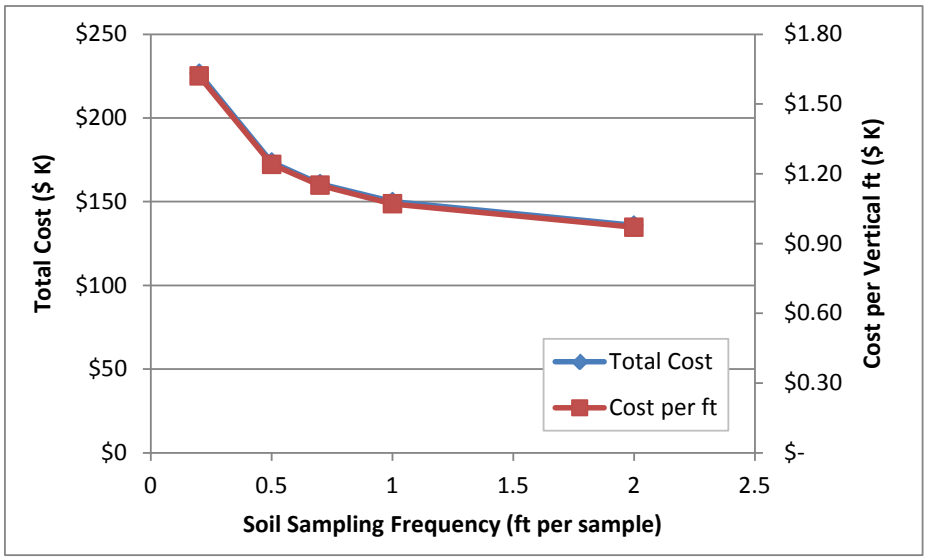


Figure 7.2. Sensitivity of Cost of Source History Characterization Approach to Soil Sampling Frequency

Both total costs and costs per foot increase at the same rate as the sampling frequency is increased. However, the curves in **Figure 7.2** show that the rate of change is relatively flat. The most significant cost increase that results from increasing the number of samples per location is associated with sample analyses. Field labor costs increase slightly because it requires more time to process cores. However, the number of cores collected does not change, and thus drilling costs exhibit only marginal increases. Labor costs for modeling and reporting also change little.

Increasing the number of samples per location essentially increases the level of confidence that an accurate soil VOC profile is obtained, and thus the style of the source history can be estimated using the model. Since the incremental costs of higher sampling frequencies are relatively modest, it is recommended that sampling programs should use as high of frequency as project budget reasonably permit. Because diffusion-dominated penetration into low permeability units generally occurs within the first 5 to 10 ft, it is recommended that sampling frequencies of no more than 1 sample per ft are used to implement this approach. Further, sampling frequencies of 1 sample per 0.2 to 0.5 ft are highly preferable within the low permeability zones.

8.0 IMPLEMENTATION ISSUES

8.1 Regulations and Permits

This technology is focused on collecting high-resolution characterization data for the purposes of modeling source history. However, the methods for collecting that data are already familiar and unlikely to be subject to additional regulatory oversight. Implementation of this technology has no permitting concerns beyond what are already associated with subsurface drilling at a contaminated site. This would include: i) digging clearance to ensure that utility lines or underground structures would not be harmed; and ii) proper disposal of investigation-derived waste (e.g., excess soil material from cores).

Based on our experience, high-resolution site characterizations of this nature are typically regulated the same way that other site investigations are. Specifically, work plans would need to be approved in advance by the appropriate regulatory entity.

8.2 End-User Concerns

The primary end-user concerns are associated with understanding how to collect site data and apply the source history model in an appropriate way, as well as understanding how to use results.

The User's Manual that was generated from this report provides detailed guidance on both data collection and how to apply the software model (see **Appendix P**). In terms of how to use these results, they should be considered a "line of evidence" for supporting MNA decision-making. For example, the output graphs from the source history model (concentration vs. time in the transmissive zone) are intended to be directly transferrable to any type of site report. This would include feasibility studies or remedy selection documents that would be submitted to a regulatory agency in support of MNA. The results are likely to be unfamiliar to a regulator, so a certain level of educating by the end-user may be necessary, as is the case with any line of evidence for MNA. The format for the model results, as well as the input parameters, were kept as simple as possible to help smooth this education process. The User's Manual is intended to provide an additional resource, and the PIs expect to publish at least one peer-reviewed article documenting the overall utility of the source history approach. Collectively, these should make a strong case for the validity of source history modeling as a line of evidence for MNA evaluations.

However, it should be understood that the source history results from the model are not "unique", meaning that they are aimed at capturing the ***style*** of the source history as opposed to matching the "true" source history. The latter, understandably, cannot be established with 100% certainty, regardless of the methods employed. First-time users of the software will appreciate that a certain level of knowledge about conditions at the site will be very helpful in determining reasonable starting values for the input parameters. The demonstration project completed a sensitivity analysis to show the importance of many of these parameters. The model is relatively

transparent, so it is easy for the user to visualize how changes in any one parameter can impact the results.

It also should be understood that the model does not perform unconstrained guesses at the source history. In other words, the user must provide an initial guess at the release date, and then adjust accordingly based on the initial results. This trial-and-error approach is normal with this type of modeling effort and can lead to a better appreciation for how the input data affect the results.

Finally, while not necessarily providing a unique solution, it can be equally valuable to use the model to understand what are ***not*** reasonable estimates of the source history for a particular location. This can be very useful for building a proper conceptual site model, as well as for evaluating whether certain pre-conceived notions about a site are technically sound based on the model output.

8.3 Procurement

There are no procurement issues related to the use of this technology. The technology does not require permanent installations at a site. Collection of screening-level characterization data and soil cores can be completed using methods that are commercially available. There are a number of technology specialists and other service providers that are experienced at collecting these types of data.

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APPENDIX A:
POINTS OF CONTACT
Determining Source Attenuation History to Support Closure by Natural Attenuation

Environmental Security and Technology Certification Program (ESTCP)
Project ER-201032

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APPENDIX B

Documents from Previous Site Reports

Appendix B.1 NAS Jacksonville OU3 Cross-Sections (Source: Remedial Investigation and Feasibility Study OU3, 2000)

Appendix B.2 CPT Stratigraphic Data (2006) from NAS Jacksonville OU3 (Source: Mike Singletary, NAVFAC)

Appendix B.3 DPT Groundwater Sample Results (2006) from Jacksonville OU3 (Source: Mike Singletary, NAVFAC)

Appendix B.4 DPT Soil Sample Locations and Results Sample Results (2007) from Jacksonville OU3 (Source: Mike Singletary, NAVFAC)

Appendix B.5 CPT/MIP Data (2006) from NAS Jacksonville OU3 (Source: Mike Singletary, NAVFAC)

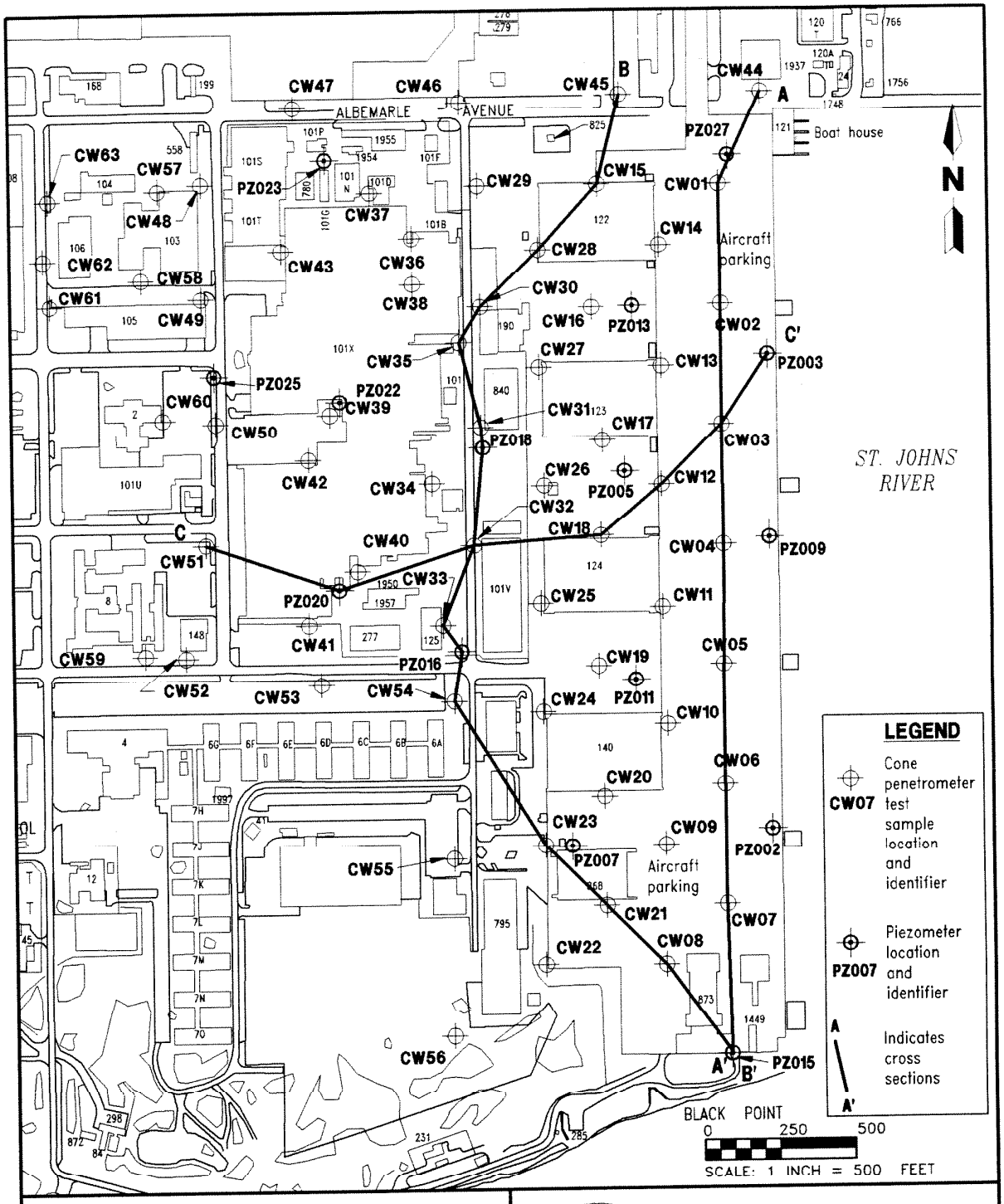
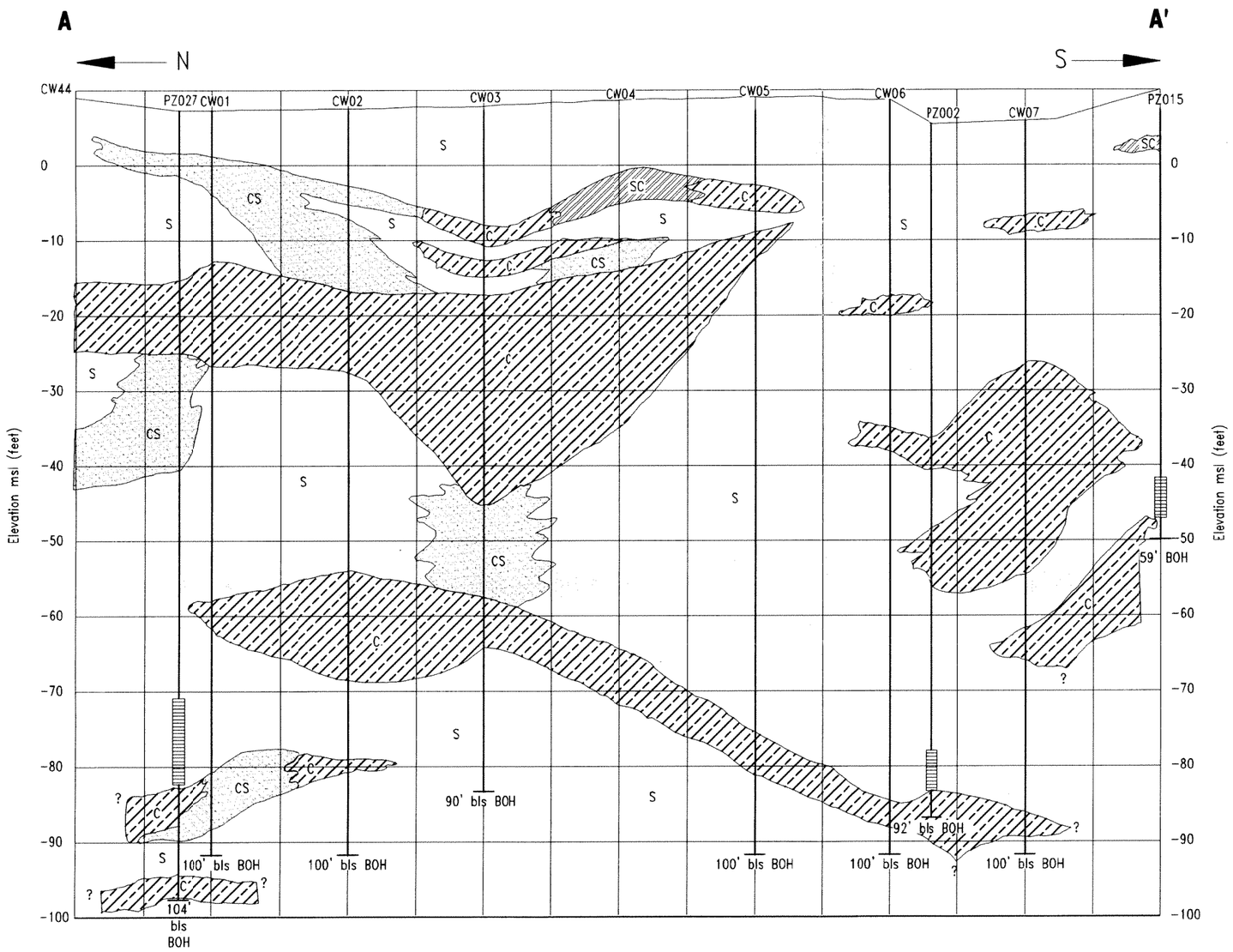


FIGURE 3-2
LOCATIONS OF GEOLOGIC CROSS-SECTION LINES

K:\02562\02562-09\RIF\02562523.DWG, VC-VC 02/15/00 08:56:21, ACAD14

REMEDIAL INVESTIGATION AND FEASIBILITY STUDY
OPERABLE UNIT 3

NAVAL AIR STATION JACKSONVILLE
JACKSONVILLE, FLORIDA



LEGEND

- C: Clay
- CS: Clayey sand
- SC: Sandy clay
- S: Sand
- ? Unknown contact
- Screened interval
- BOH Bottom of hole
- bls Below land surface
- msl Mean sea level

0 200 400

SCALE: 1 INCH = 400 FEET

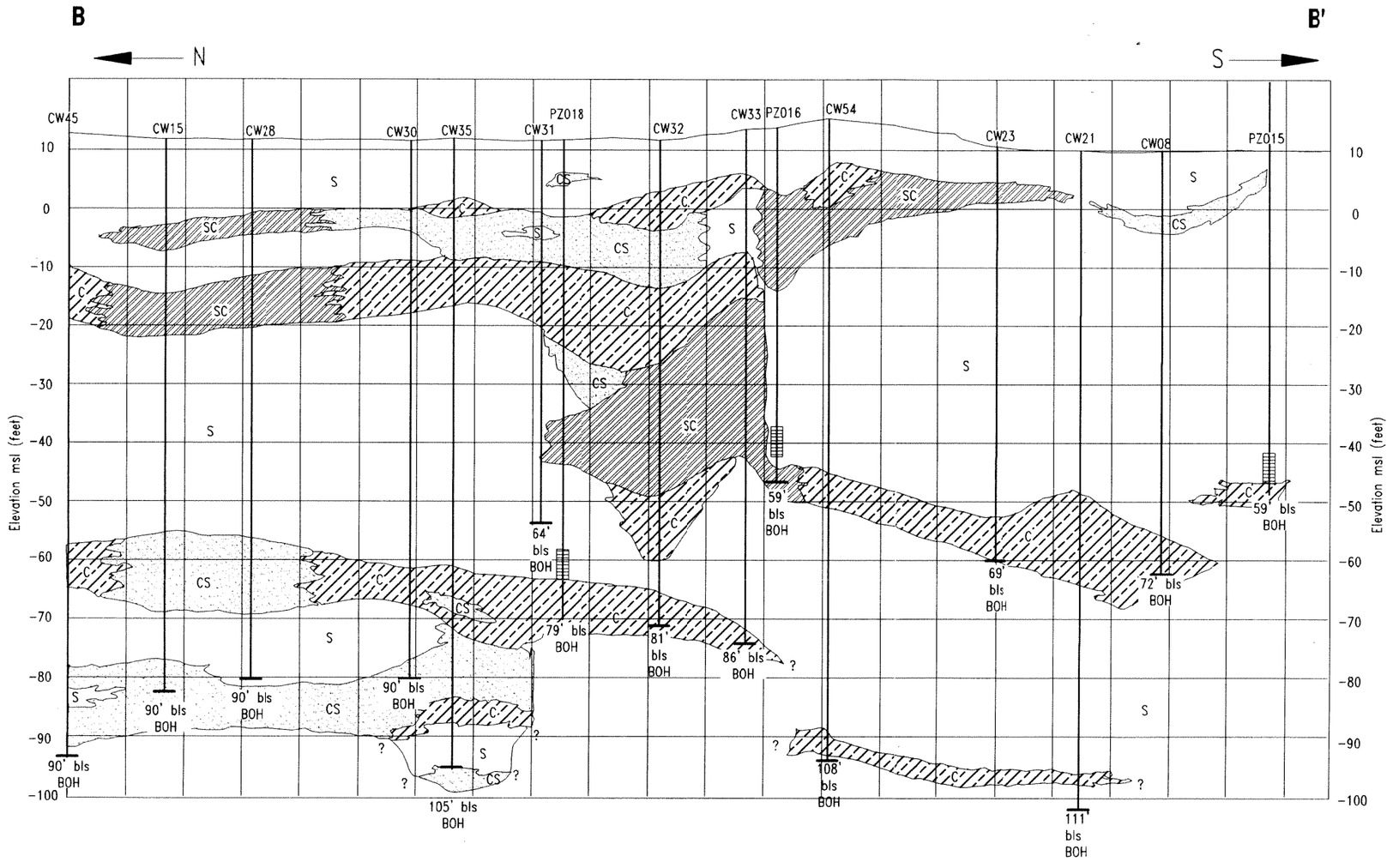
Vertical exaggeration 20:1

FIGURE 3-3
GEOLOGIC CROSS SECTION
A - A'

REMEDIAL INVESTIGATION
AND FEASIBILITY STUDY
OPERABLE UNIT 3

NAVAL AIR STATION JACKSONVILLE
JACKSONVILLE, FLORIDA

K:\02582\02582-09\RIF\02582524.DWG, PDP-VC 05/25/99 11:21:22, AutoCAD R14



LEGEND

- C: Clay
- CS: Clayey sand
- SC: Sandy clay
- S: Sand
- ? Unknown contact
- Screened interval
- BOH Bottom of hole
- bls Below land surface
- msl Mean sea level

0 200 400

SCALE: 1 INCH = 400 FEET

Vertical exaggeration 20:1

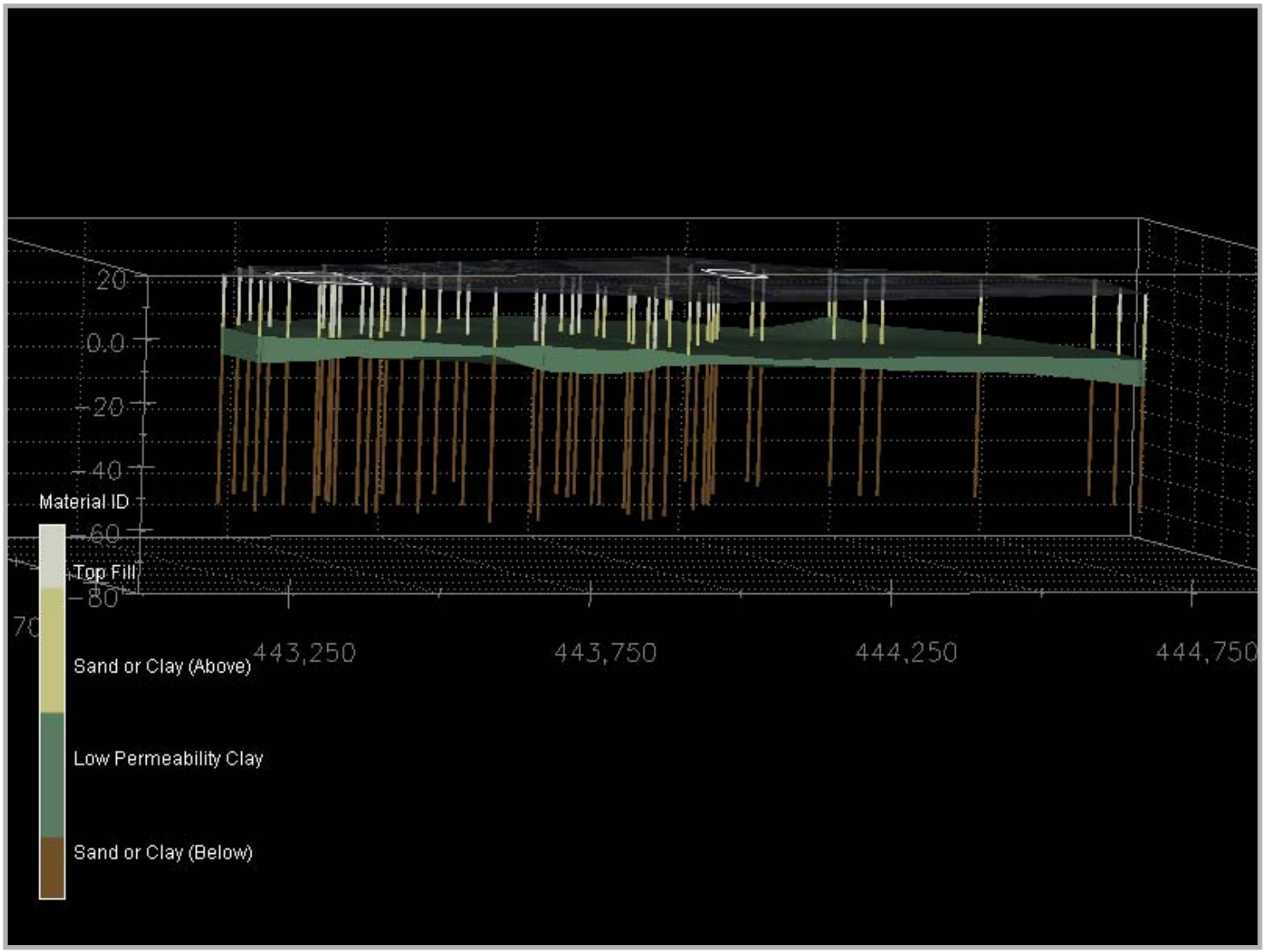
FIGURE 3-4
GEOLOGIC CROSS SECTION
B - B'

REMEDIAL INVESTIGATION
AND FEASIBILITY STUDY
OPERABLE UNIT 3

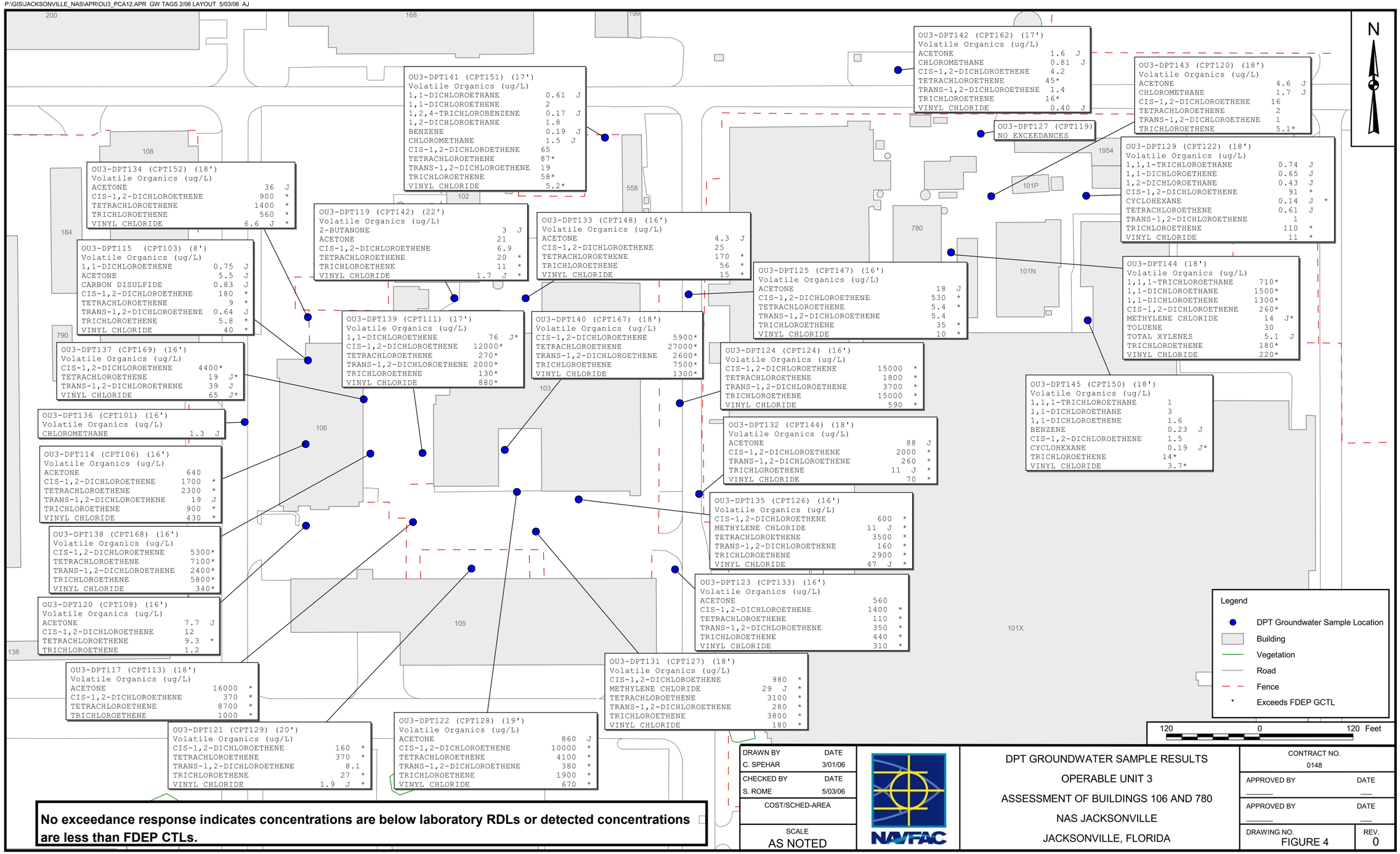
NAVAL AIR STATION JACKSONVILLE
JACKSONVILLE, FLORIDA

K:\02562\02562-09\RIF\02562525.DWG, PDP-VC 05/25/99 11:36:33, AutoCAD R14

MIP/CPT Borings



P:\GIS\JACKSONVILLE_NAS\APR\OU3_PCA12.APR GW TAGS 2/06 LAYOUT 5/03/06 AJ



No exceedance response indicates concentrations are below laboratory RDLs or detected concentrations are less than FDEP CTLs.

DRAWN BY	DATE
C. SPEHAR	3/01/06
CHECKED BY	DATE
S. ROME	5/03/06
COST/SCHED-AREA	
SCALE	AS NOTED

NAVFAC

DPT GROUNDWATER SAMPLE RESULTS

OPERABLE UNIT 3

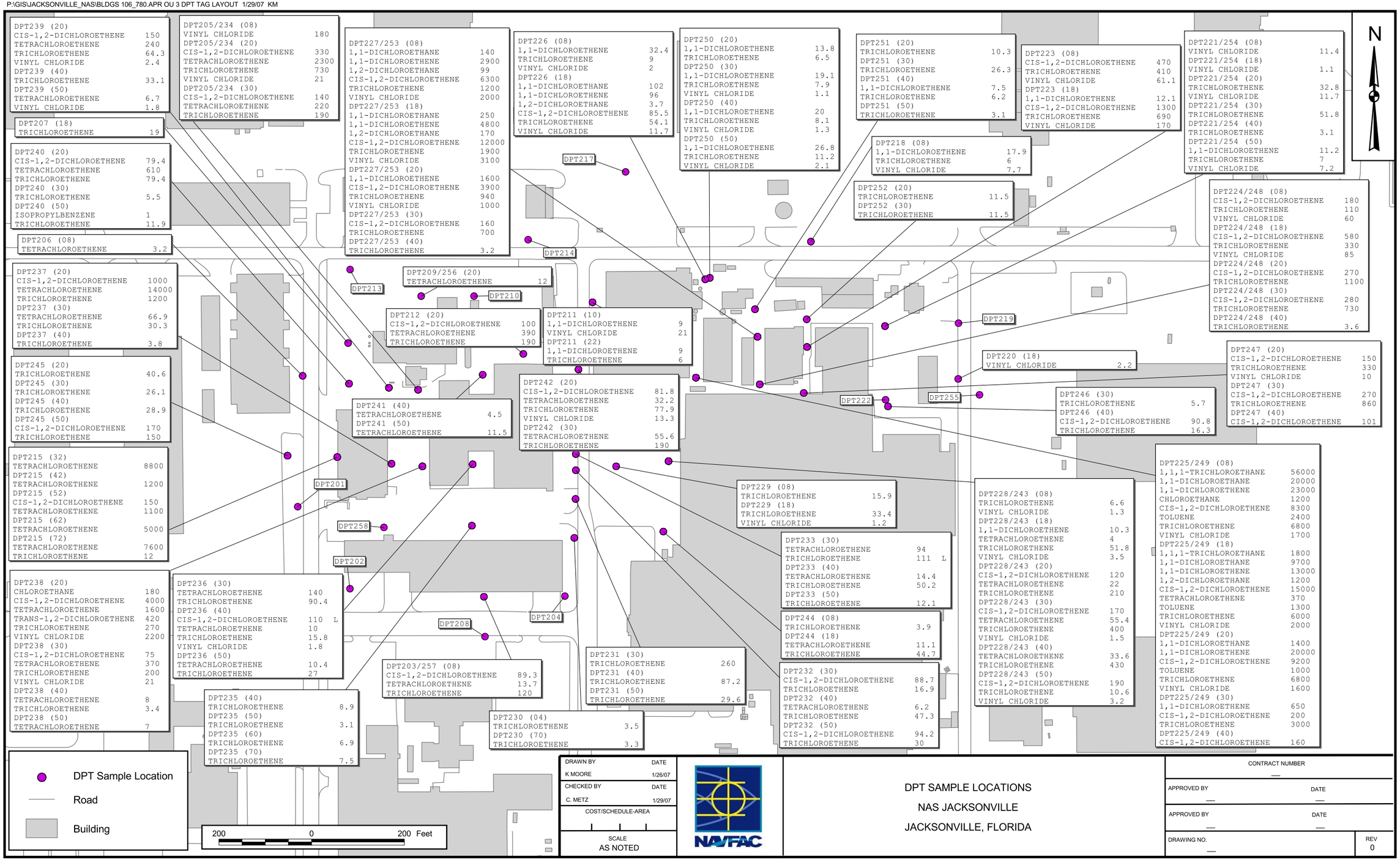
ASSESSMENT OF BUILDINGS 106 AND 780

NAS JACKSONVILLE

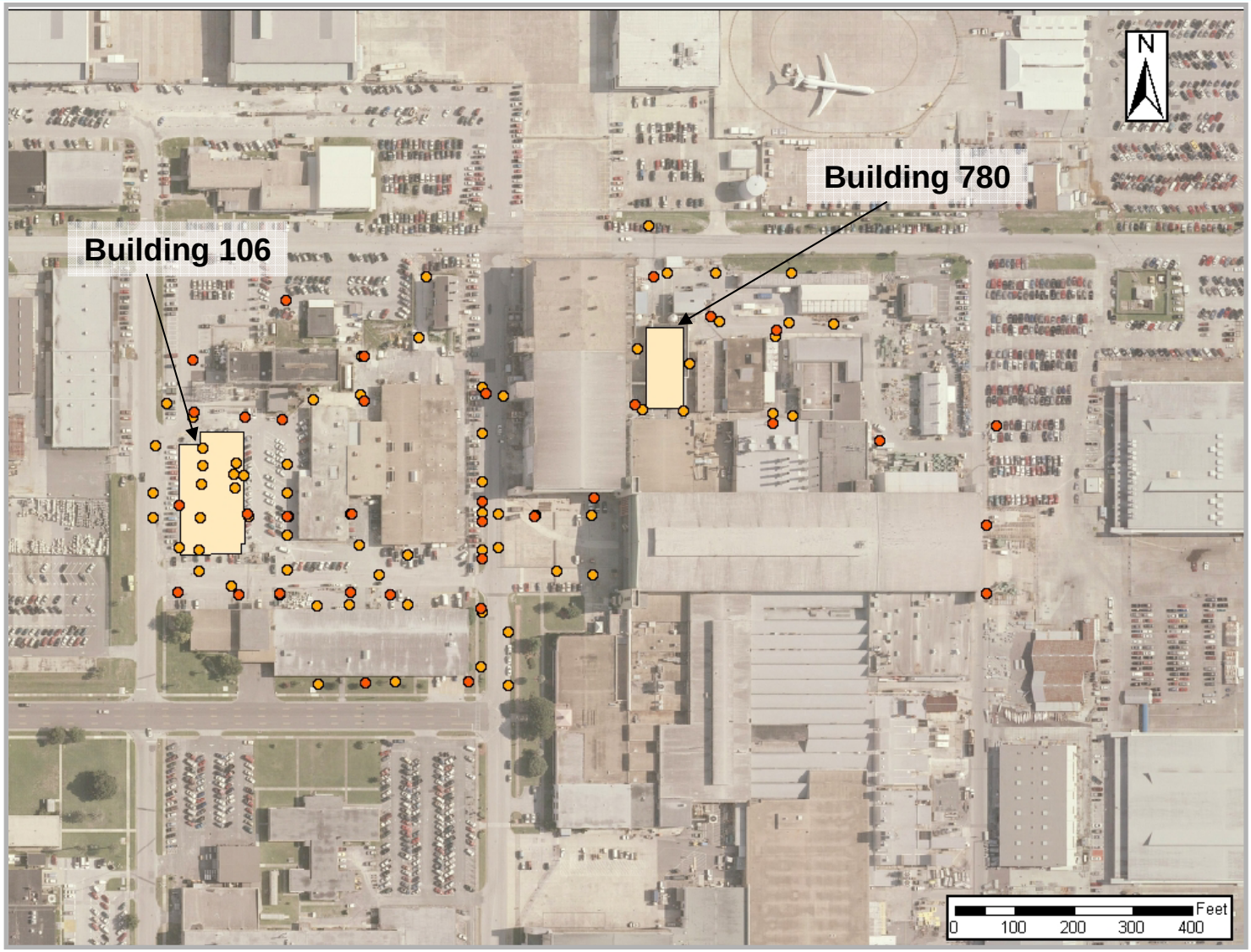
JACKSONVILLE, FLORIDA

CONTRACT NO.	0148
APPROVED BY	DATE
APPROVED BY	DATE
DRAWING NO.	FIGURE 4
REV.	0

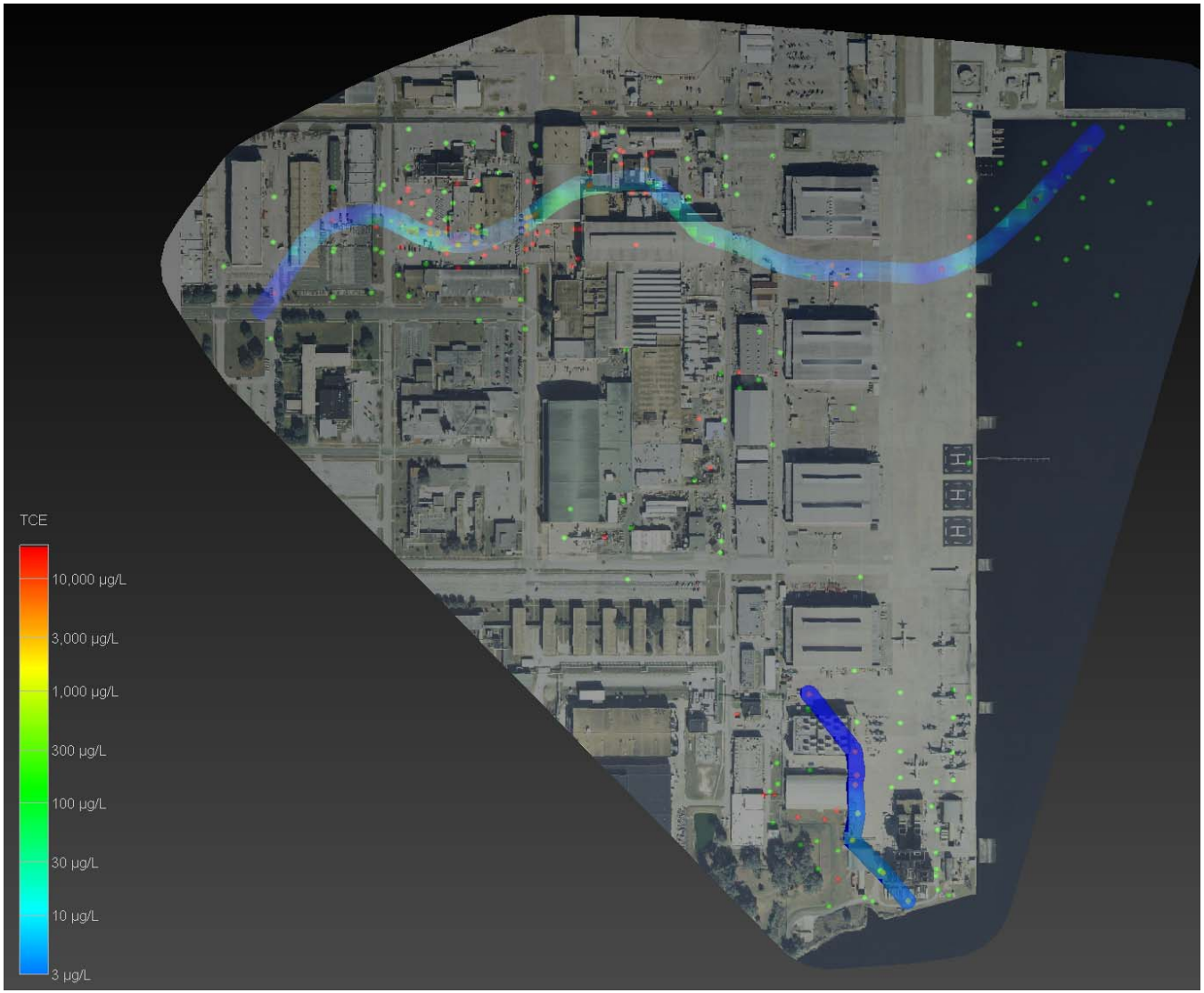
P:\GIS\JACKSONVILLE_NAS\BLDGS 106_780.APR OU 3 DPT TAG LAYOUT 1/29/07 KM



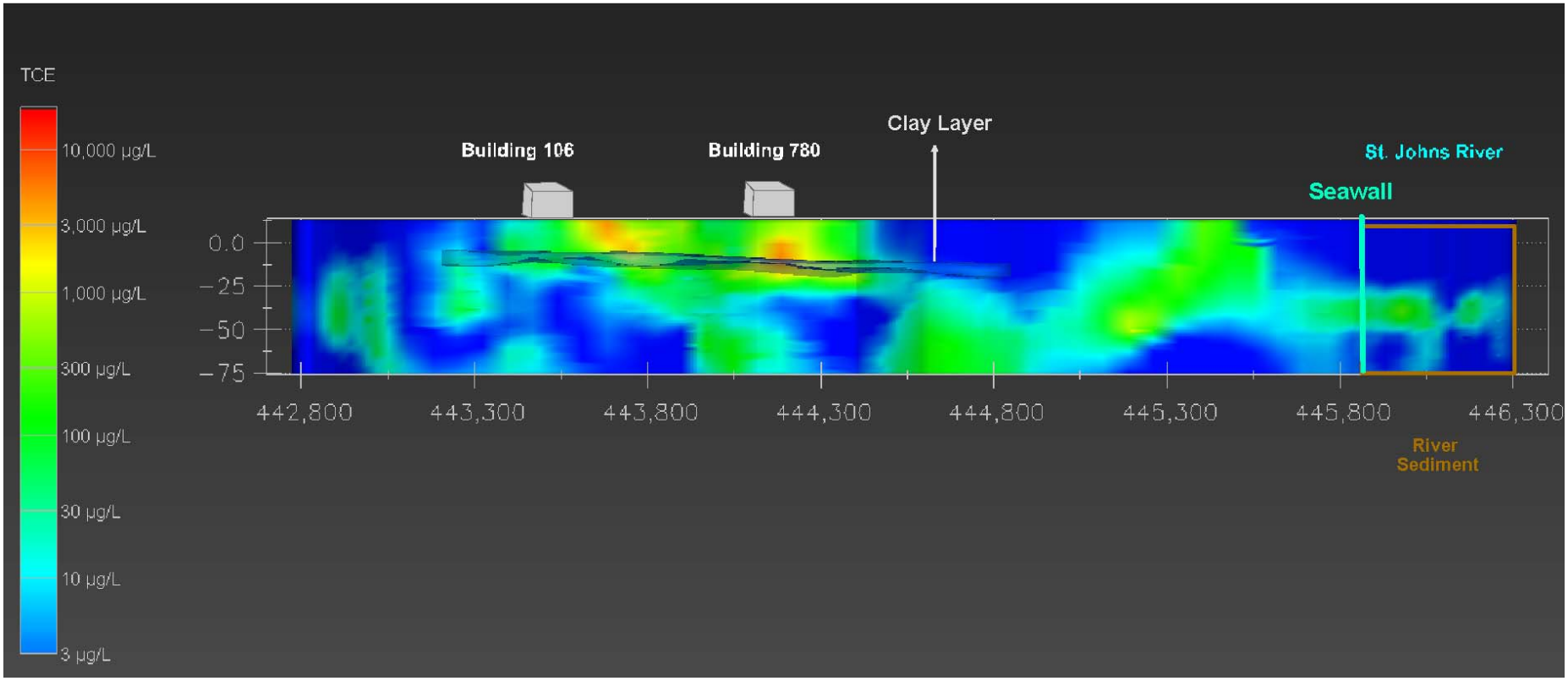
CPT/MIP Locations



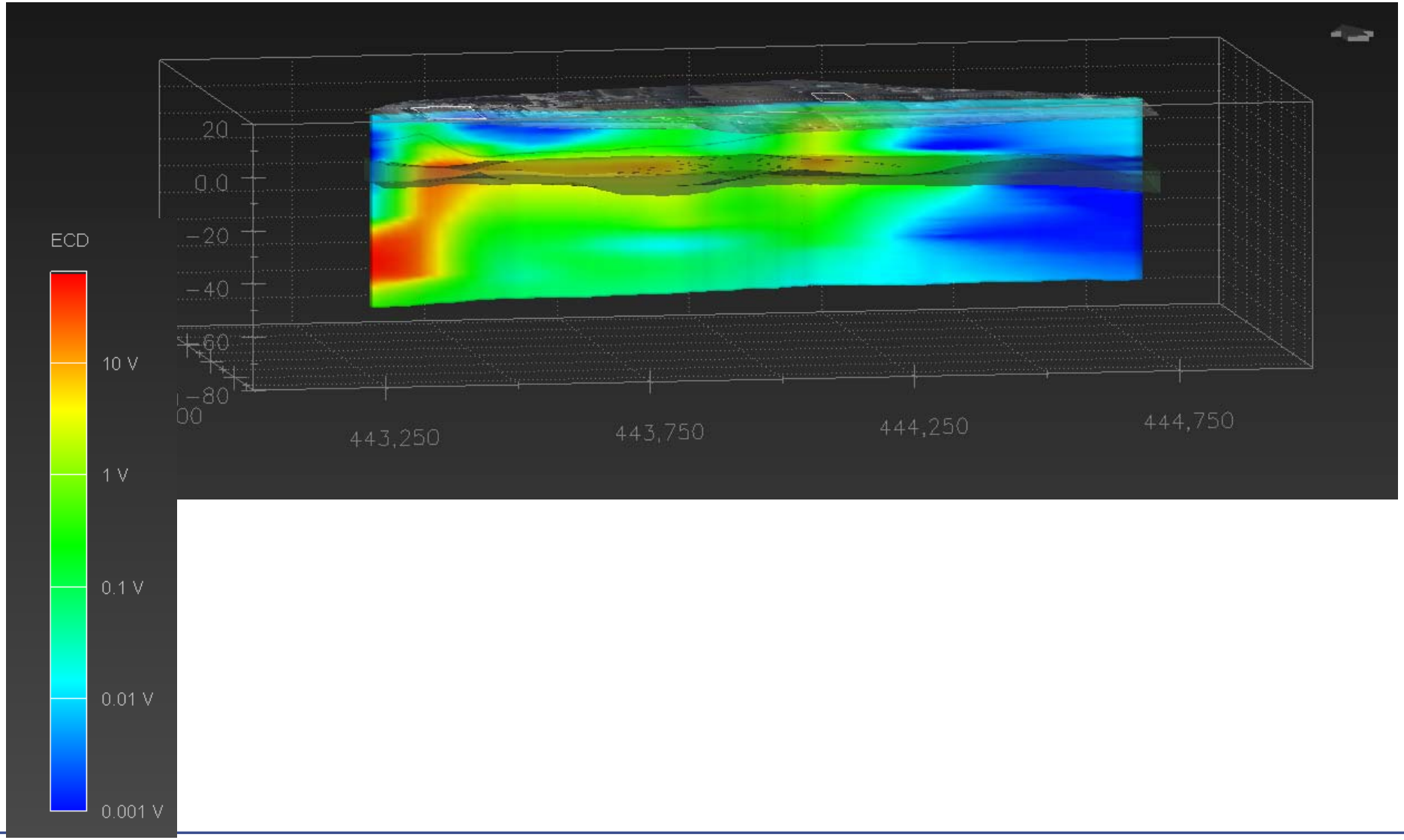
Cross-Section Path



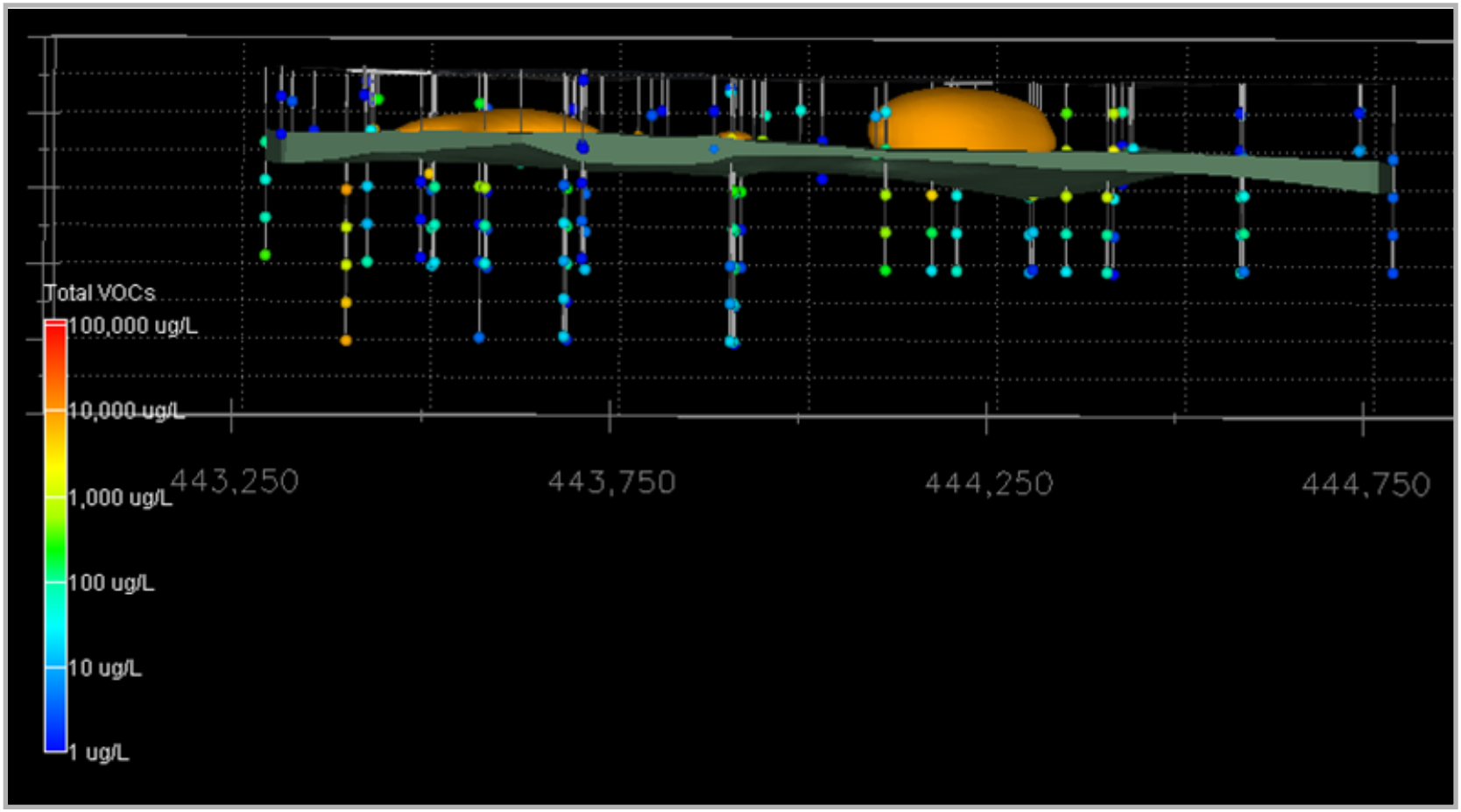
TCE Concentrations (DPT Samples)



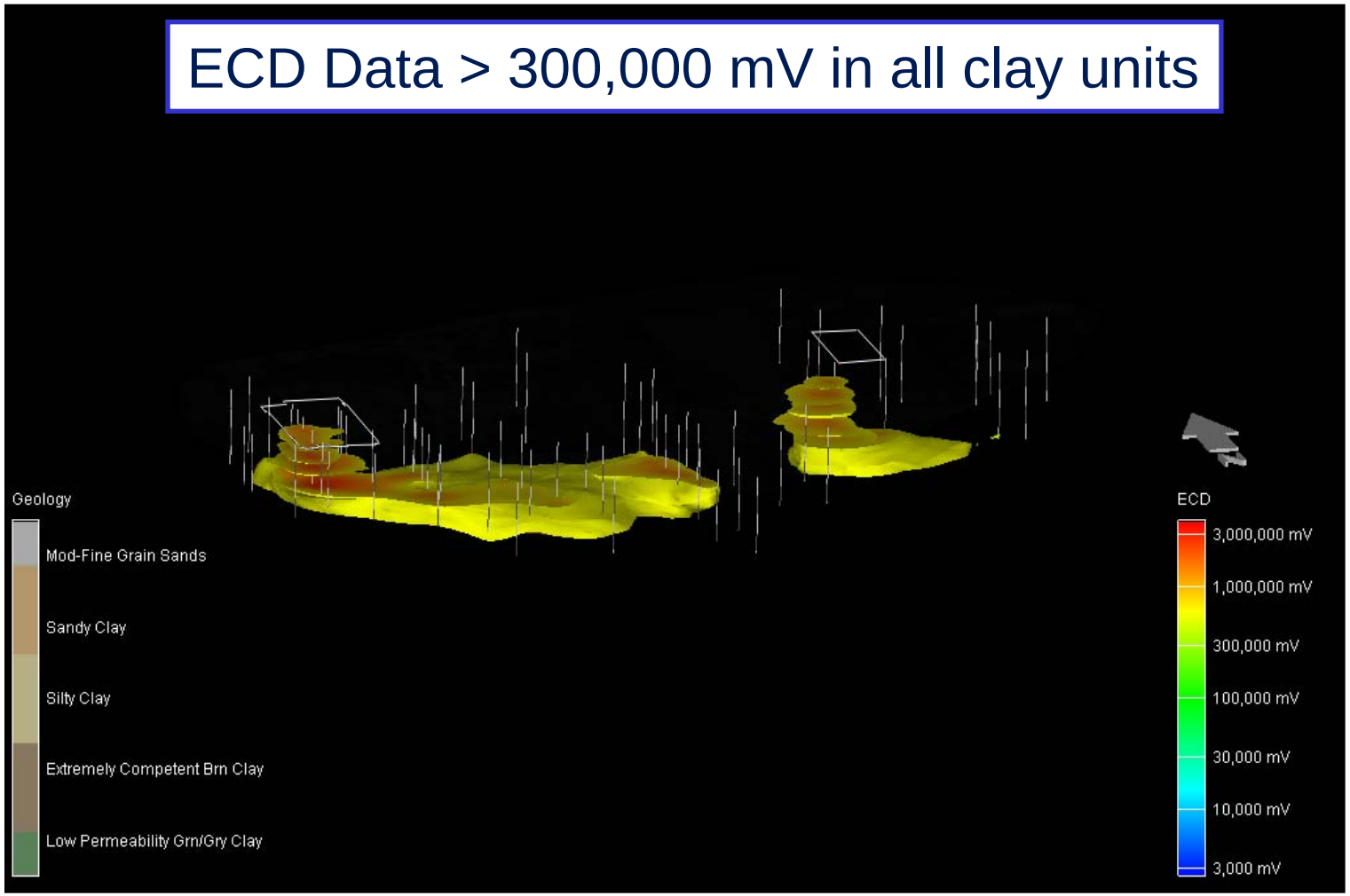
MIP Response (V) Profile



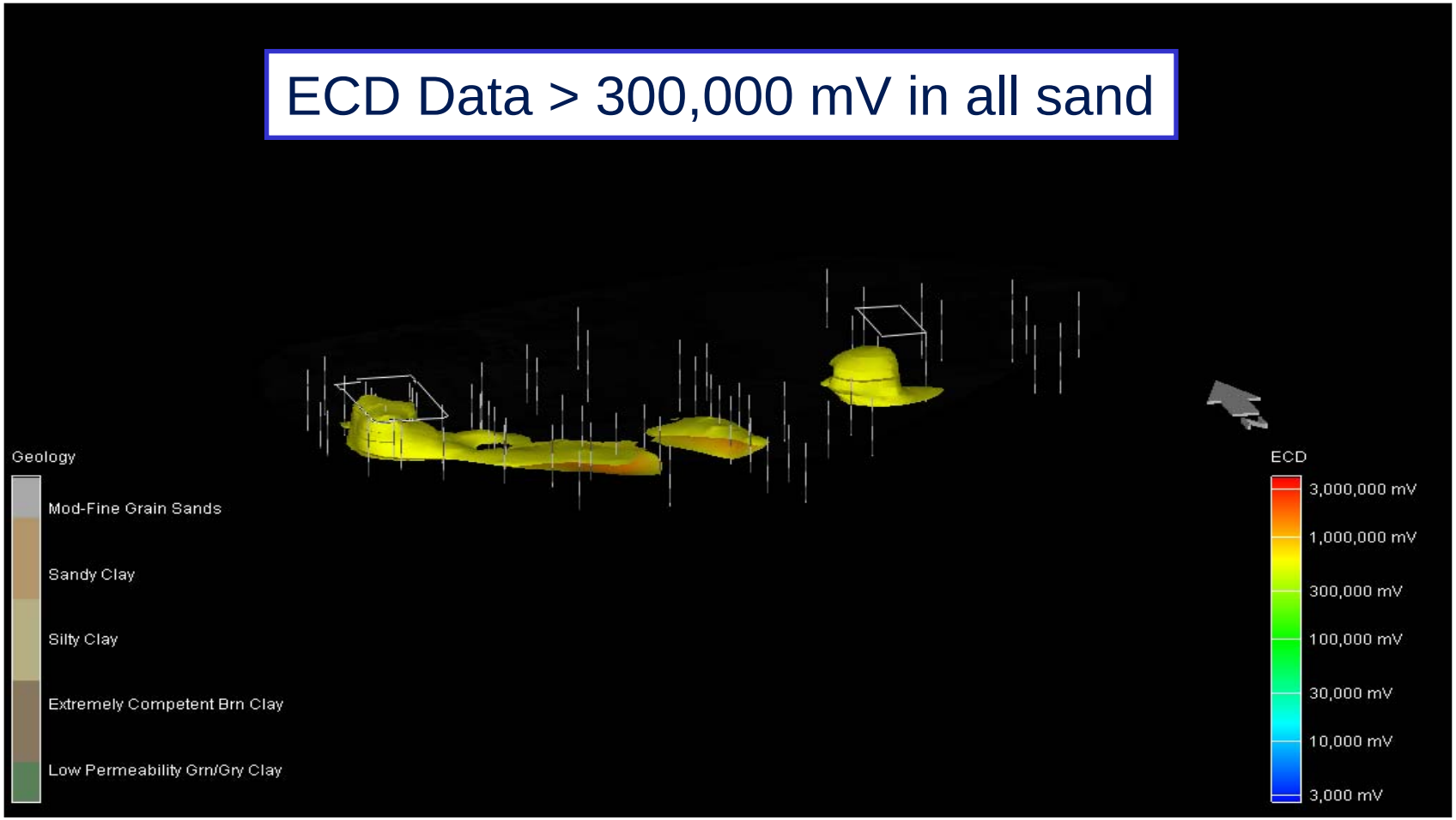
Total VOCs >10,000 µg/L



Mass Storage in Clay Strata



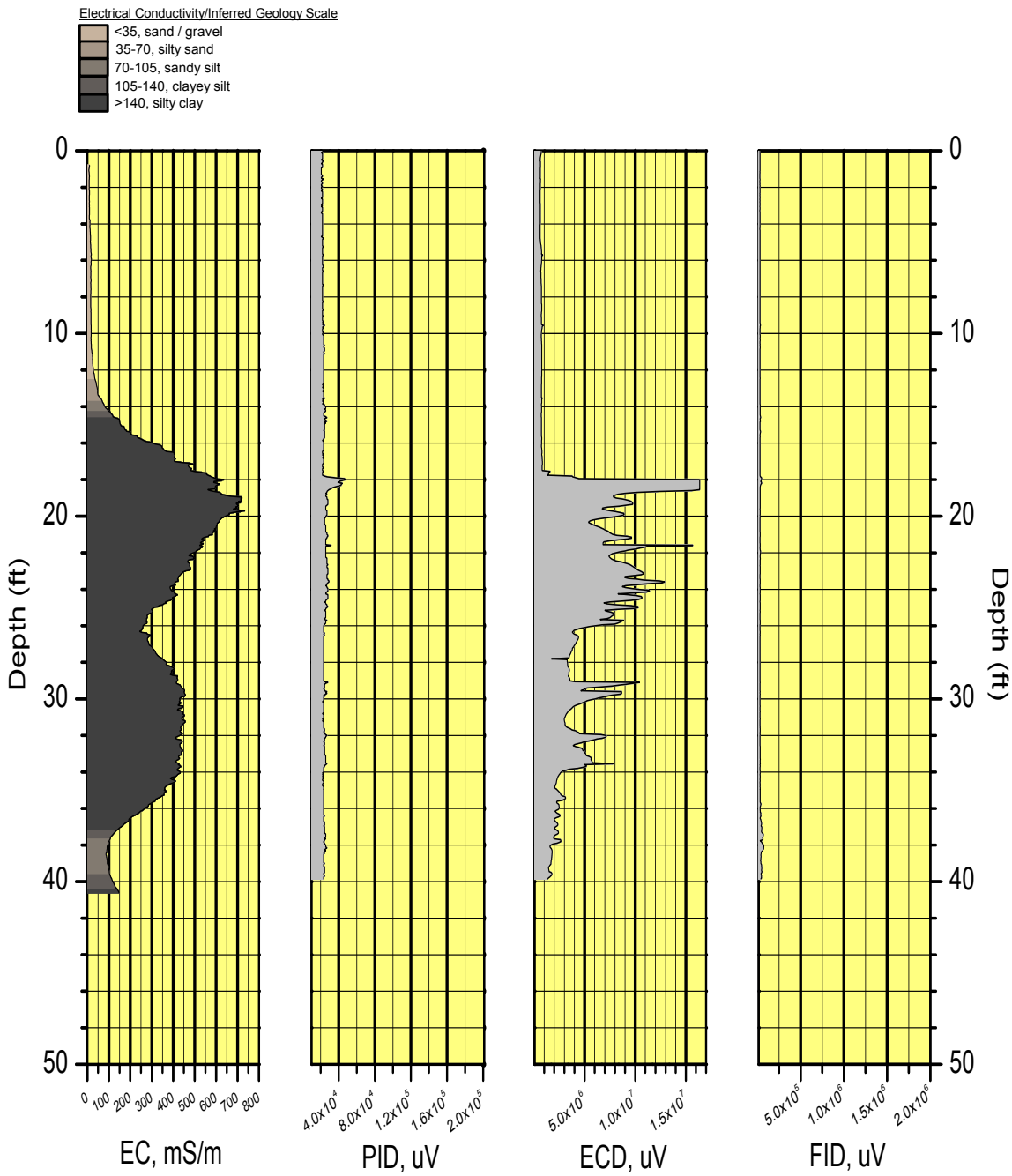
Contaminant Mass in Sand Layers



APPENDIX C

Membrane Interface Probe (MIP) Results from Demonstration Project

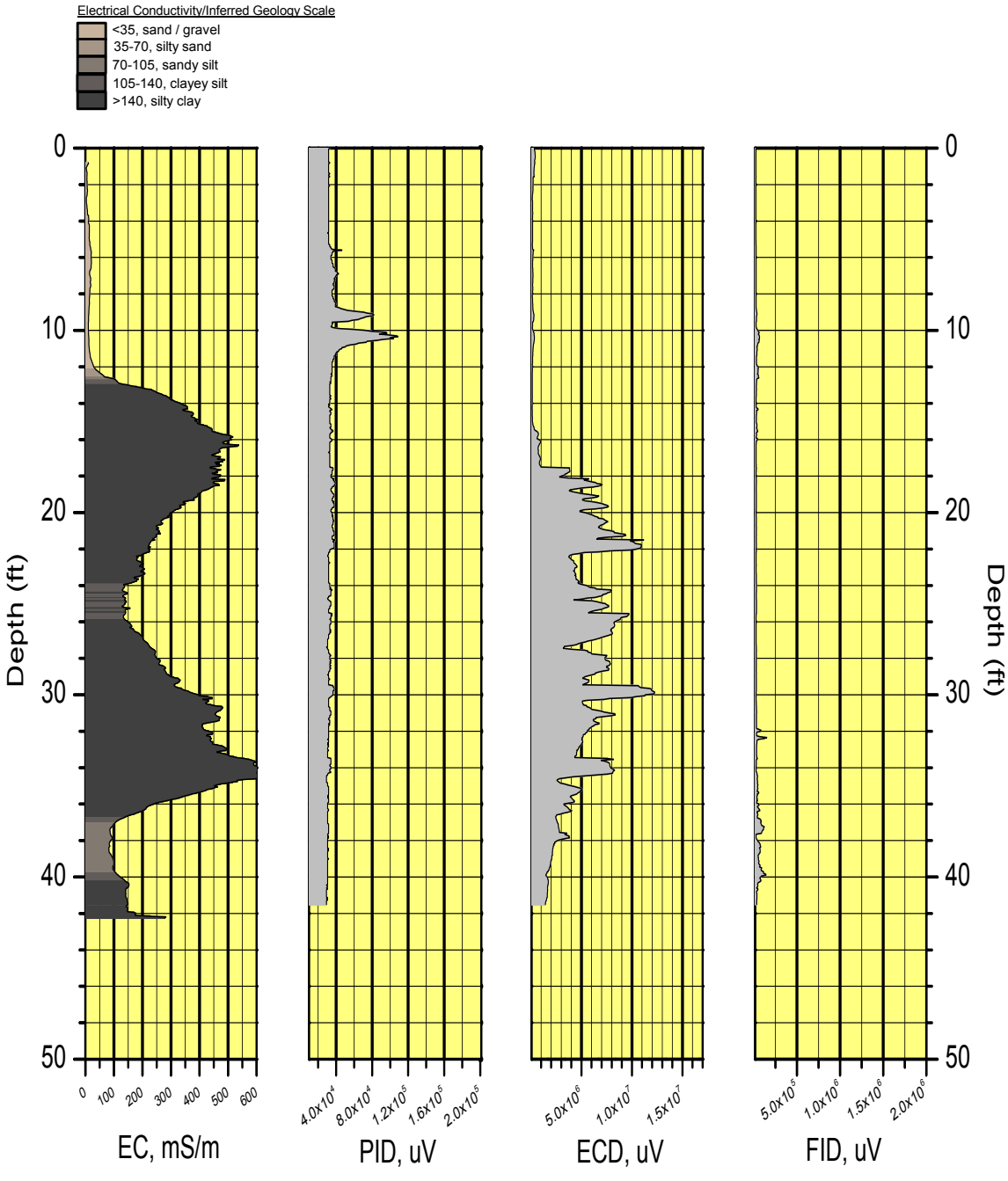
Attorney - Client Communication and Attorney Work Product. All Privileges Claimed.



OU3-1 (PTL)
GSI / JAX NAS
Date Logged : 07/18/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-1 PTL.opj
Date: 07/18/2011 MJM & MDR

STONE ENVIRONMENTAL INC

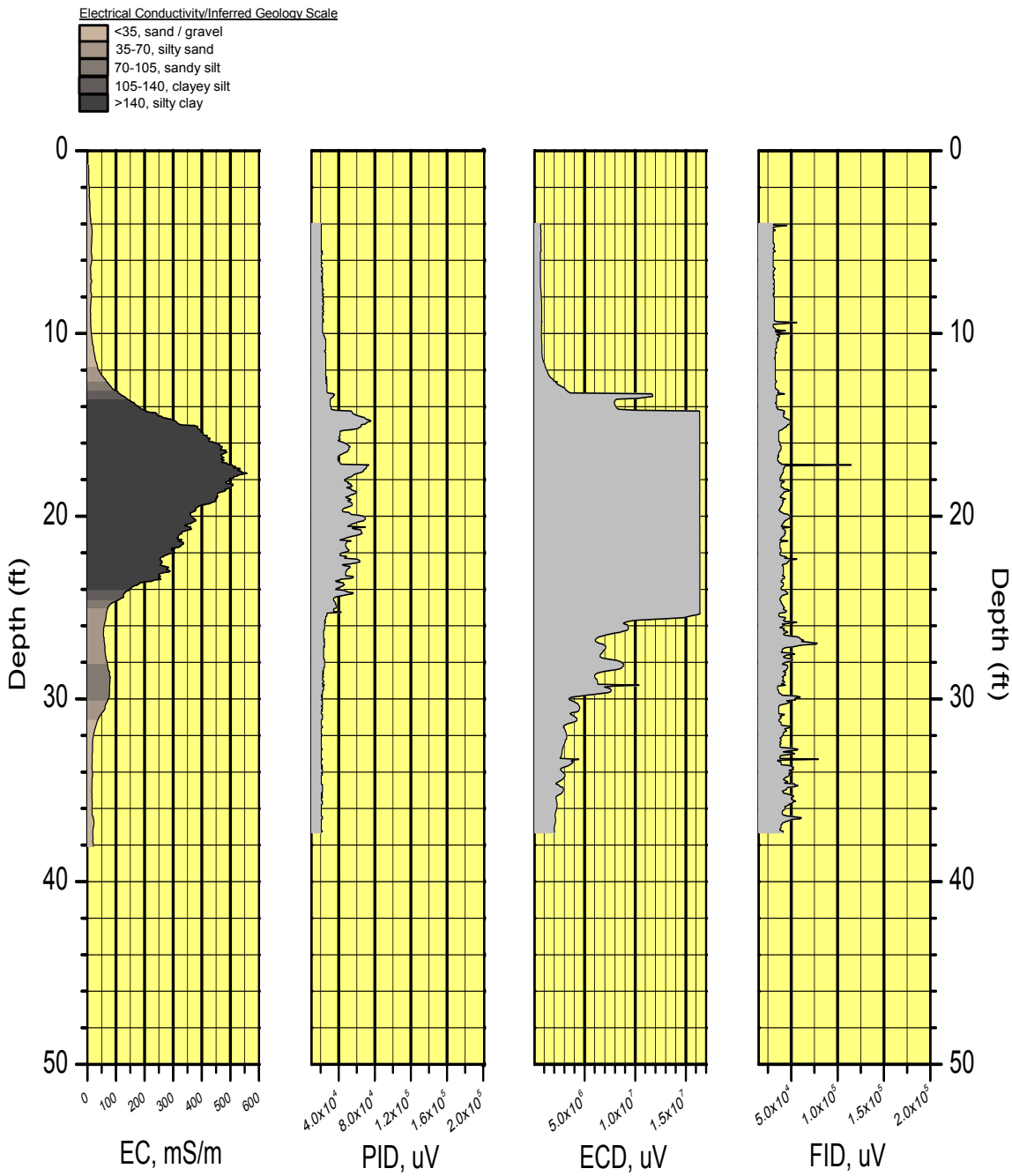


OU3-2 (HTL)
GSI / JAX NAS
Date Logged : 07/21/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-2 HTL.opj
Date: 07/21/2011 MJM & MDR

STONE ENVIRONMENTAL INC

Attorney - Client Communication and Attorney Work Product. All Privileges Claimed.

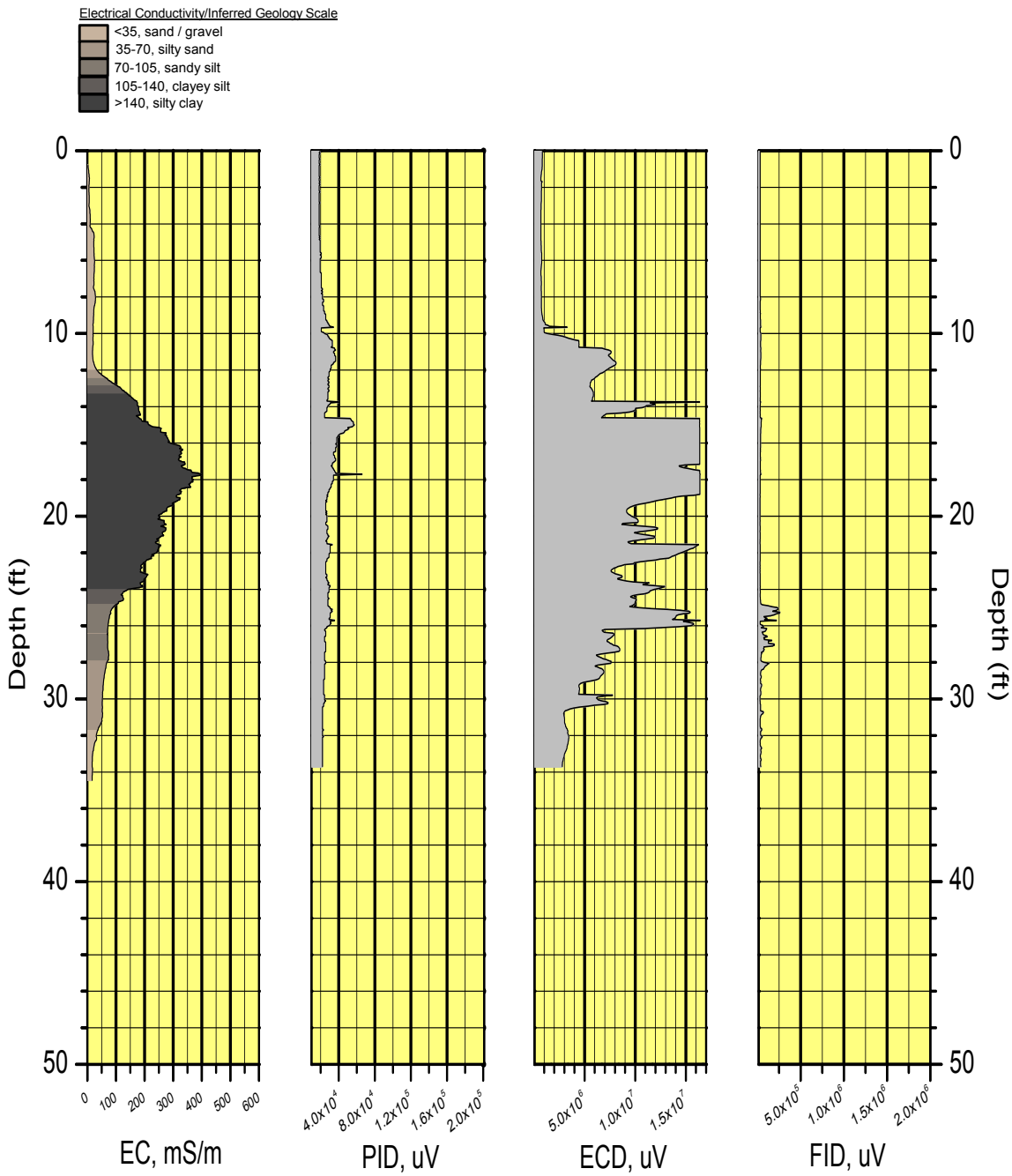


OU3-3 (PTL)
GSI / JAX NAS
Date Logged : 07/18/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-3 PTL.opj
Date: 07/18/2011 MJM & MDR

STONE ENVIRONMENTAL INC

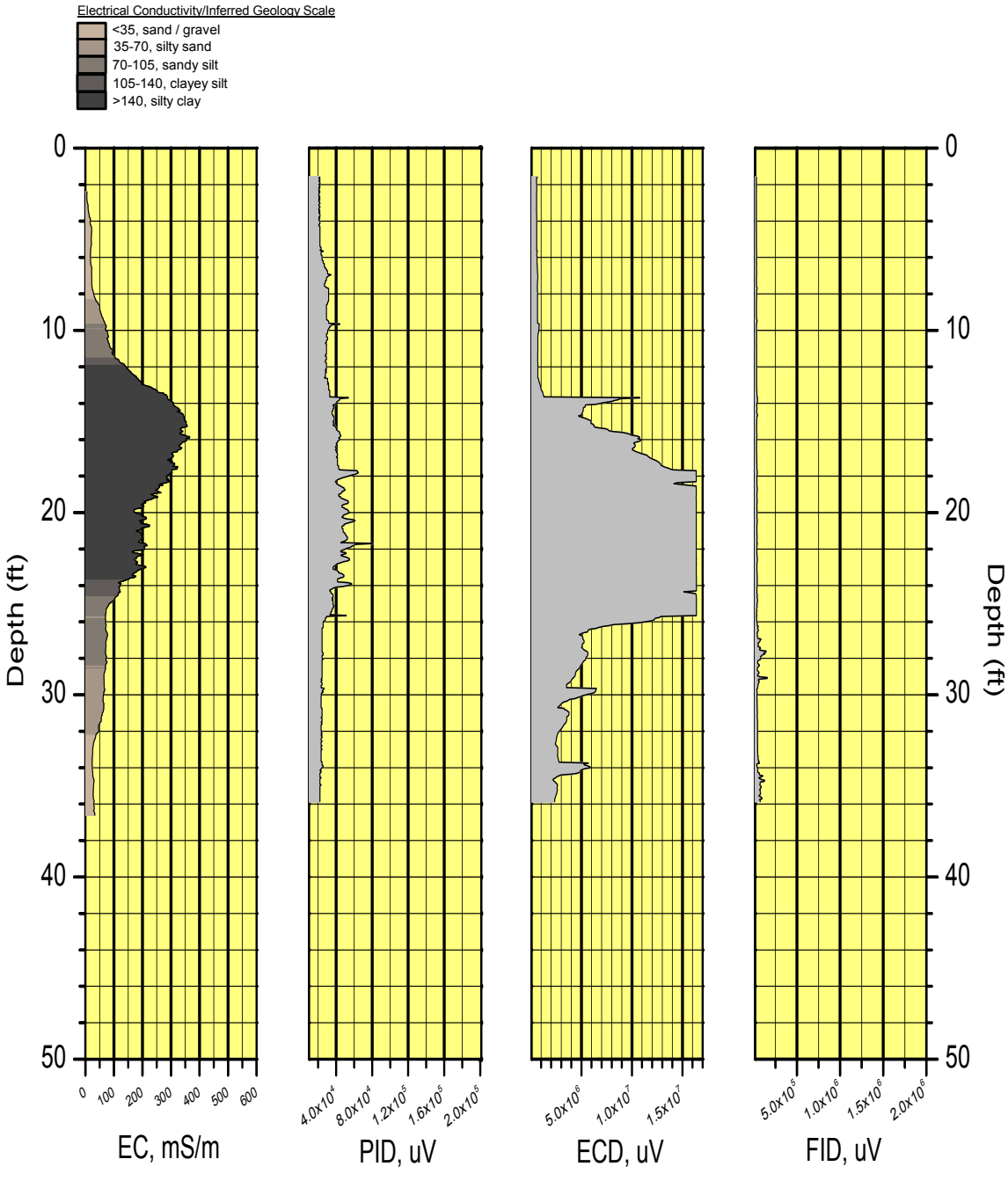
Attorney - Client Communication and Attorney Work Product. All Privileges Claimed.



OU3-4 (PTL)
GSI / JAX NAS
Date Logged : 07/18/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-4 PTL.opj
Date: 07/18/2011 MJM & MDR

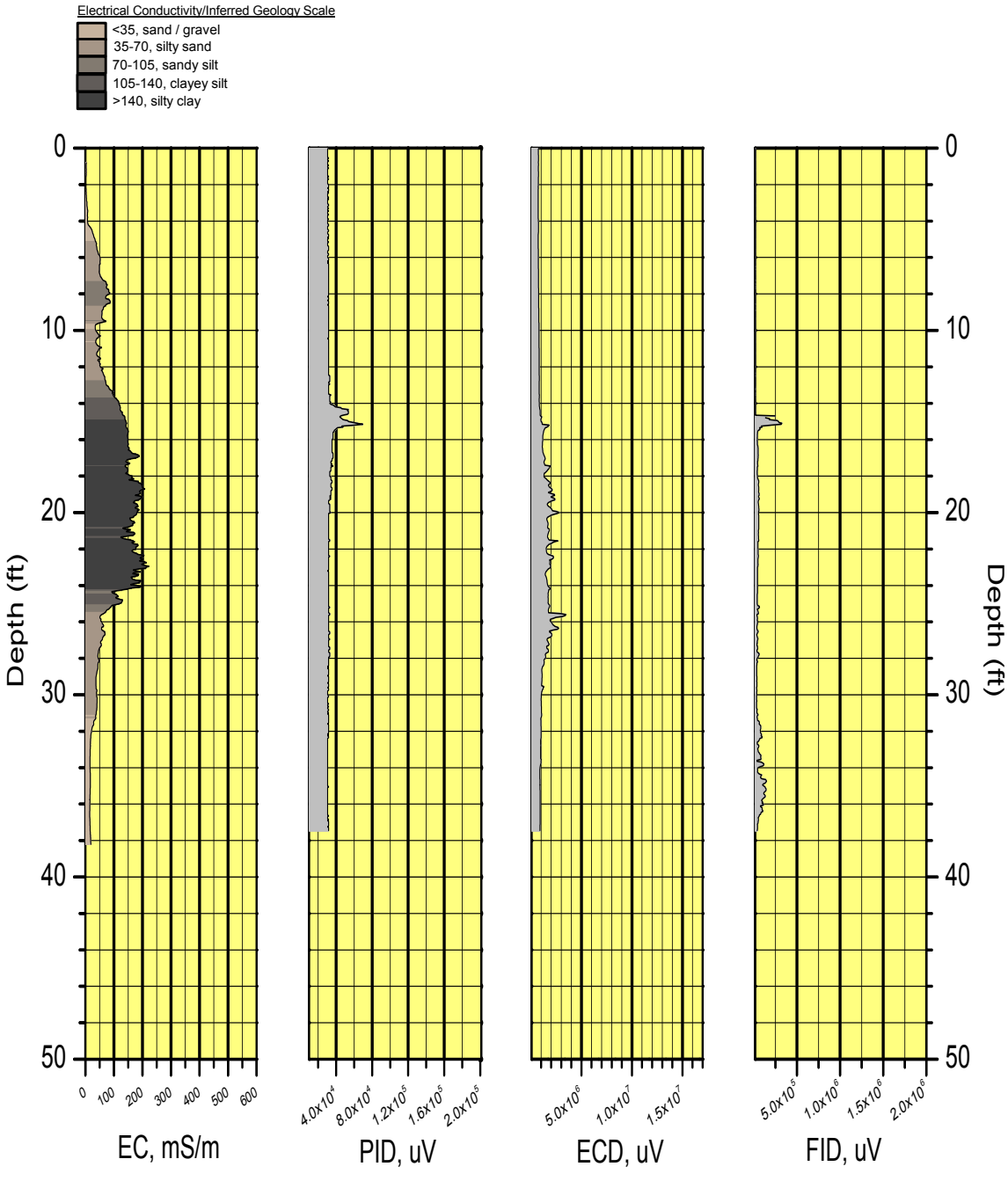
STONE ENVIRONMENTAL INC



OU3-5 (PTL)
GSI / JAX NAS
Date Logged : 07/18/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-5 PTL.opj
Date: 07/18/2011 MJM & MDR

STONE ENVIRONMENTAL INC



OU3-6 (PTL)
GSI / JAX NAS
Date Logged : 07/20/2011

Source: Stone - Membrane Interface Probe Data
Path: C:\projects\GSI, JAX NAS\Origin\OU3-6 PTL.opj
Date: 07/20/2011 MJM & MDR

STONE ENVIRONMENTAL INC

APPENDIX D

Waterloo$^{APS\ TM}$ Results from Demonstration Project

Appendix D.1 Groundwater Volatile Organic Compound (VOC) Concentration Plots

Appendix D.2 Index of Hydraulic Conductivity (I_k) and Field Parameter Data Plots

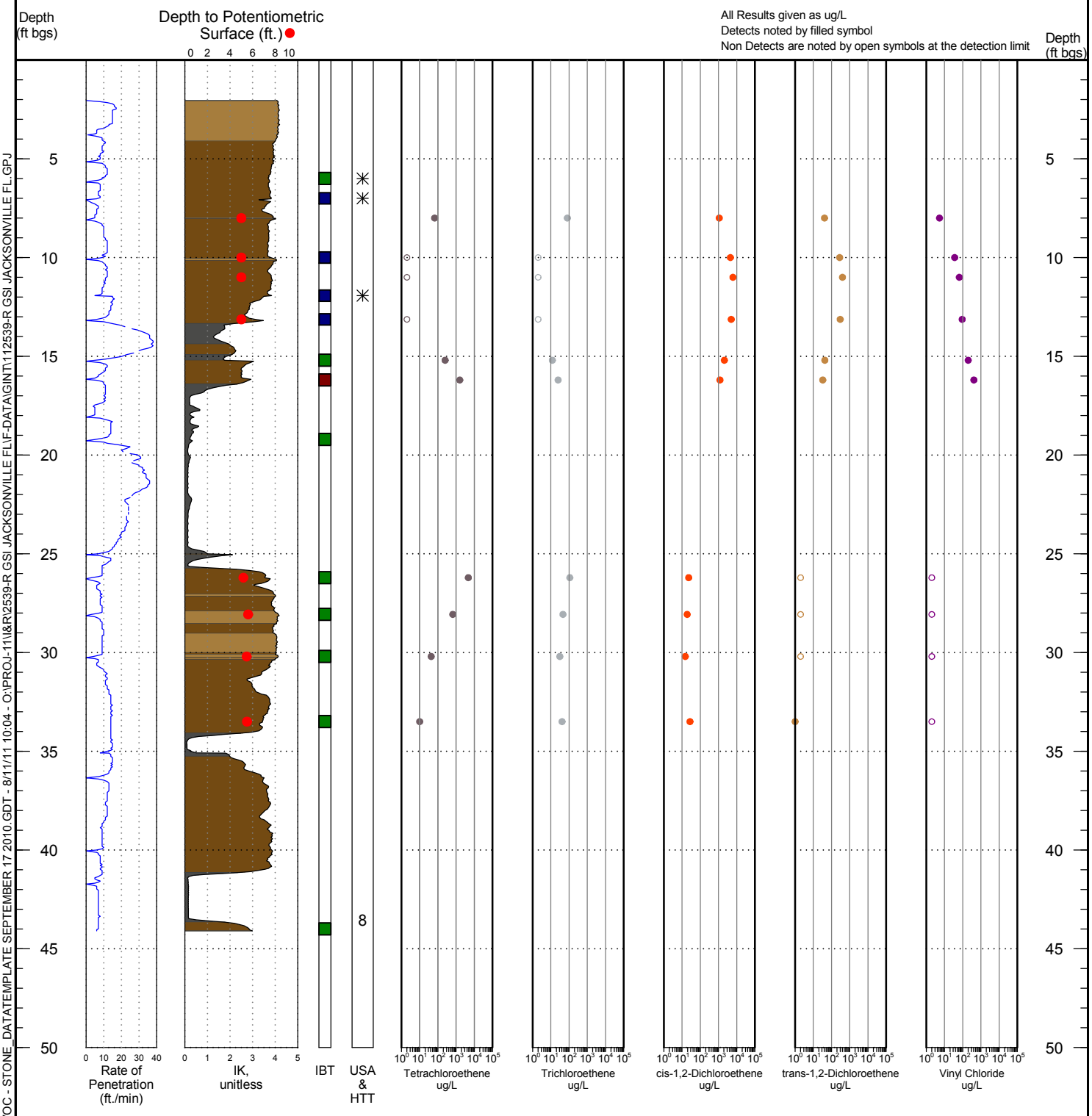
BORING NAME OU3-1-WP

Total Depth 44 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:04 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

BORING NAME OU3-2-WP

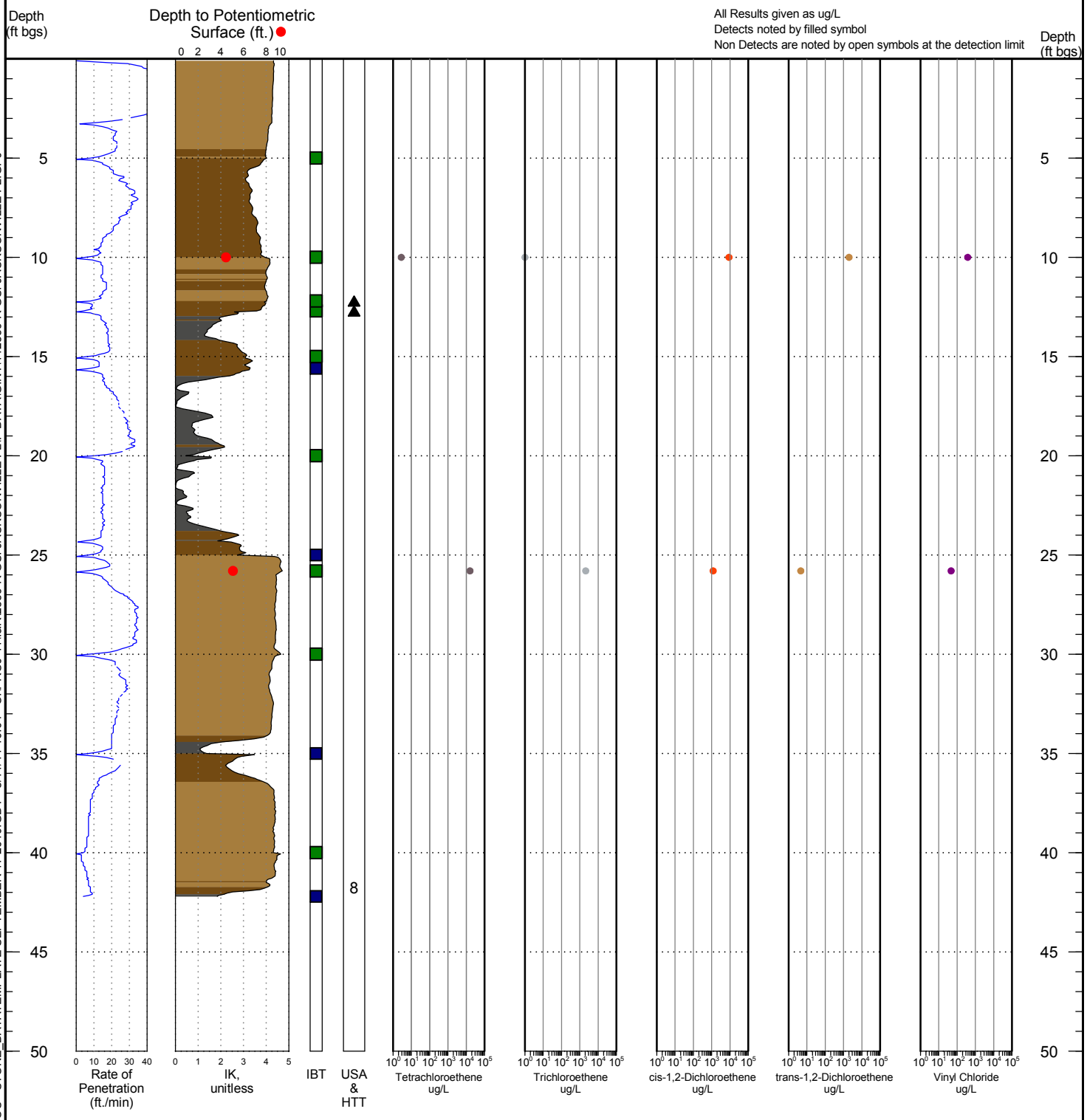
Total Depth 42.2 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump

All Results given as ug/L
Detects noted by filled symbol
Non Detects are noted by open symbols at the detection limit



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:04 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

BORING NAME OU3-3-WP

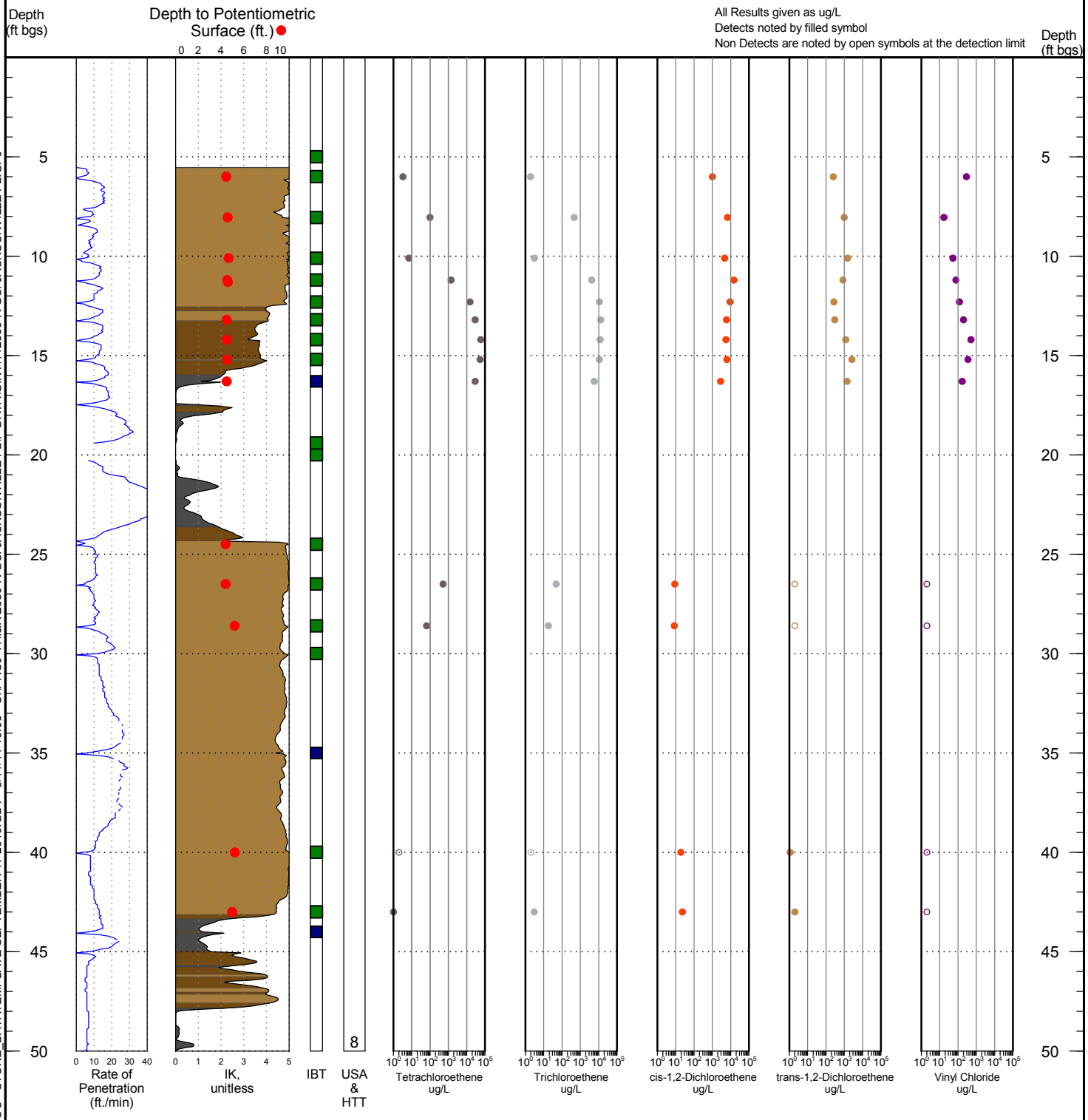
Total Depth 50 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump

All Results given as ug/L
Detects noted by filled symbol
Non Detects are noted by open symbols at the detection limit



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:05 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

BORING NAME OU3-4-WP

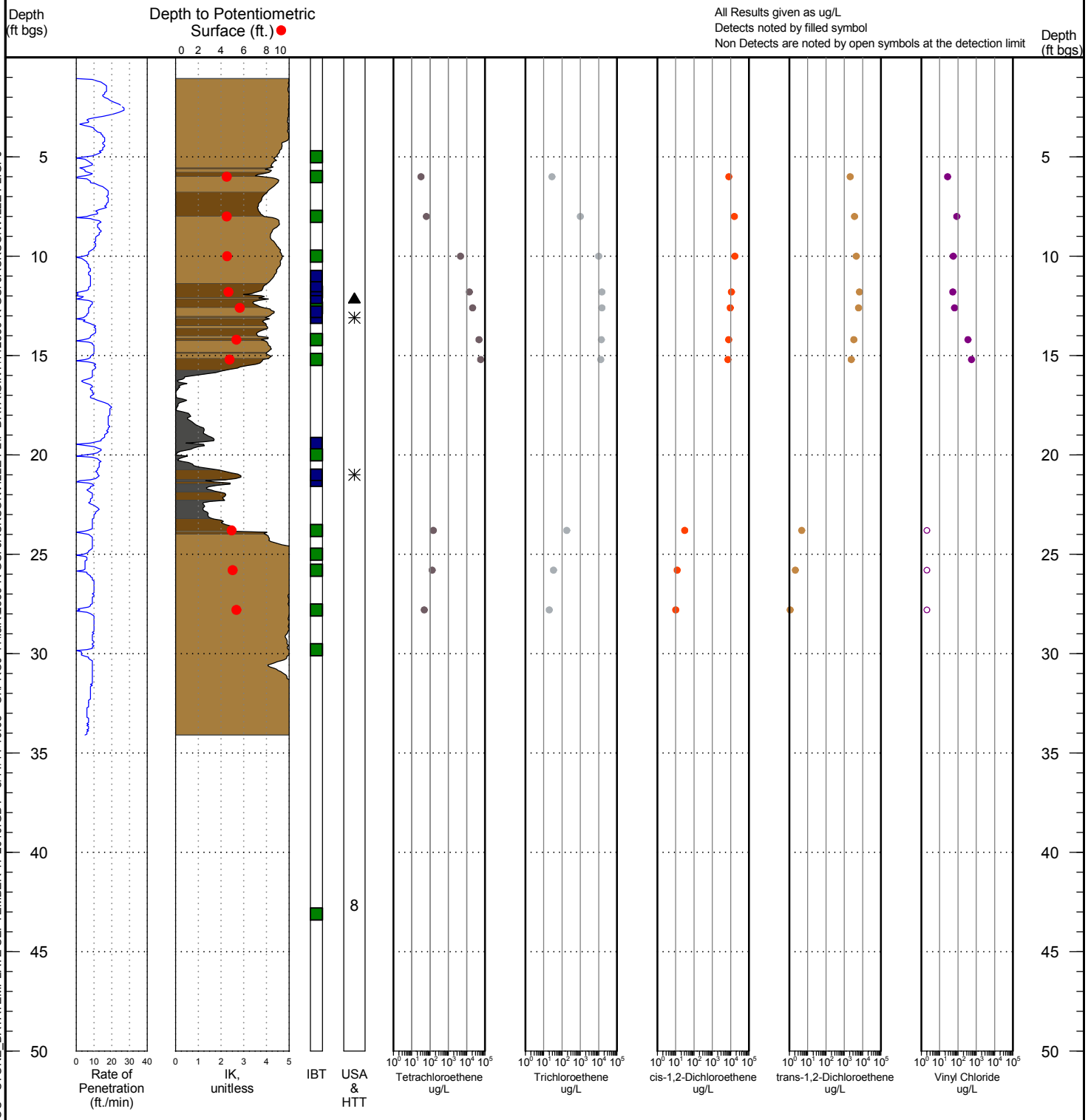
Total Depth 43.1 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump

All Results given as ug/L
Detects noted by filled symbol
Non Detects are noted by open symbols at the detection limit



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:05 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

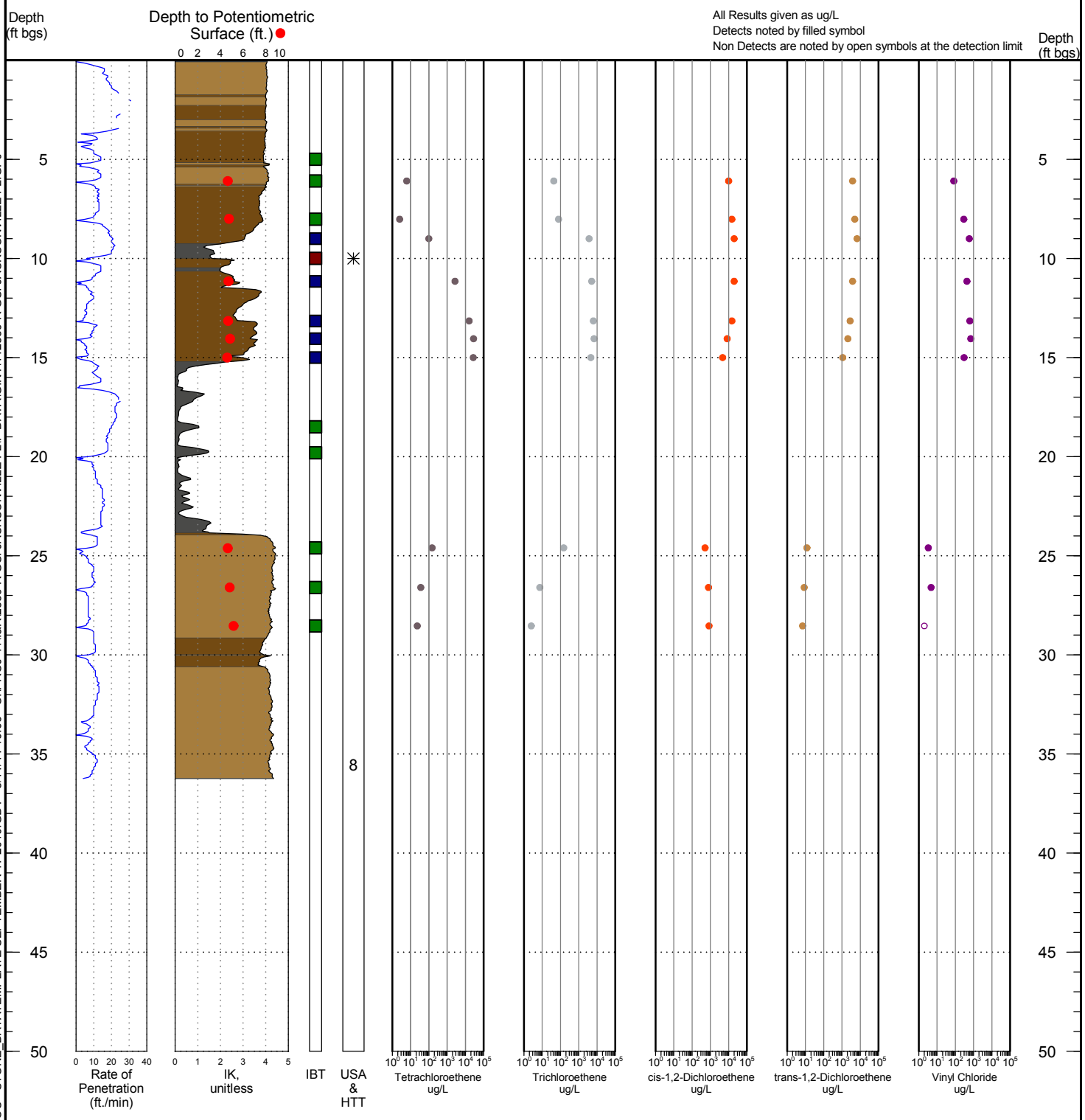
BORING NAME OU3-5-WP

Total Depth 36 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:06 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

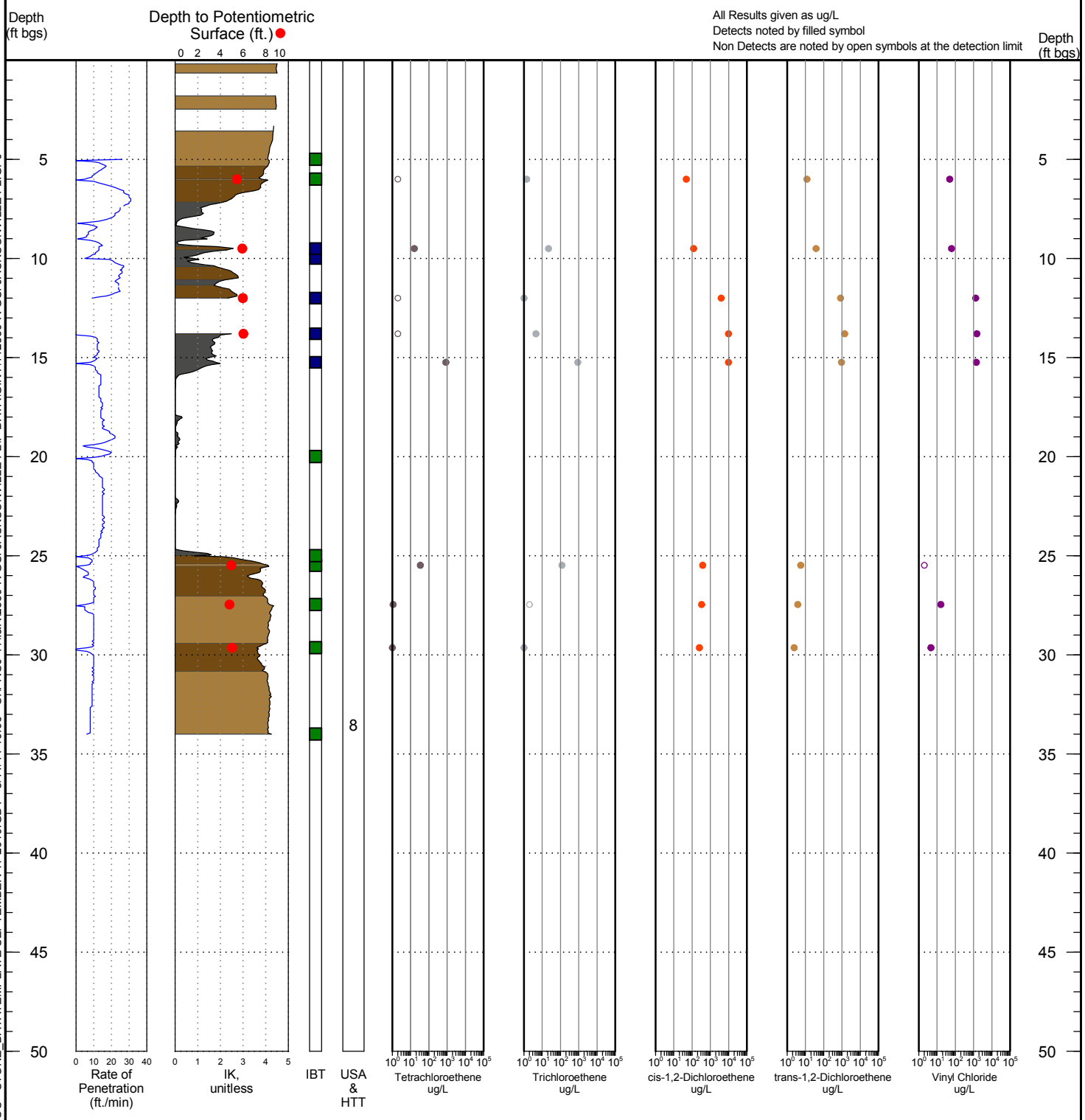
BORING NAME OU3-6-WP

Total Depth 34 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:06 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

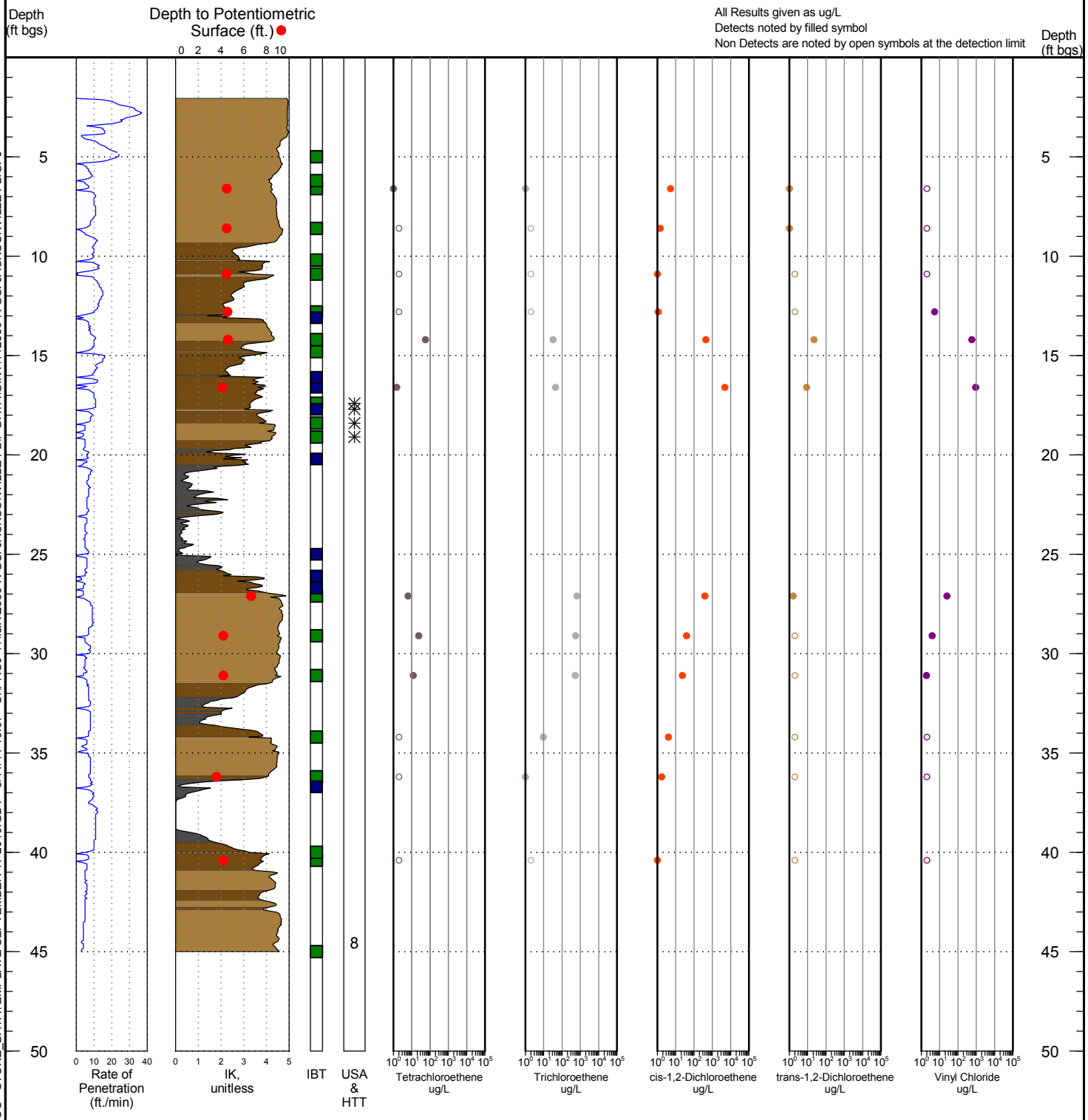
BORING NAME OU3-9-WP

Total Depth 45 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/28/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:07 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

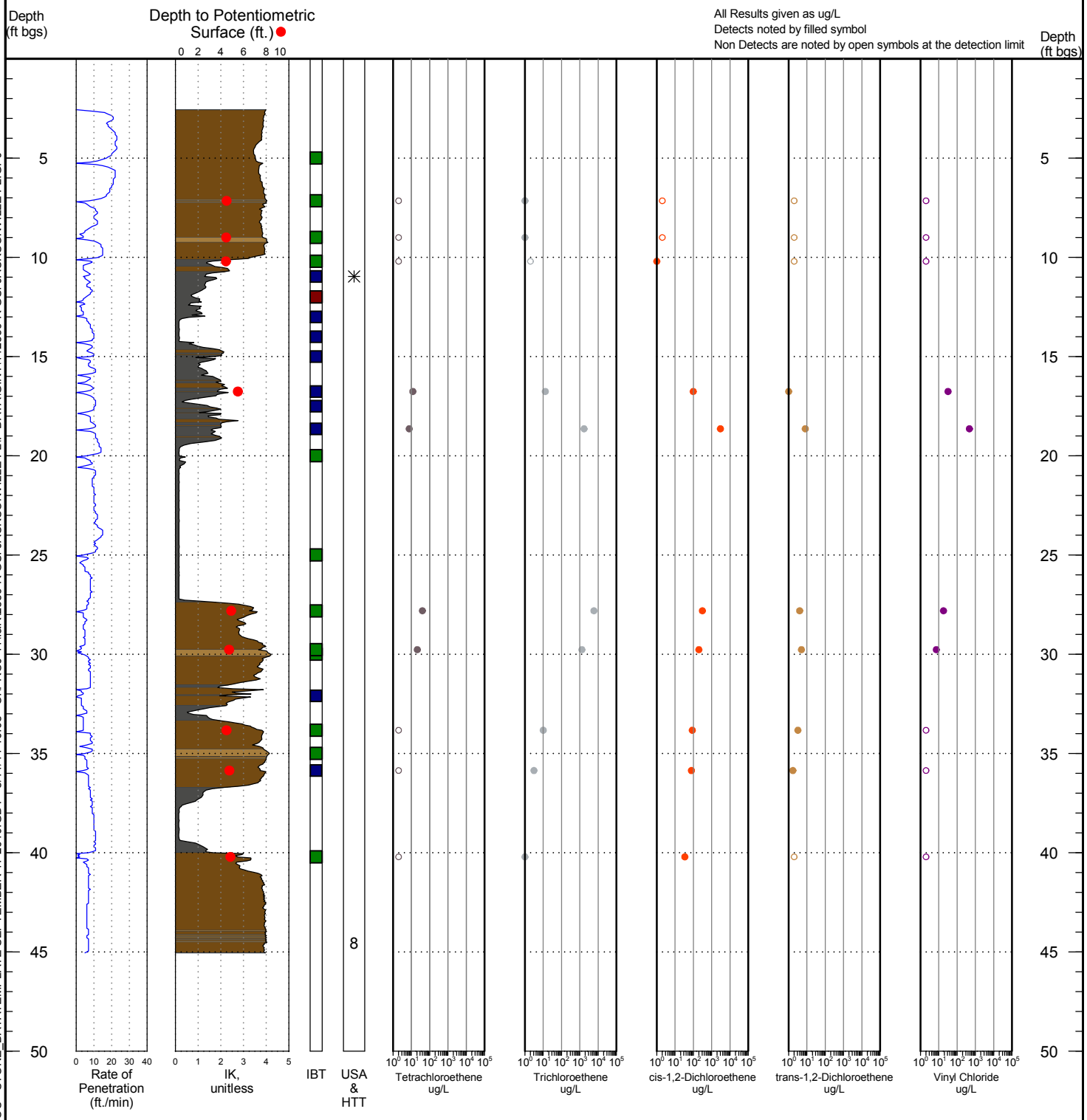
BORING NAME OU3-10-WP

Total Depth 45 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/27/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:08 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

BORING NAME OU3-11-WP

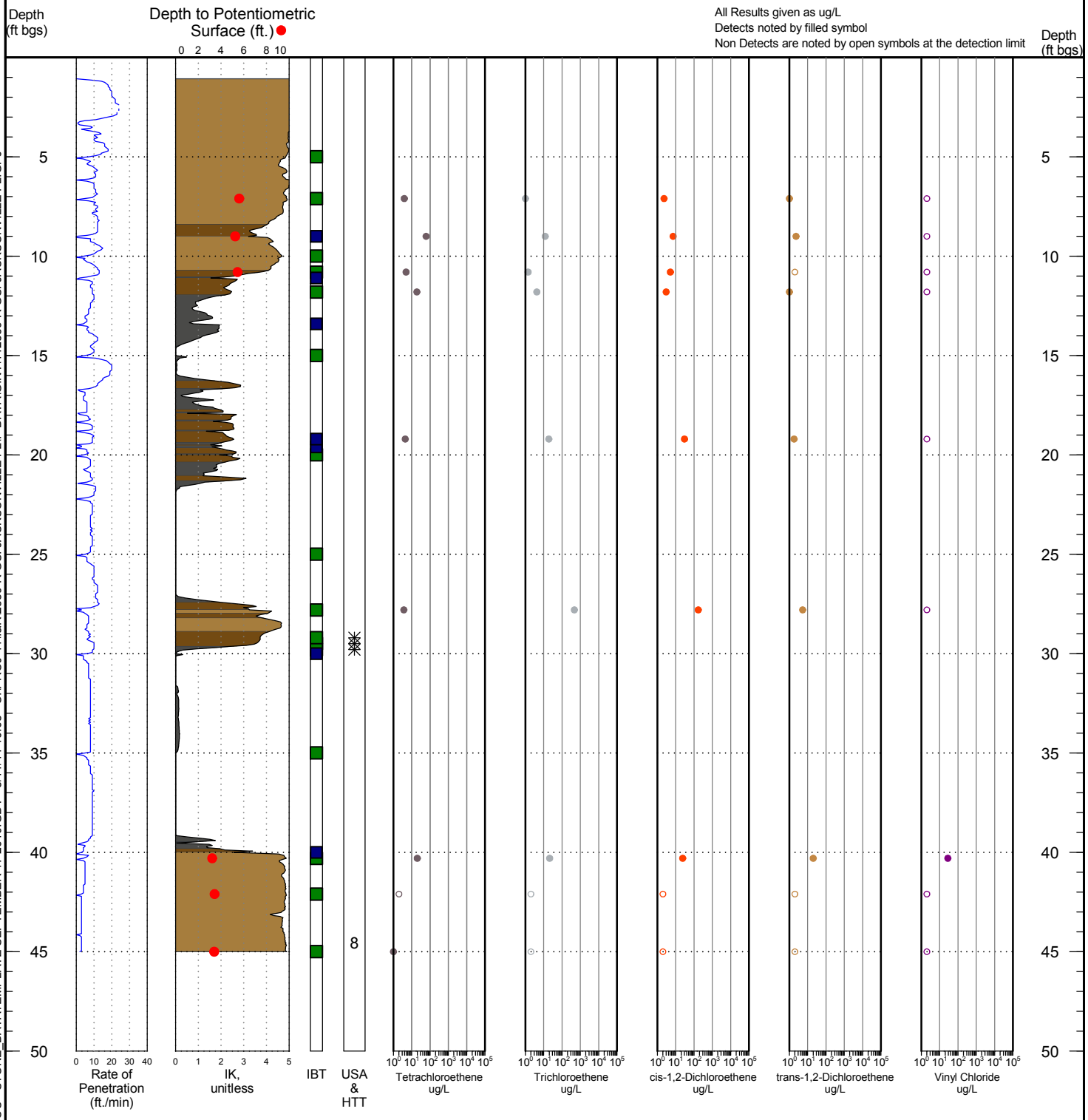
Total Depth 45 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/27/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump

All Results given as ug/L
Detects noted by filled symbol
Non Detects are noted by open symbols at the detection limit



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:08 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

BORING NAME OU3-12-WP

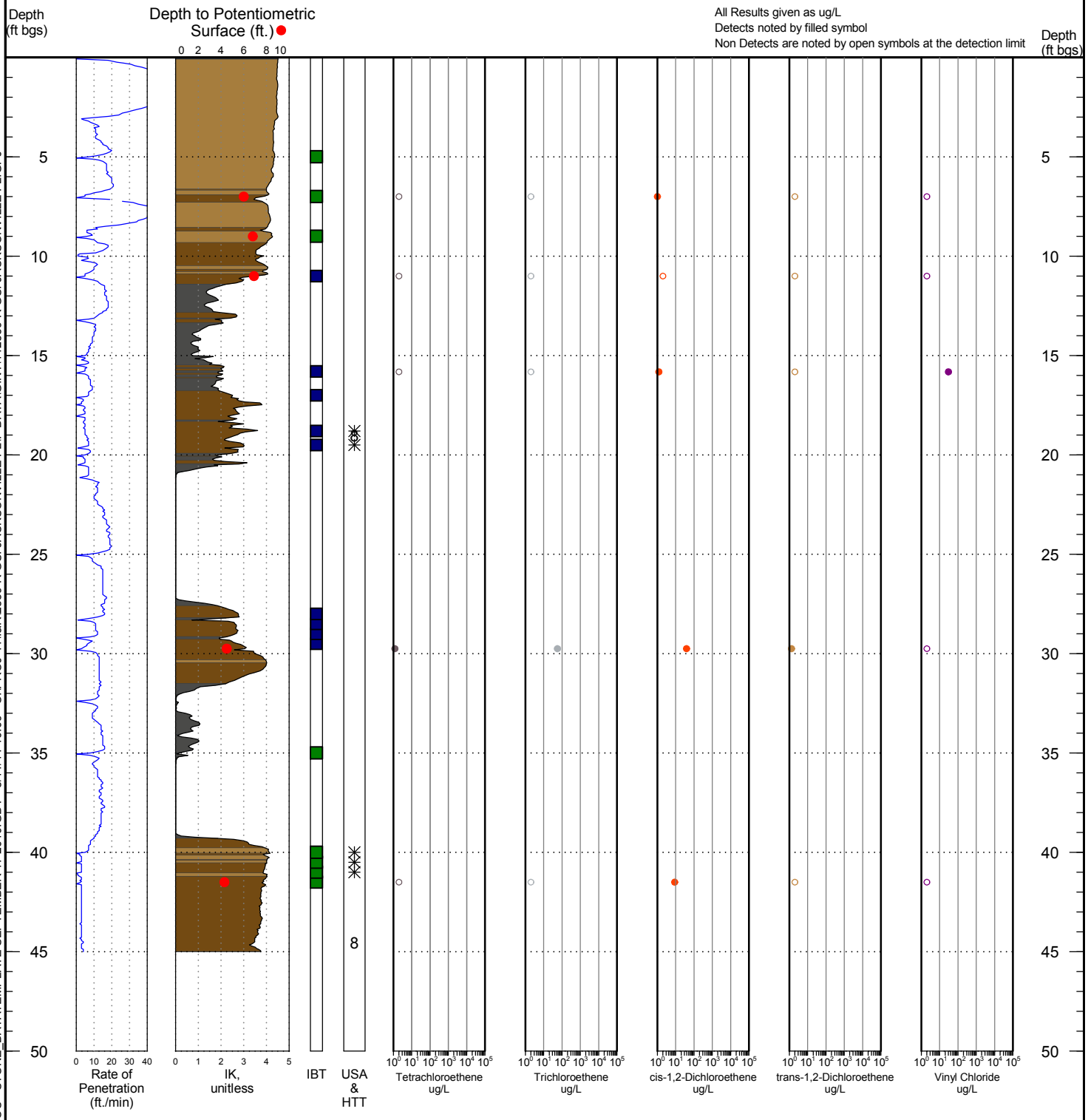
Total Depth 45 ft.

MobiLab™
DEFENSIBLE REAL-TIME ANALYTICS

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/28/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump

All Results given as ug/L
Detects noted by filled symbol
Non Detects are noted by open symbols at the detection limit



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS & VOC - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/11/11 10:09 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

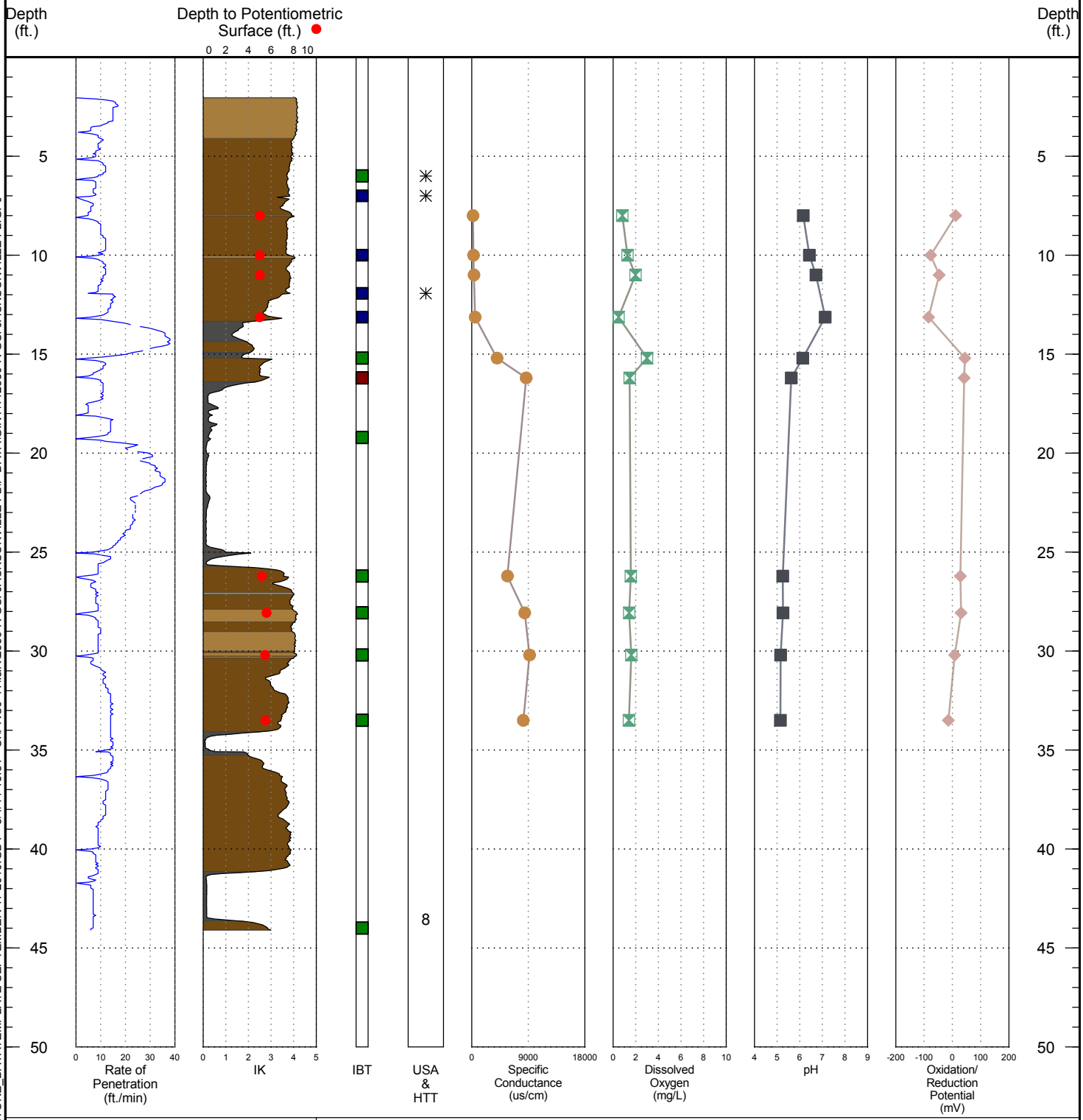
BORING NAME OU3-1-WP

Total Depth 44 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:51 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

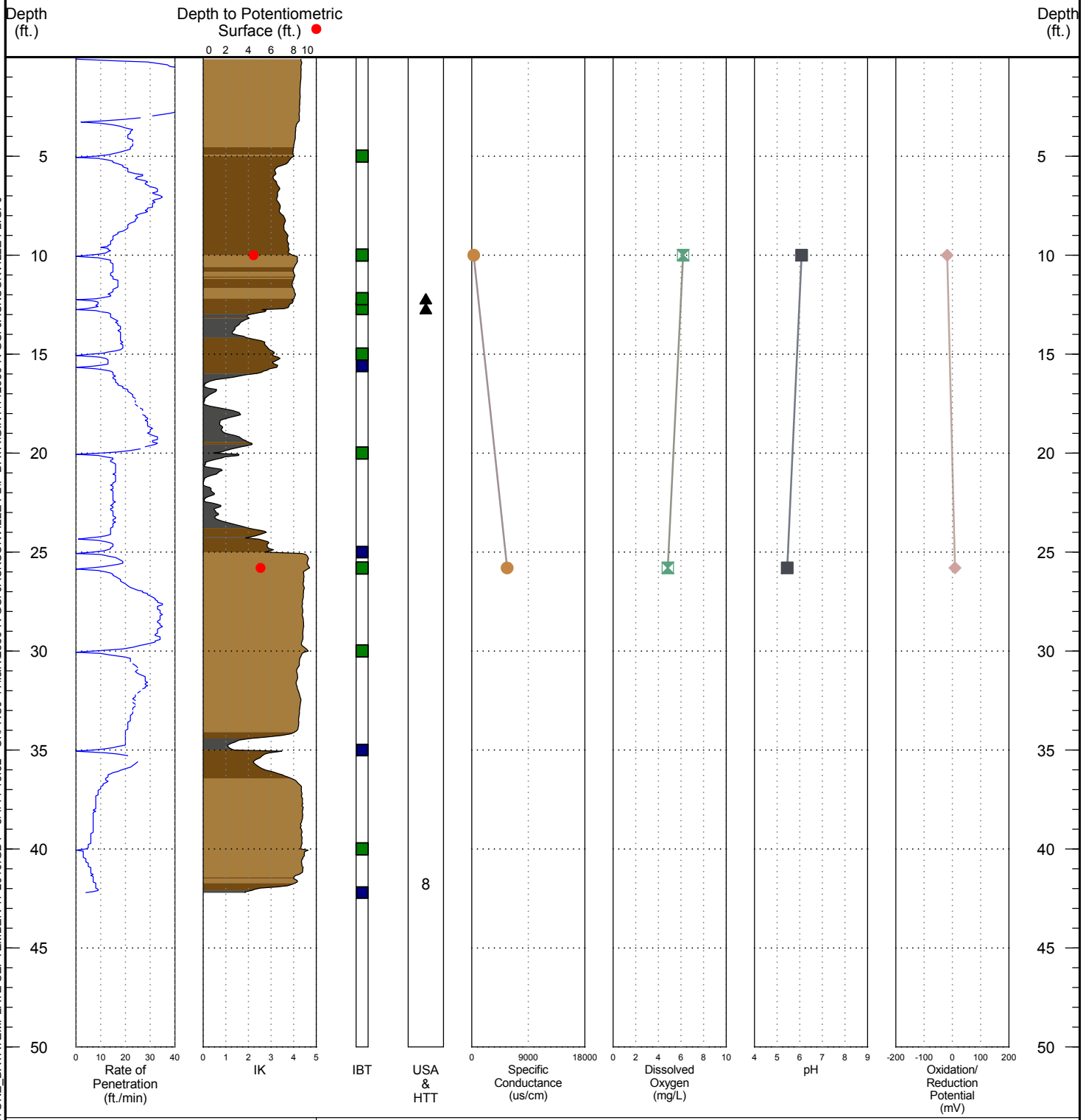
BORING NAME OU3-2-WP

Total Depth 42.2 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:52 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

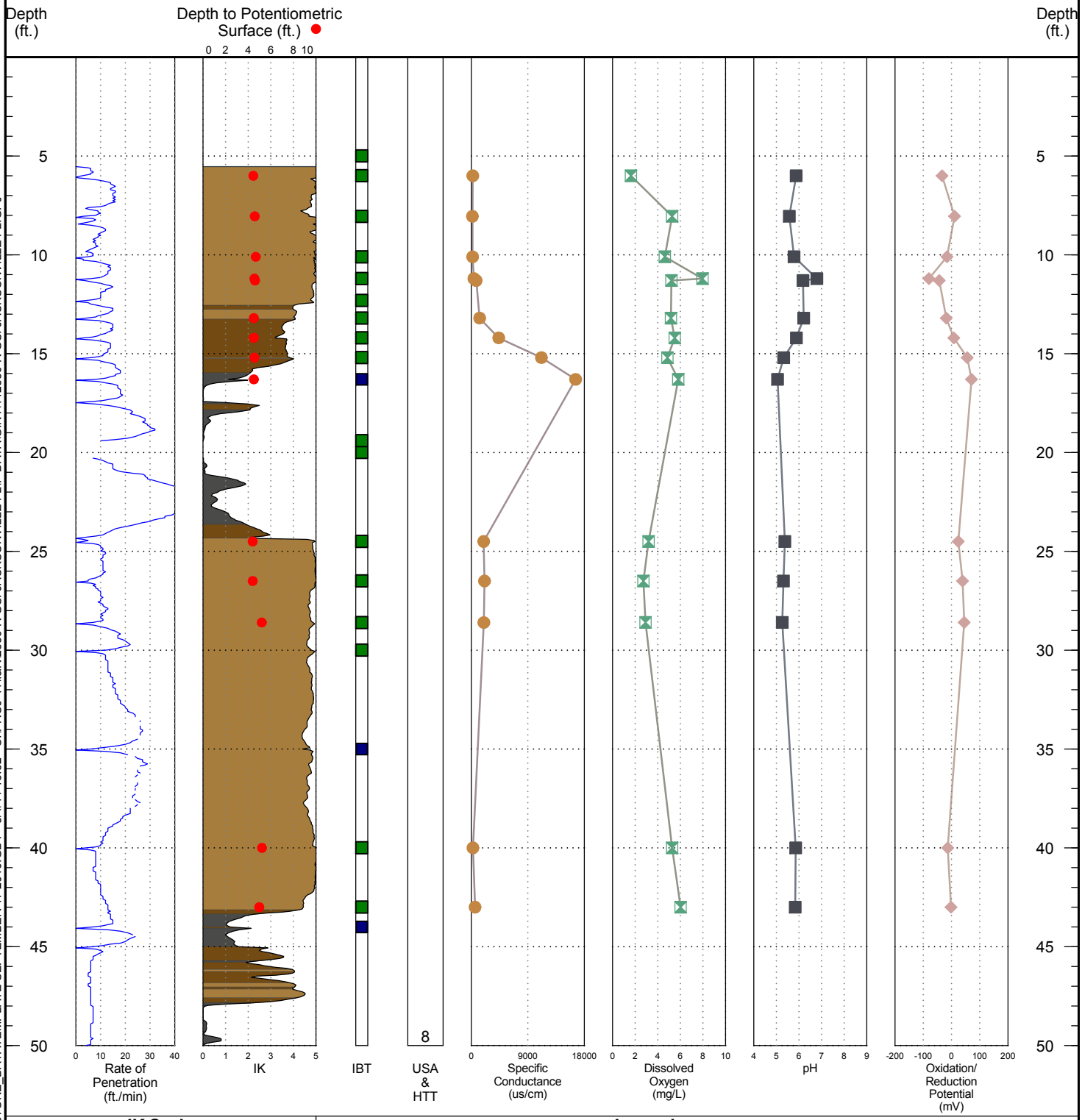
BORING NAME OU3-3-WP

Total Depth 50 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:52 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

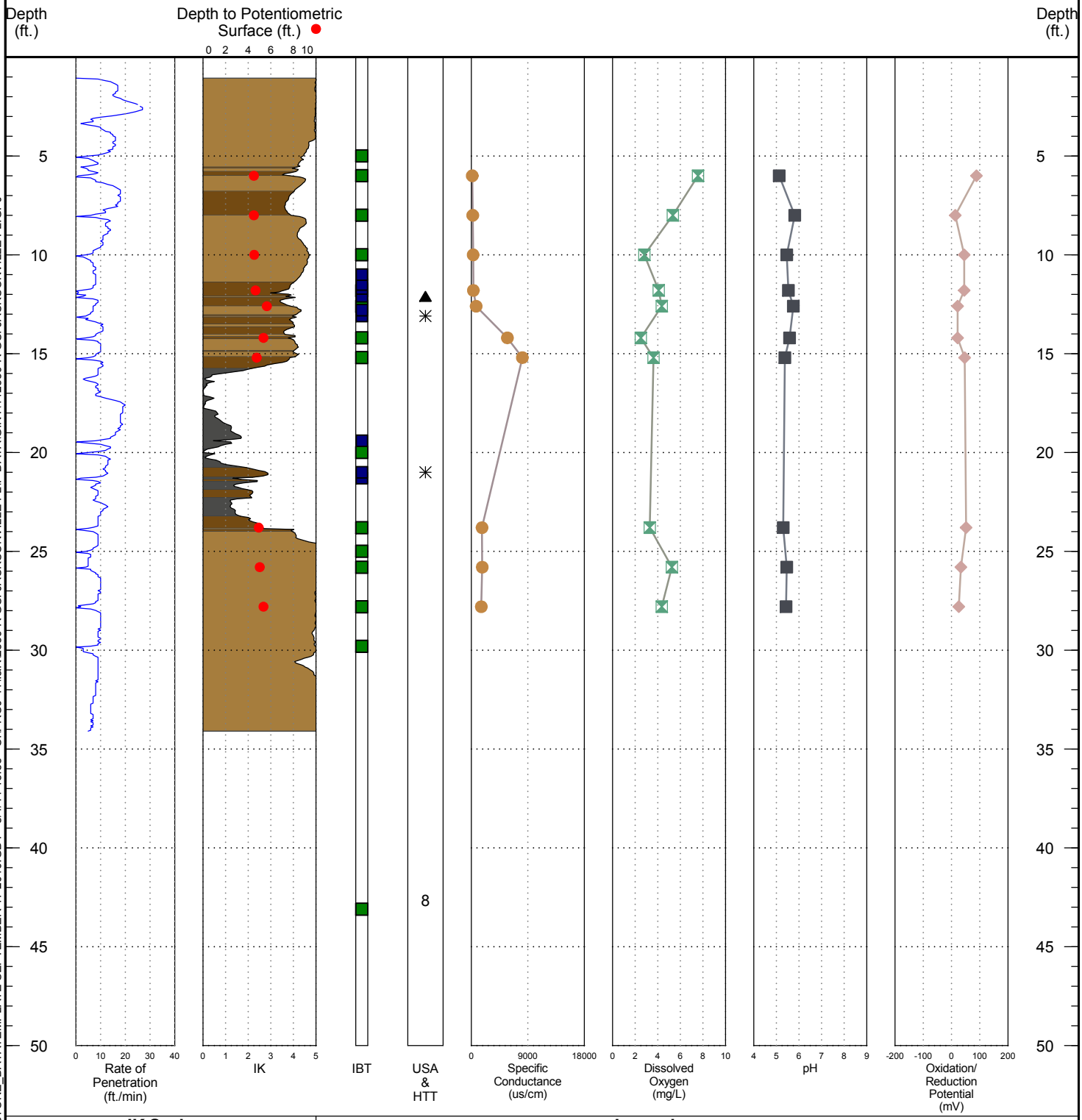
BORING NAME OU3-4-WP

Total Depth 43.1 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:53 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

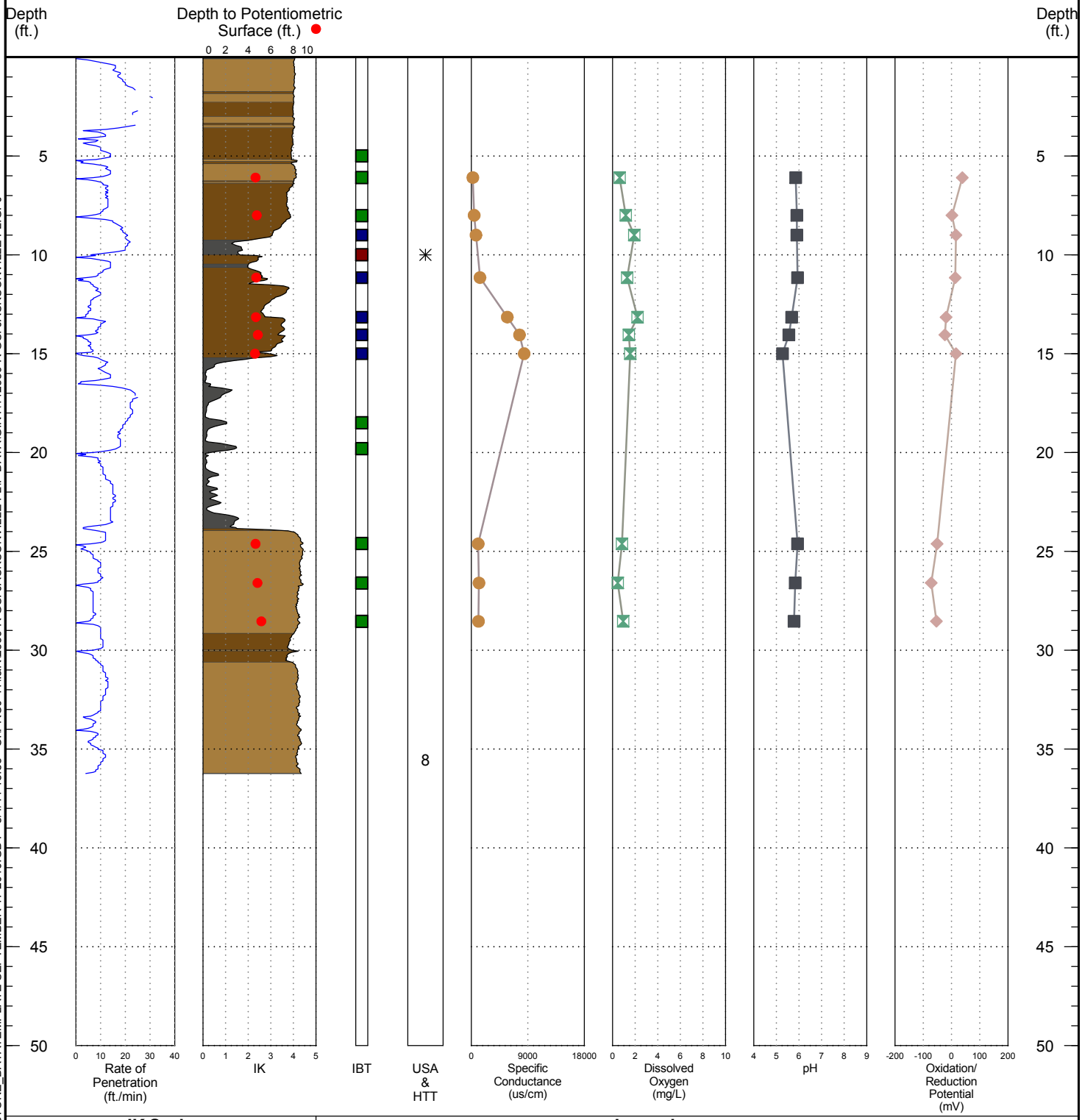
BORING NAME OU3-5-WP

Total Depth 36 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/26/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:53 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

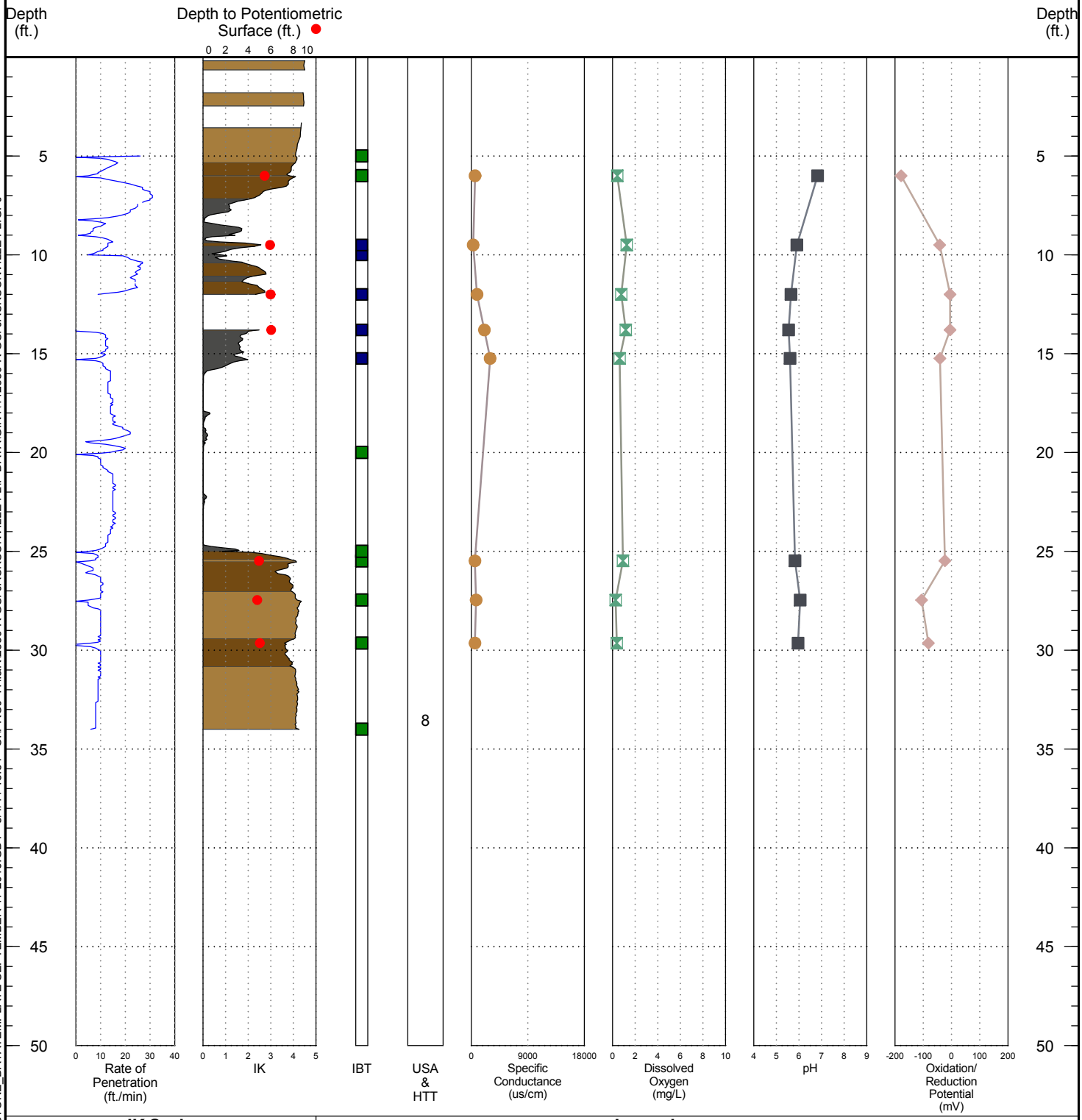
BORING NAME OU3-6-WP

Total Depth 34 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/29/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:54 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

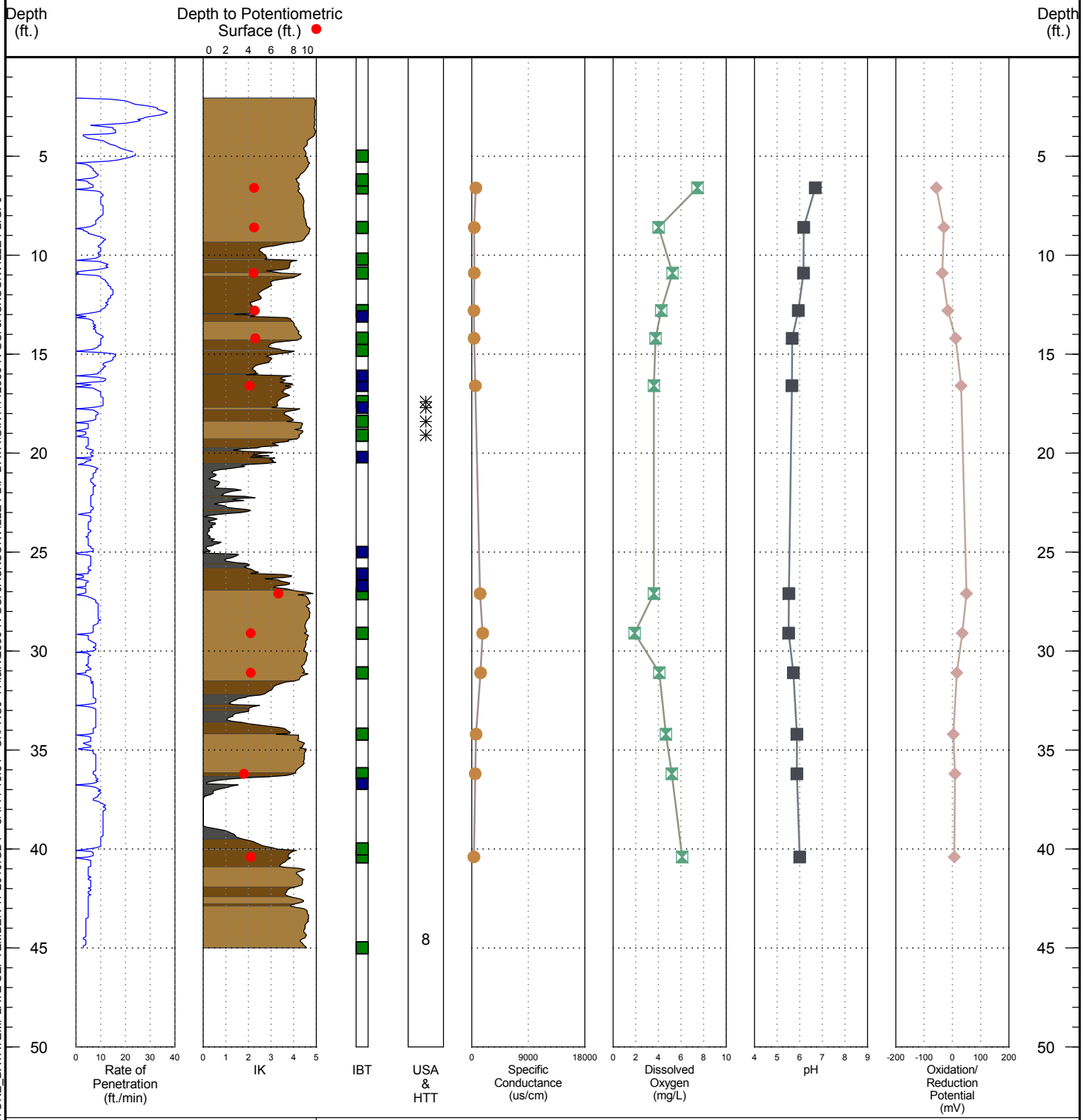
BORING NAME OU3-9-WP

Total Depth 45 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/28/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:54 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

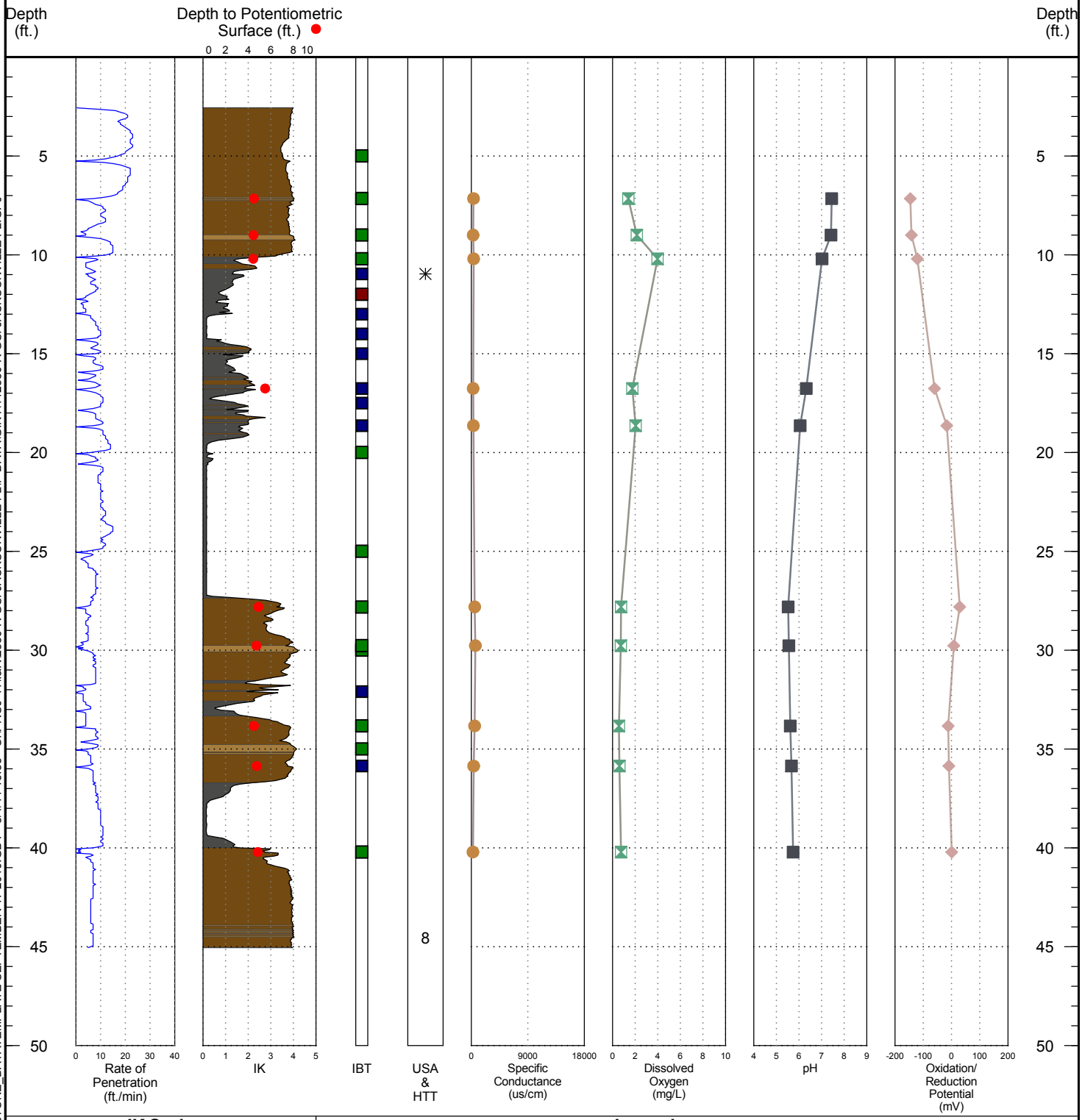
BORING NAME OU3-10-WP

Total Depth 45 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/27/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:55 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

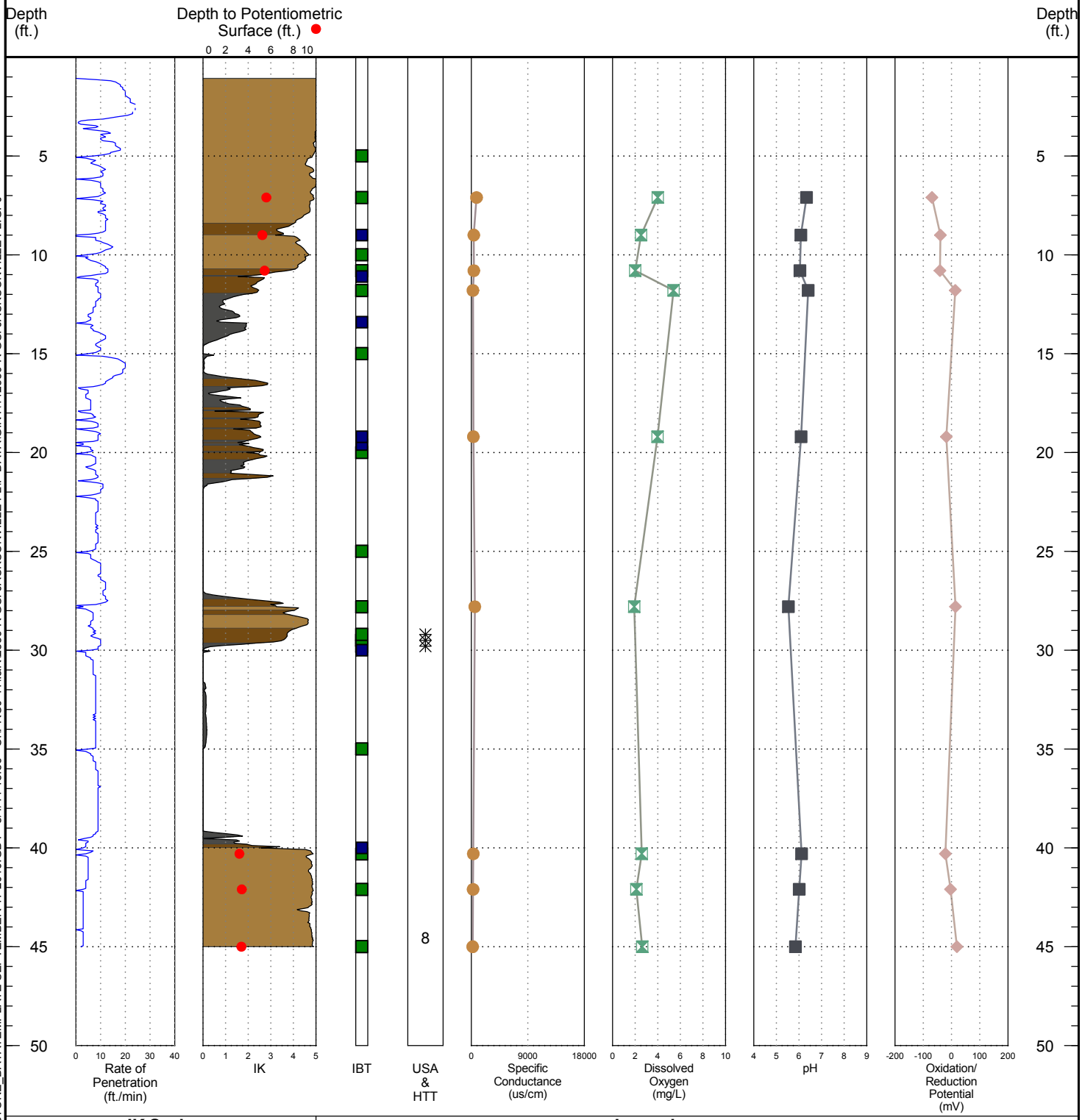
BORING NAME OU3-11-WP

Total Depth 45 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/27/2011
Sampler(s) WJW
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:56 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

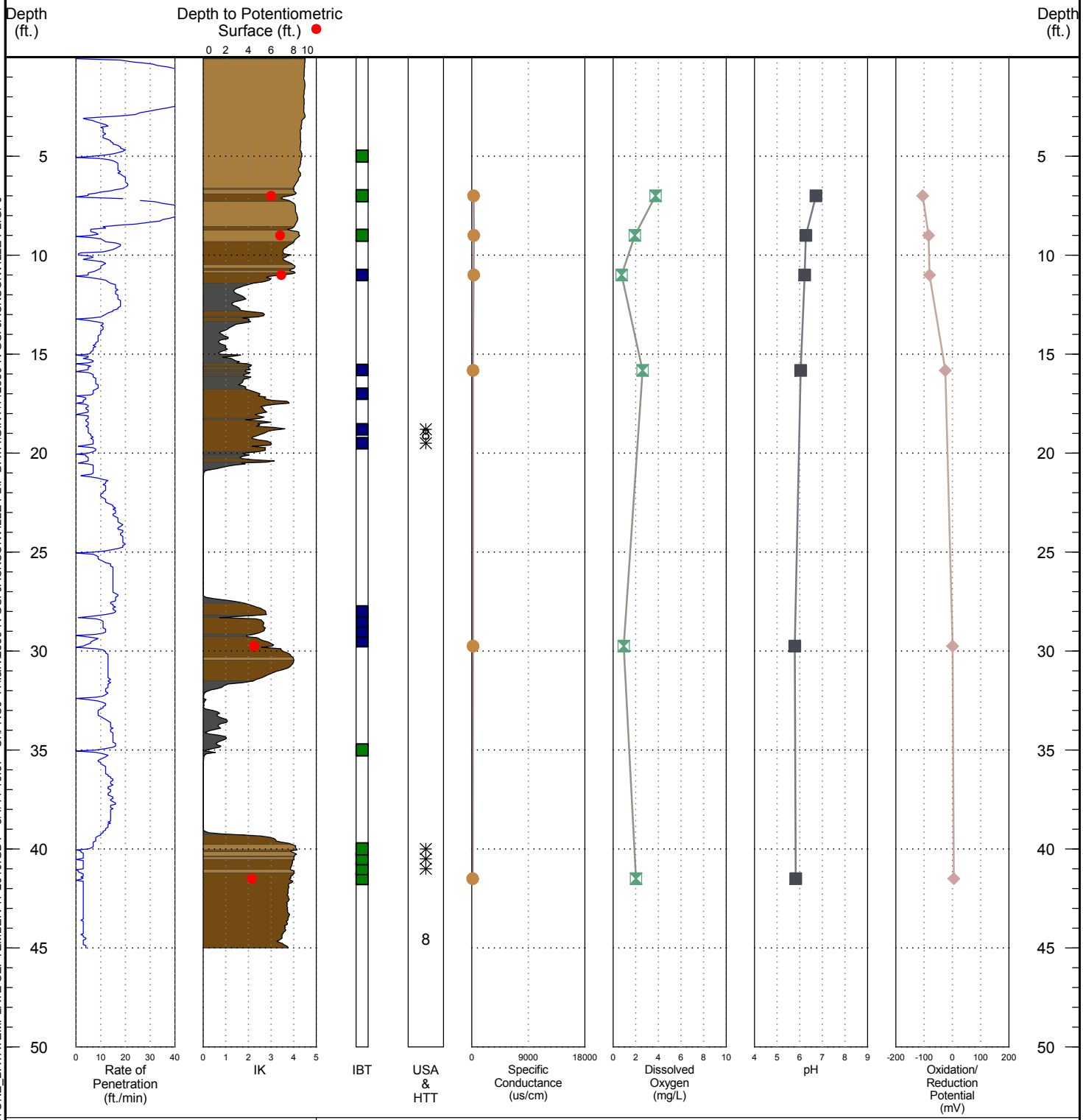
BORING NAME OU3-12-WP

Total Depth 45 ft.

Waterloo APS-D™ ADVANCED PROFILING SYSTEM

Project Name GSI Jacksonville, FL
Client GSI
Stone Project Number 112539-R
Project Location NAS Jacksonville FL

Date Completed 7/28/2011
Sampler(s) VLD
Drilling Contractor Probe Domain
Gas Drive or Peri Pump Peri Pump



IK Scale

0 to 0.1
0.1 to 2
2 to 4
4 to 6
>6

Legend

IBT = IK Behavior Type
- = IK increase when hammer stops
- = IK decrease when hammer stops
- = No change when hammer stops

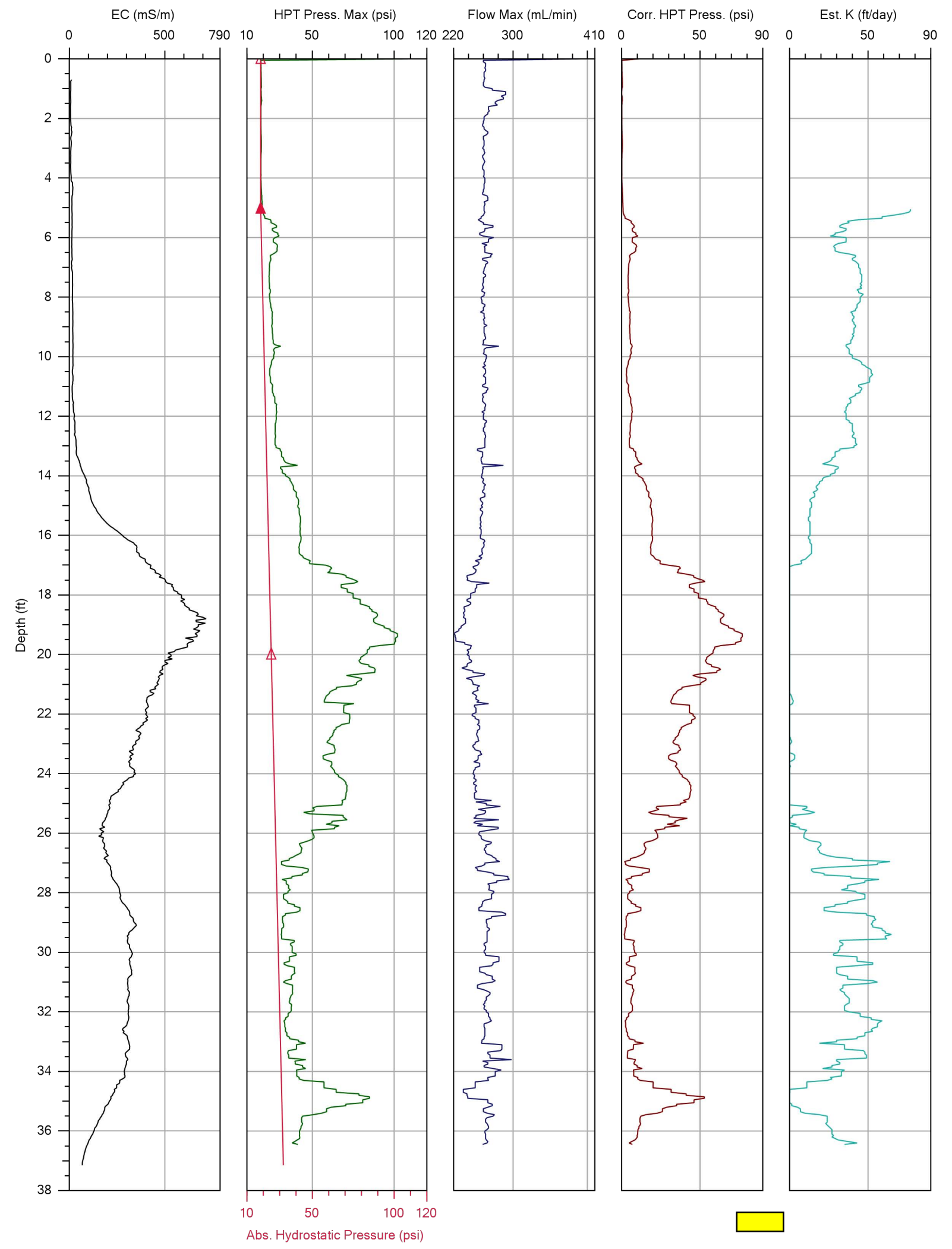
USA = Unsuccessful Sample Attempt
- ✳ = Could not produce water
- ▲ = Yield deemed too slow
- ■ = Equipment issue

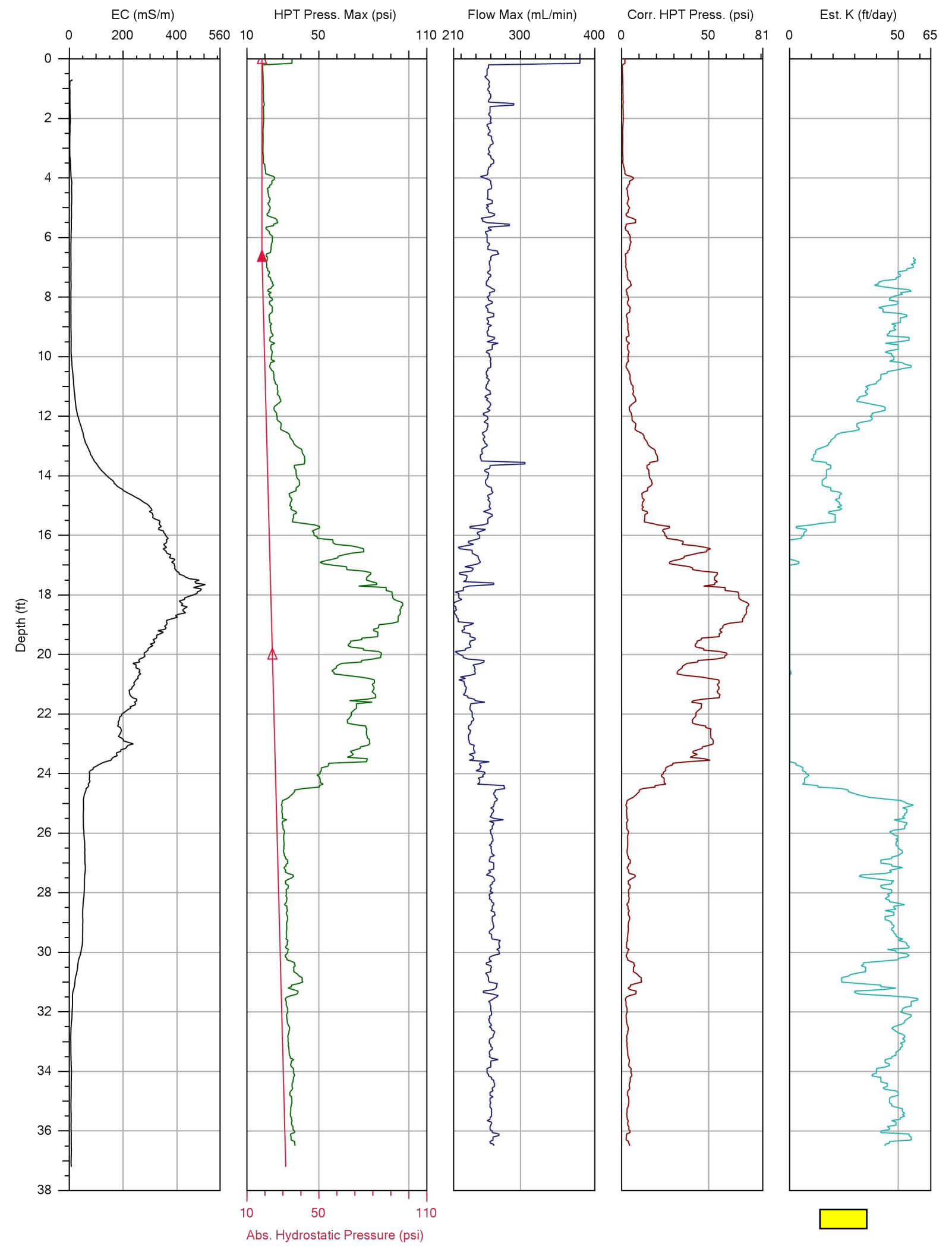
HTT = Hole Termination Type
- 7 = Broken downhole equipment
- 8 = Reached Target Depth
- 9 = ROP dropped below threshold
- 10 = Sudden Hard Refusal

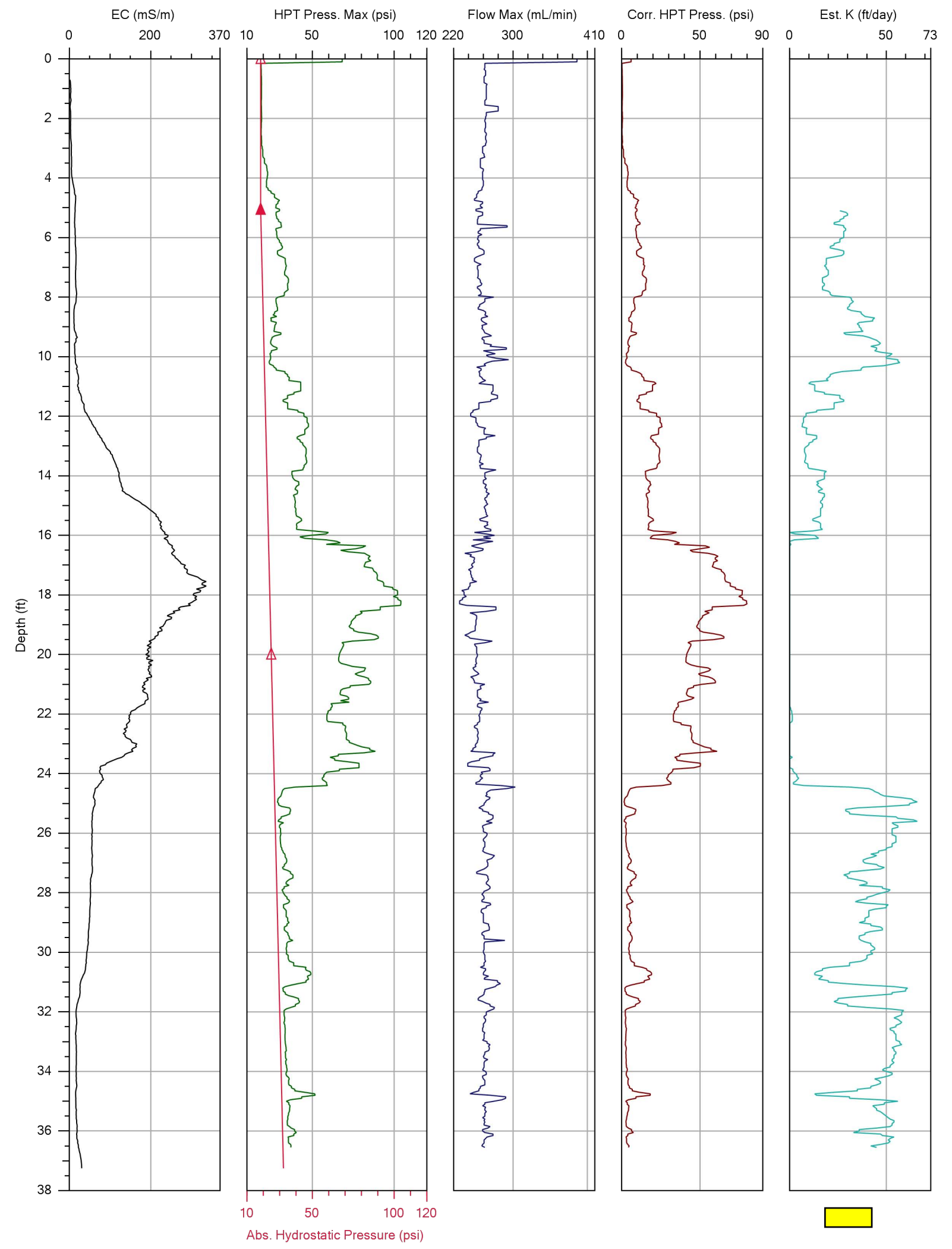
WATERLOO APS - STONE_DATATEMPLATE SEPTEMBER 17 2010.GDT - 8/4/11 13:57 - O:\PROJ-11\I&R\2539-R GSI JACKSONVILLE FL\F-DATA\GINT\112539-R GSI JACKSONVILLE FL.GPJ

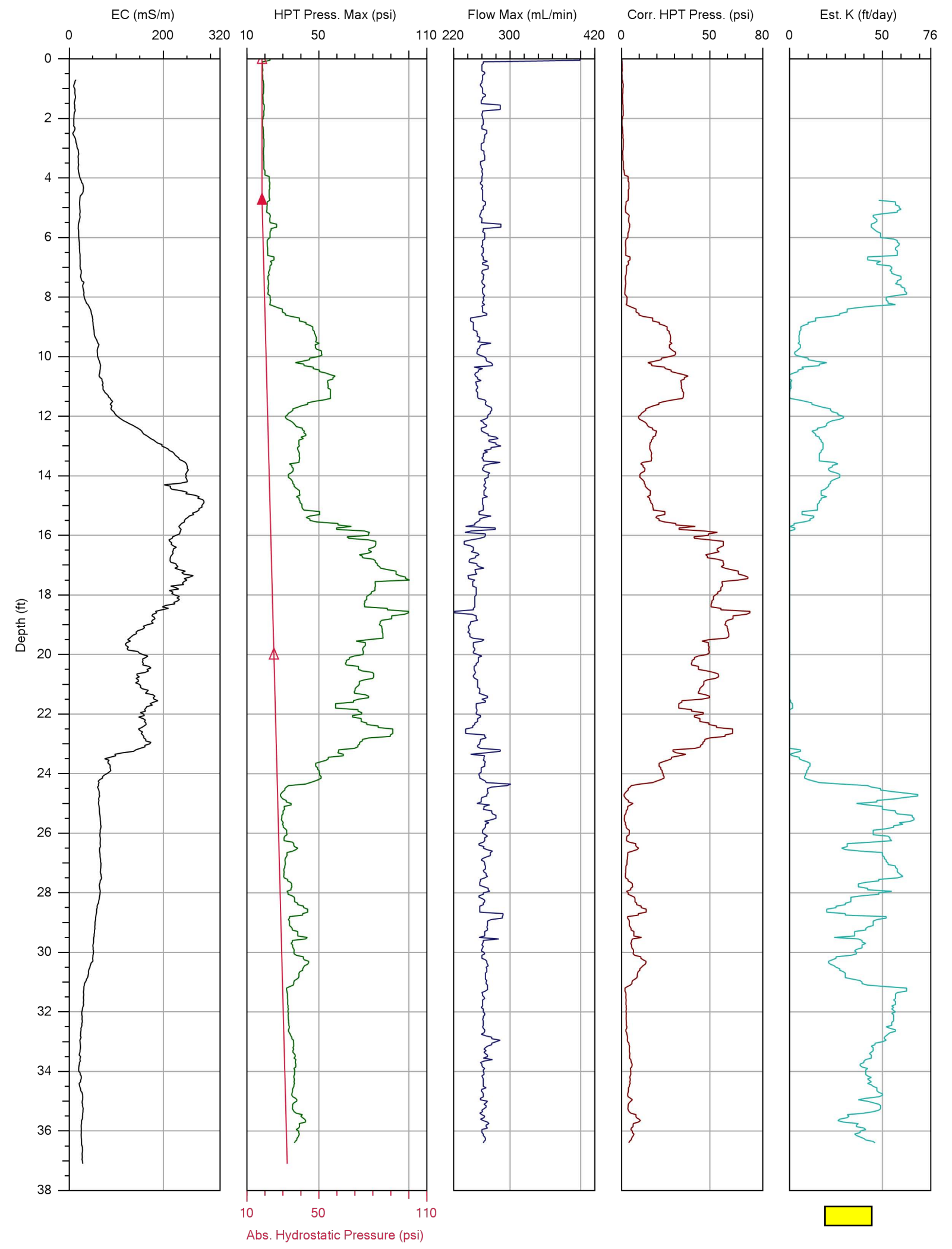
APPENDIX E

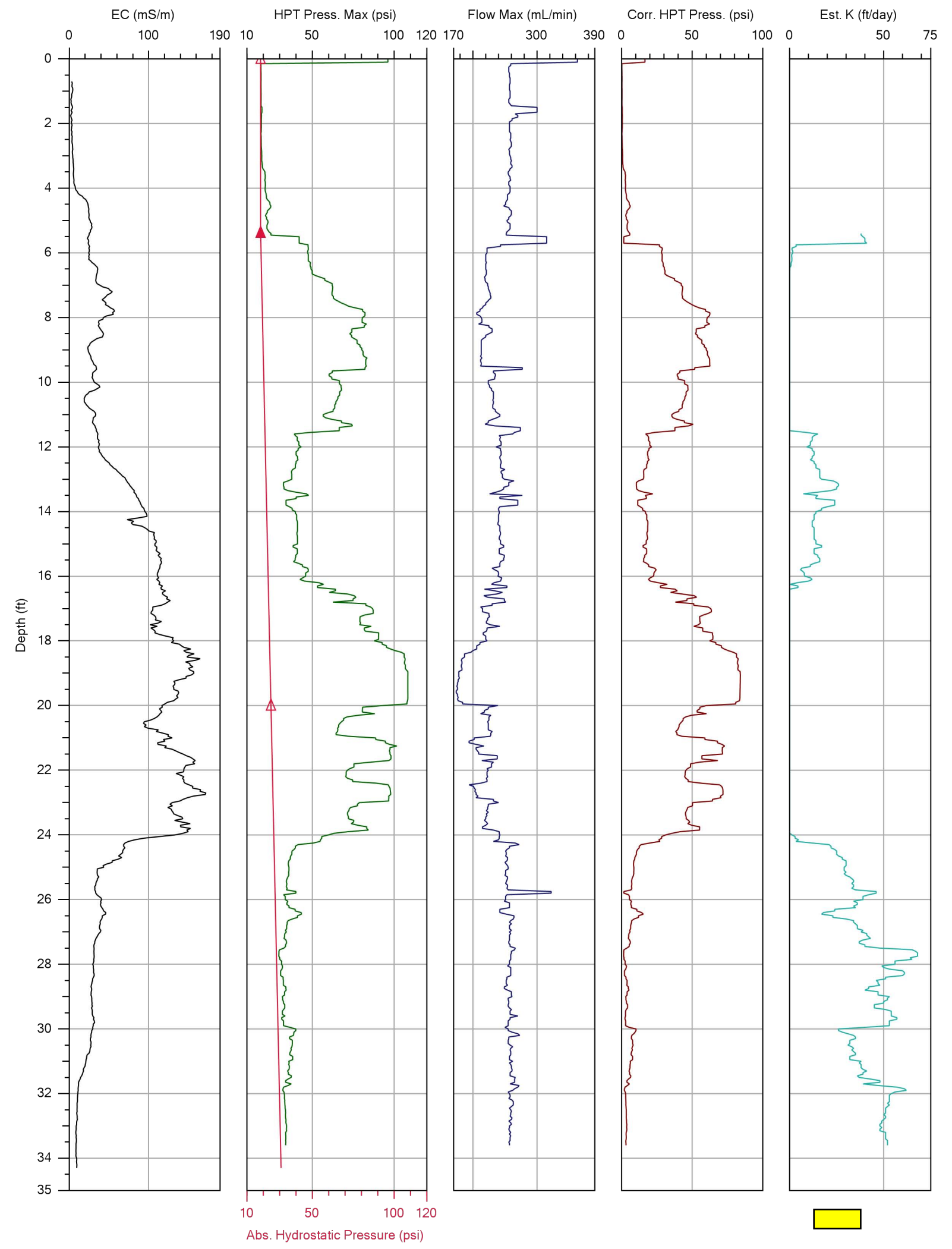
Geoprobe HPT Results from Demonstration Project


EC (mS/m)
0
500
790
HPT Press. Max (psi)
10
50
100
120
Flow Max (mL/min)
220
300
410
Corr. HPT Press. (psi)
0
50
90
Est. K (ft/day)
0
50
90
Depth (ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
10
50
100
120
Abs. Hydrostatic Pressure (psi)


EC (mS/m)
0
200
400
560
HPT Press. Max (psi)
10
50
110
Flow Max (mL/min)
210
300
400
Corr. HPT Press. (psi)
0
50
81
Est. K (ft/day)
0
50
65
Depth (ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
10
50
110
Abs. Hydrostatic Pressure (psi)


EC (mS/m)
0
200
370
HPT Press. Max (psi)
10
50
100
120
Flow Max (mL/min)
220
300
410
Corr. HPT Press. (psi)
0
50
90
Est. K (ft/day)
0
50
73
Depth (ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
10
50
100
120
Abs. Hydrostatic Pressure (psi)

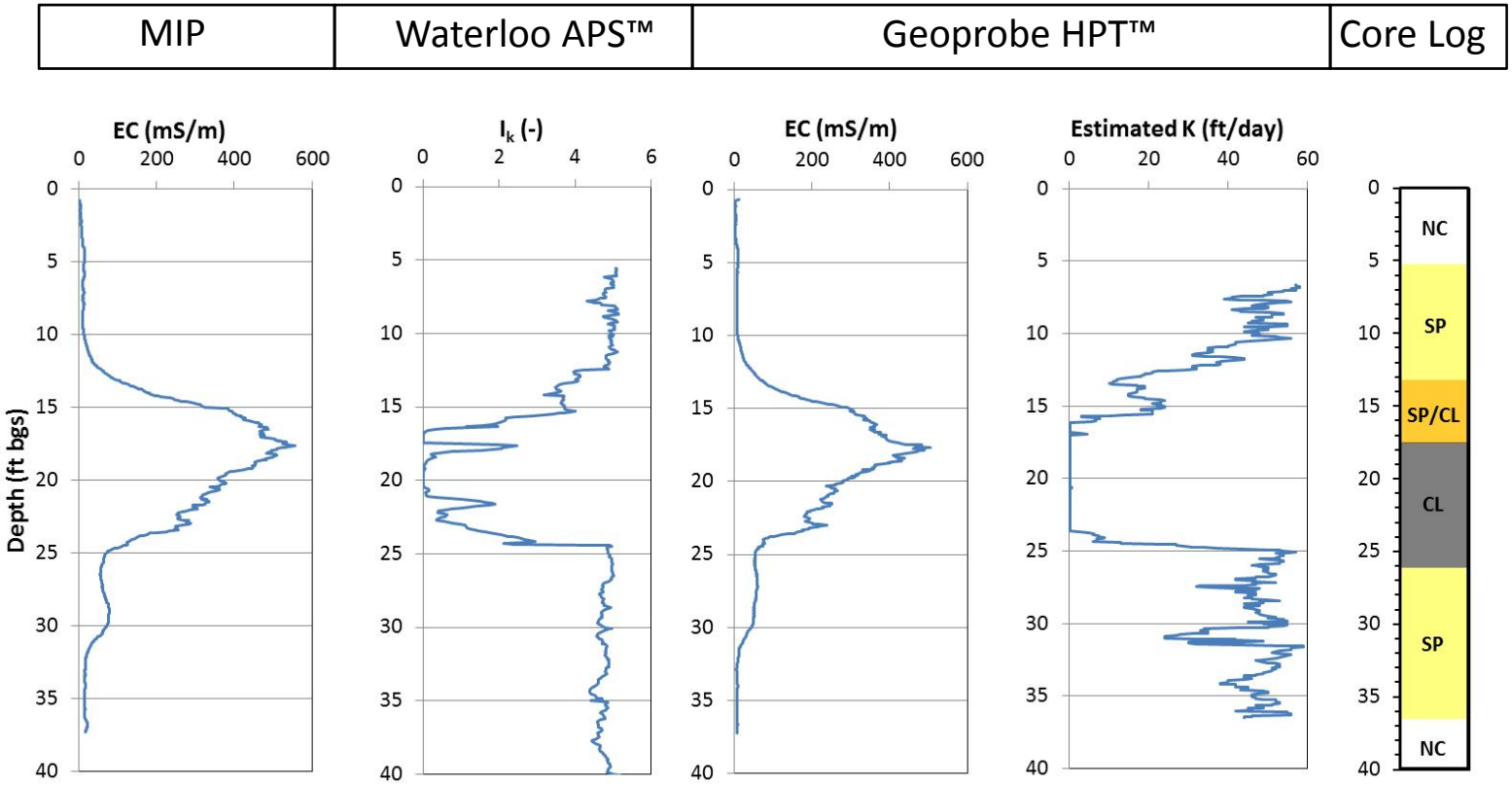

EC (mS/m)
0
200
320
HPT Press. Max (psi)
10
50
110
Flow Max (mL/min)
220
300
420
Corr. HPT Press. (psi)
0
50
80
Est. K (ft/day)
0
50
76
Depth (ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
10
50
110
Abs. Hydrostatic Pressure (psi)


EC (mS/m)
0
100
190
HPT Press. Max (psi)
10
50
100
120
Flow Max (mL/min)
170
300
390
Corr. HPT Press. (psi)
0
50
100
Est. K (ft/day)
0
50
75
Depth (ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
35
10
50
100
120
Abs. Hydrostatic Pressure (psi)

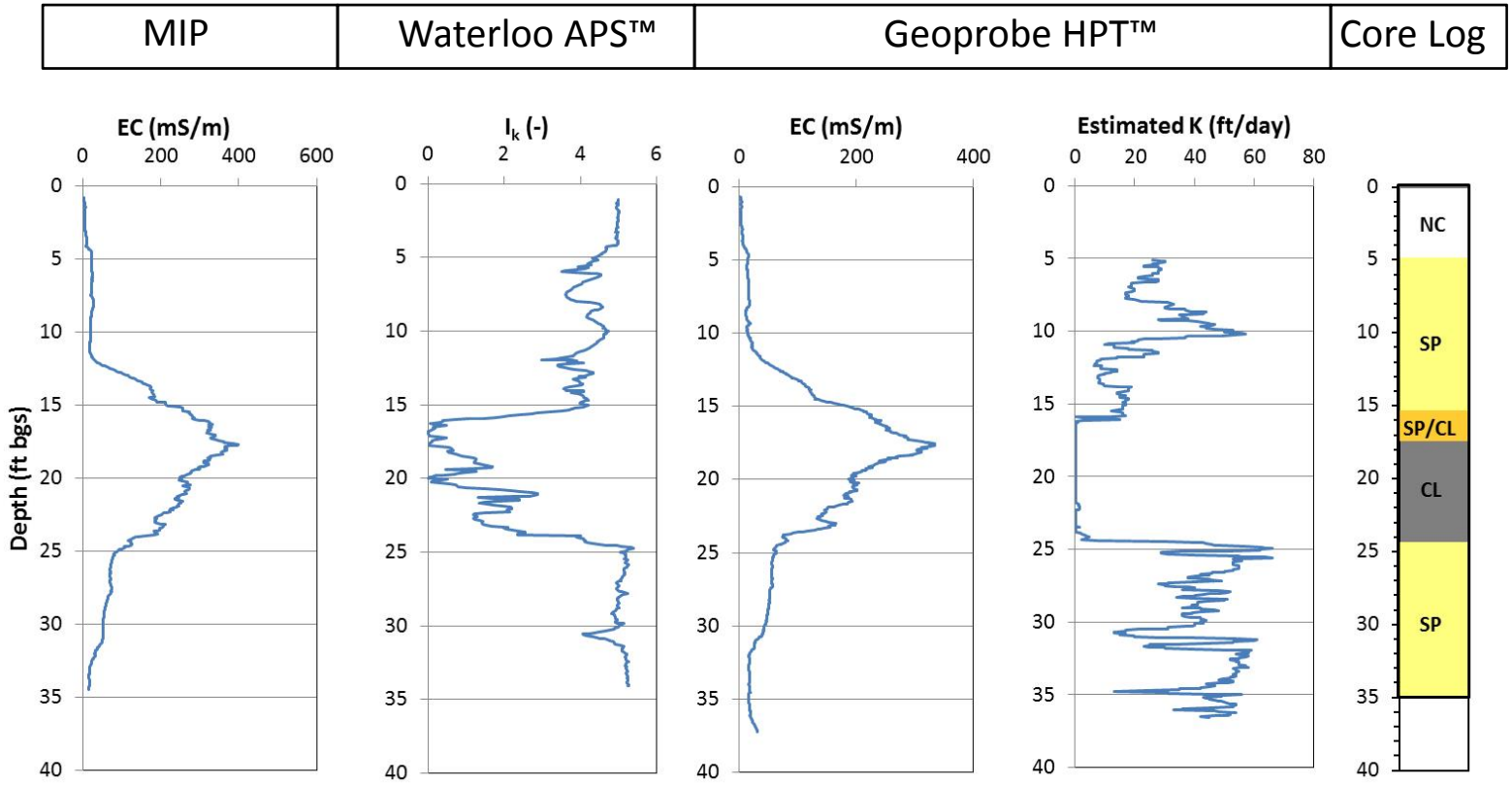
APPENDIX F

Plots of Stratigraphic Data from Various Characterization Methods

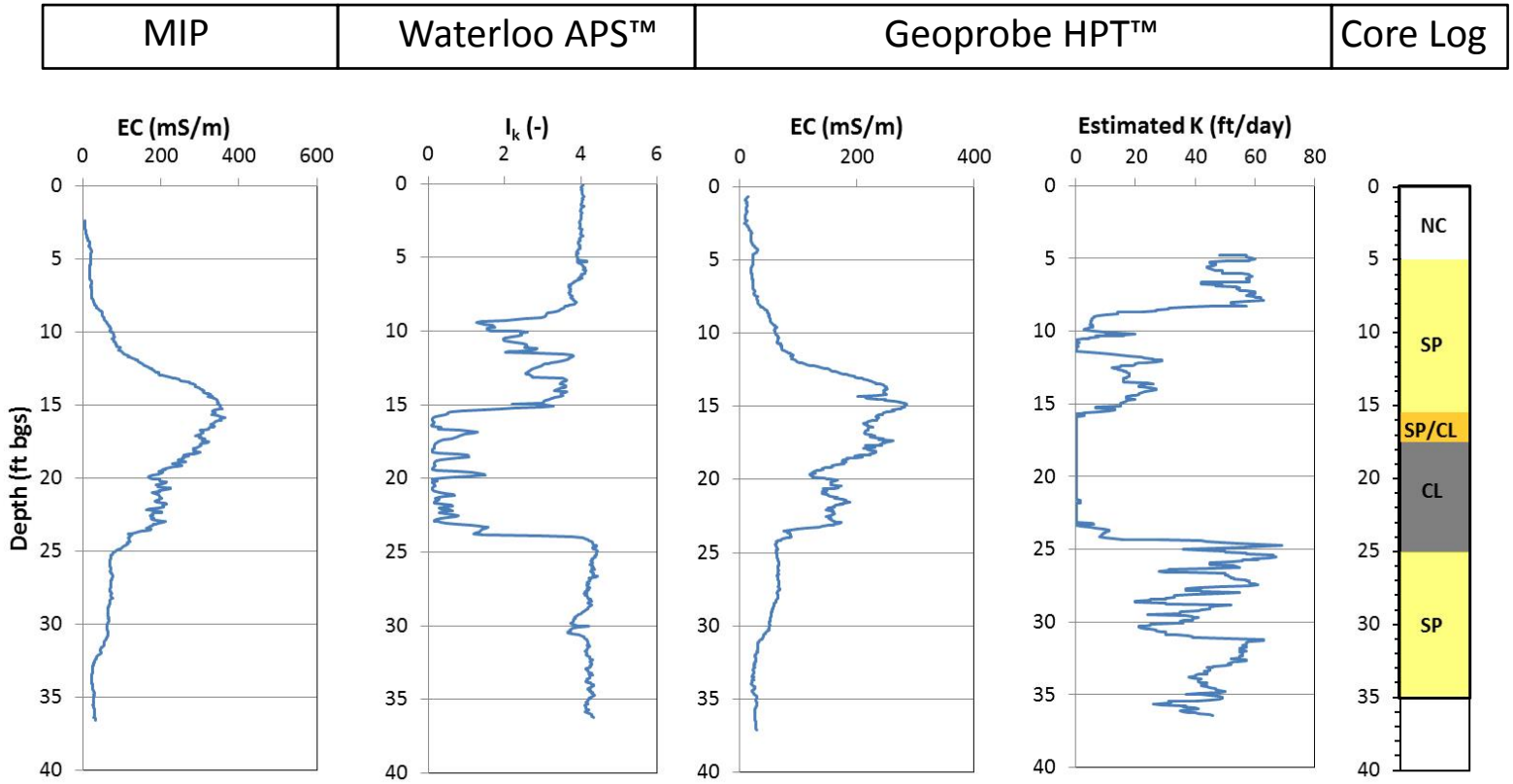
(a) **OU3-3**


MIP
Waterloo APS™
Geoprobe HPT™
Core Log
EC (mS/m)
0
200
400
600
I_k (-)
0
2
4
6
EC (mS/m)
0
200
400
600
Estimated K (ft/day)
0
20
40
60
Depth (ft bgs)
0
5
10
15
20
25
30
35
40
NC
SP
SP/CL
CL
SP
NC

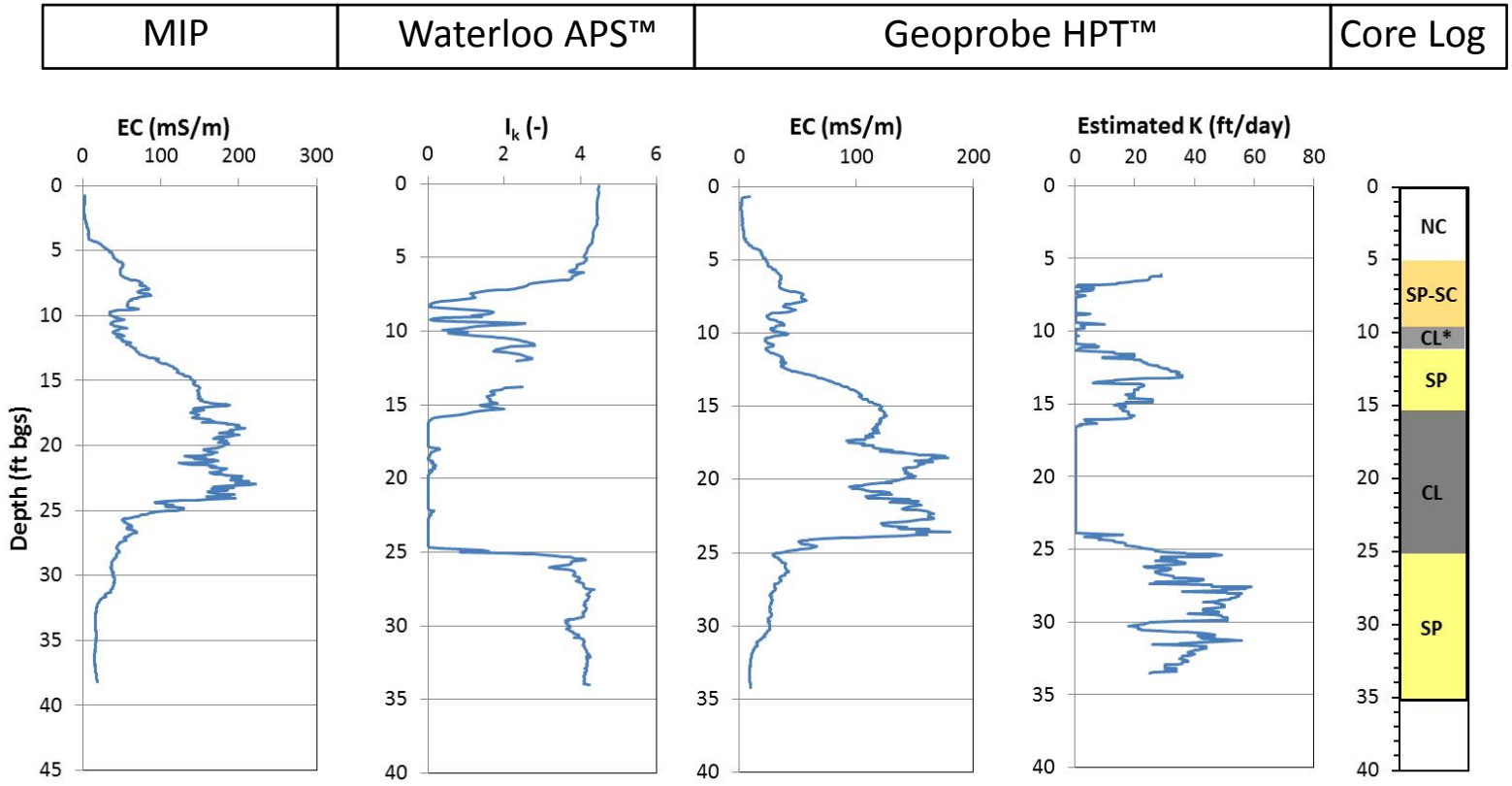
(b) **OU3-4**


MIP
Waterloo APS™
Geoprobe HPT™
Core Log
EC (mS/m)
0
200
400
600
I_k (-)
0
2
4
6
EC (mS/m)
0
200
400
Estimated K (ft/day)
0
20
40
60
80
Depth (ft bgs)
0
5
10
15
20
25
30
35
40
NC
SP
SP/CL
CL
SP

(c) **OU3-5**


MIP
Waterloo APS™
Geoprobe HPT™
Core Log
EC (mS/m)
0
200
400
600
I_k (-)
0
2
4
6
EC (mS/m)
0
200
400
Estimated K (ft/day)
0
20
40
60
80
Depth (ft bgs)
0
5
10
15
20
25
30
35
40
NC
SP
SP/CL
CL
SP

(d) **OU3-6**

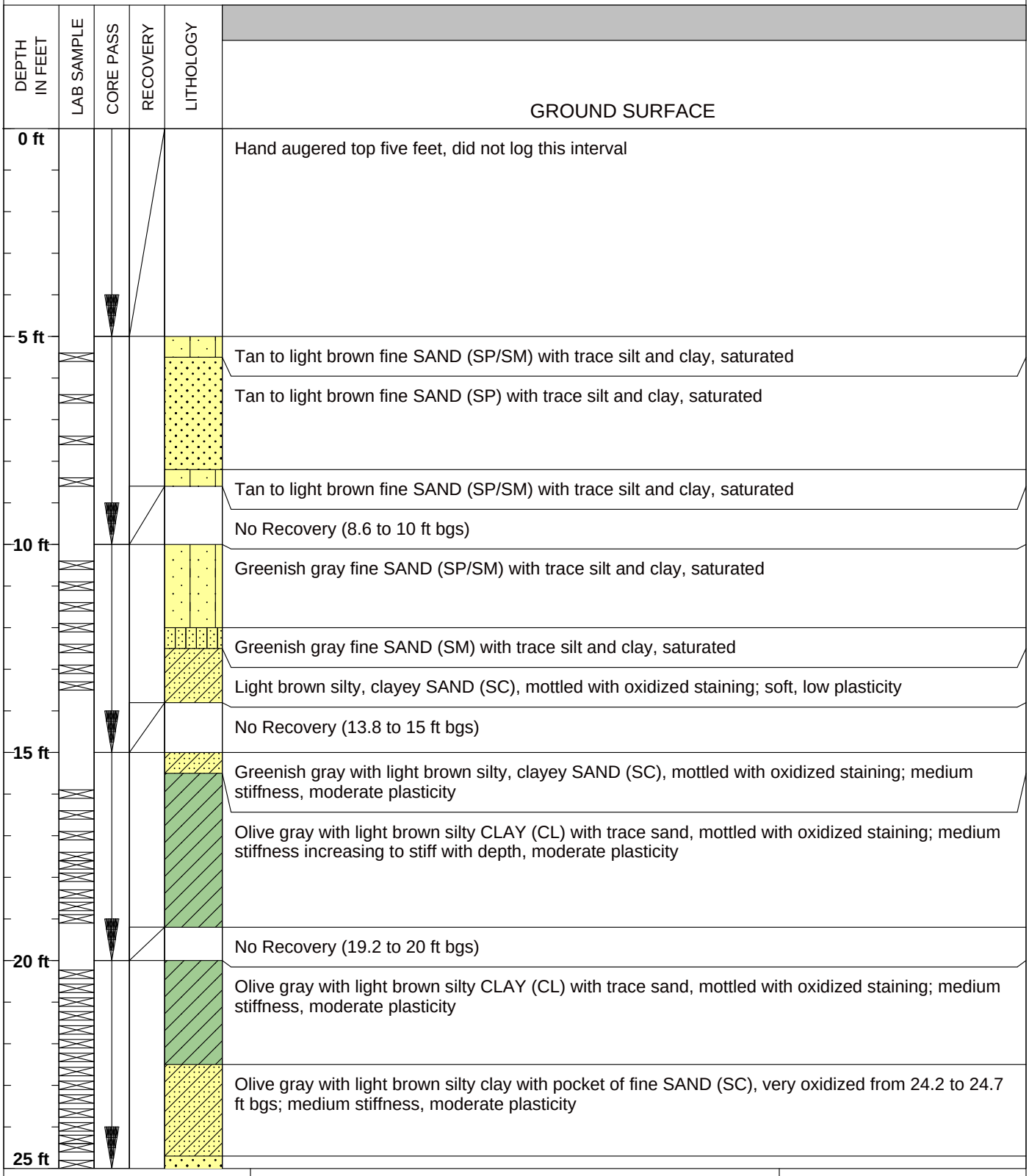

MIP
Waterloo APS™
Geoprobe HPT™
Core Log
EC (mS/m)
0
100
200
300
Depth (ft bgs)
0
5
10
15
20
25
30
35
40
45
I_k (-)
0
2
4
6
EC (mS/m)
0
100
200
Estimated K (ft/day)
0
20
40
60
80
NC
SP-SC
CL*
SP
CL
SP

APPENDIX G

Soil Boring Logs

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 18 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-3

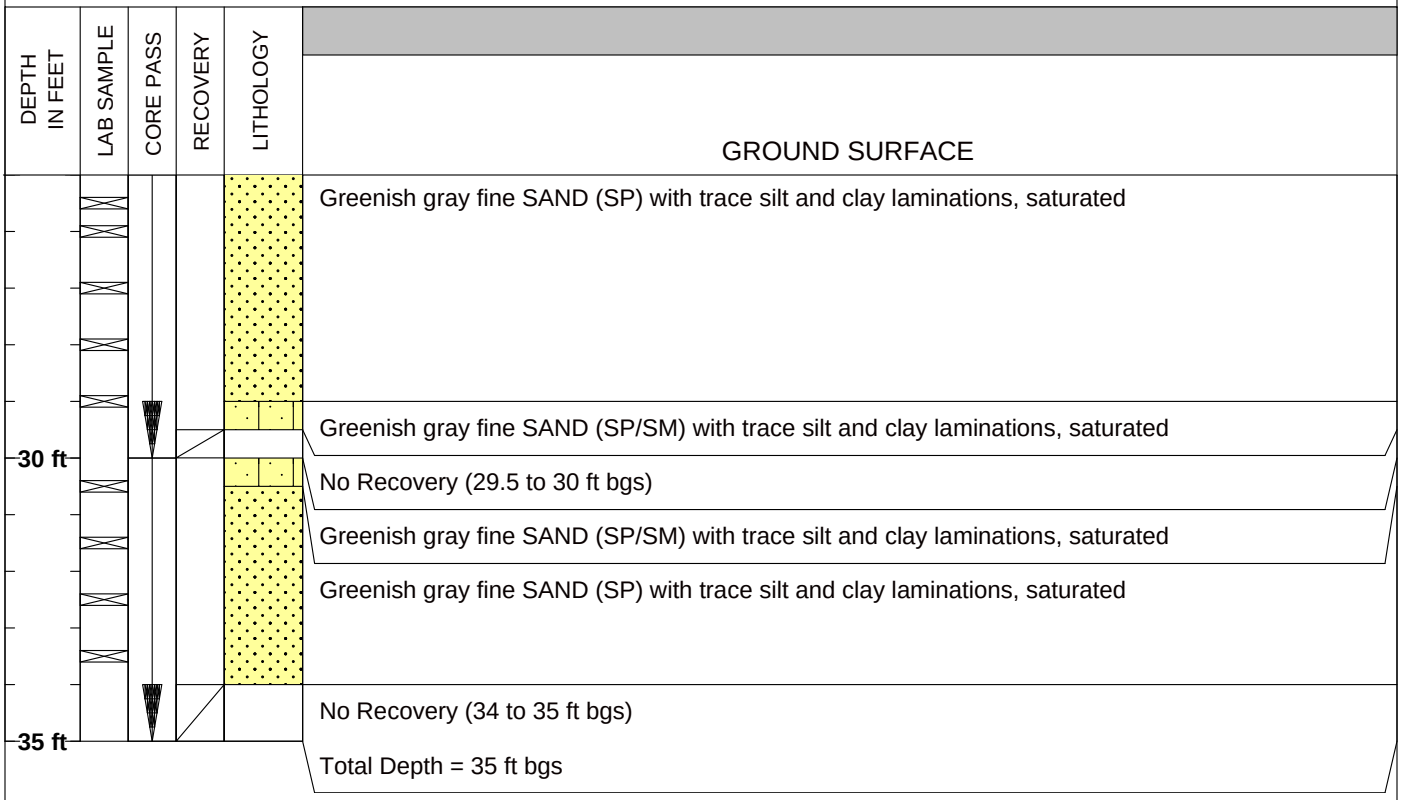
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 18 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-3

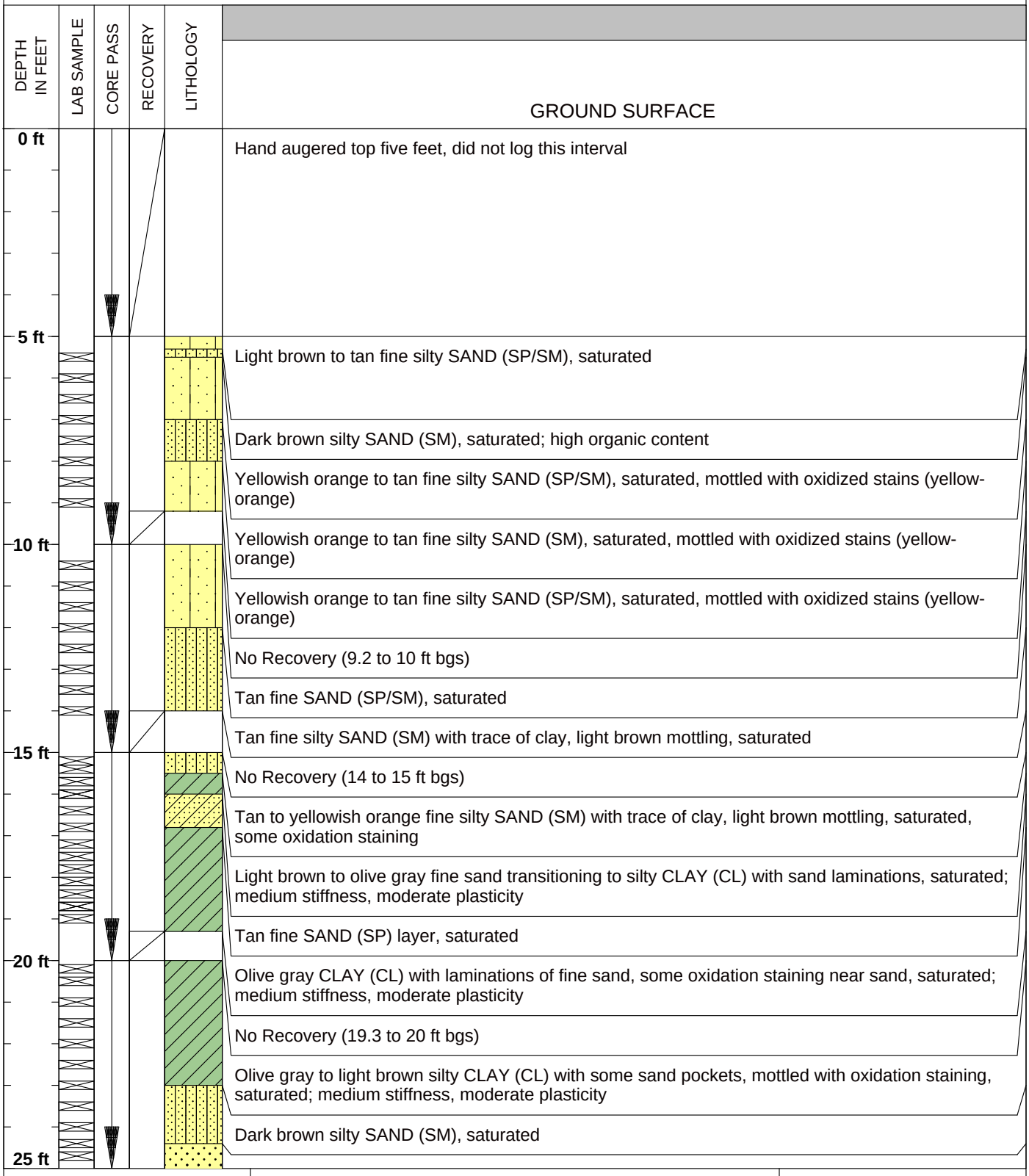
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 15 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-4

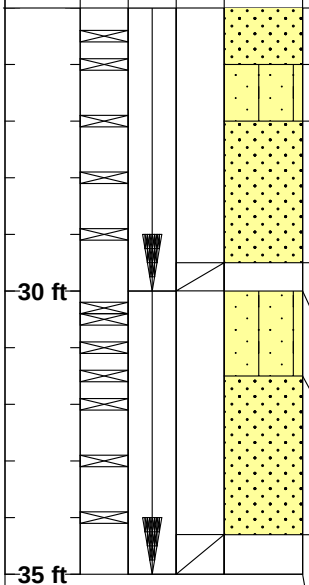
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 15 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Brown fine SAND (SP) with trace silt and clay pockets, some oxidation staining, saturated

Brown fine SAND (SP/SM) with trace silt and clay pockets, some oxidation staining, saturated

Brown fine SAND (SP) with trace silt and clay pockets, some oxidation staining, saturated

No Recovery (29.5 to 30 ft bgs)

Tan to yellowish orange fine silty SAND (SP/SM) with some pockets of clay, mottled with oxidation stains, saturated

Tannish orange fine SAND (SP) with trace silt and clay, saturated; increasing grain size with depth

No Recovery (34.3 to 35 ft bgs)

Total Depth = 35 ft bgs

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-4

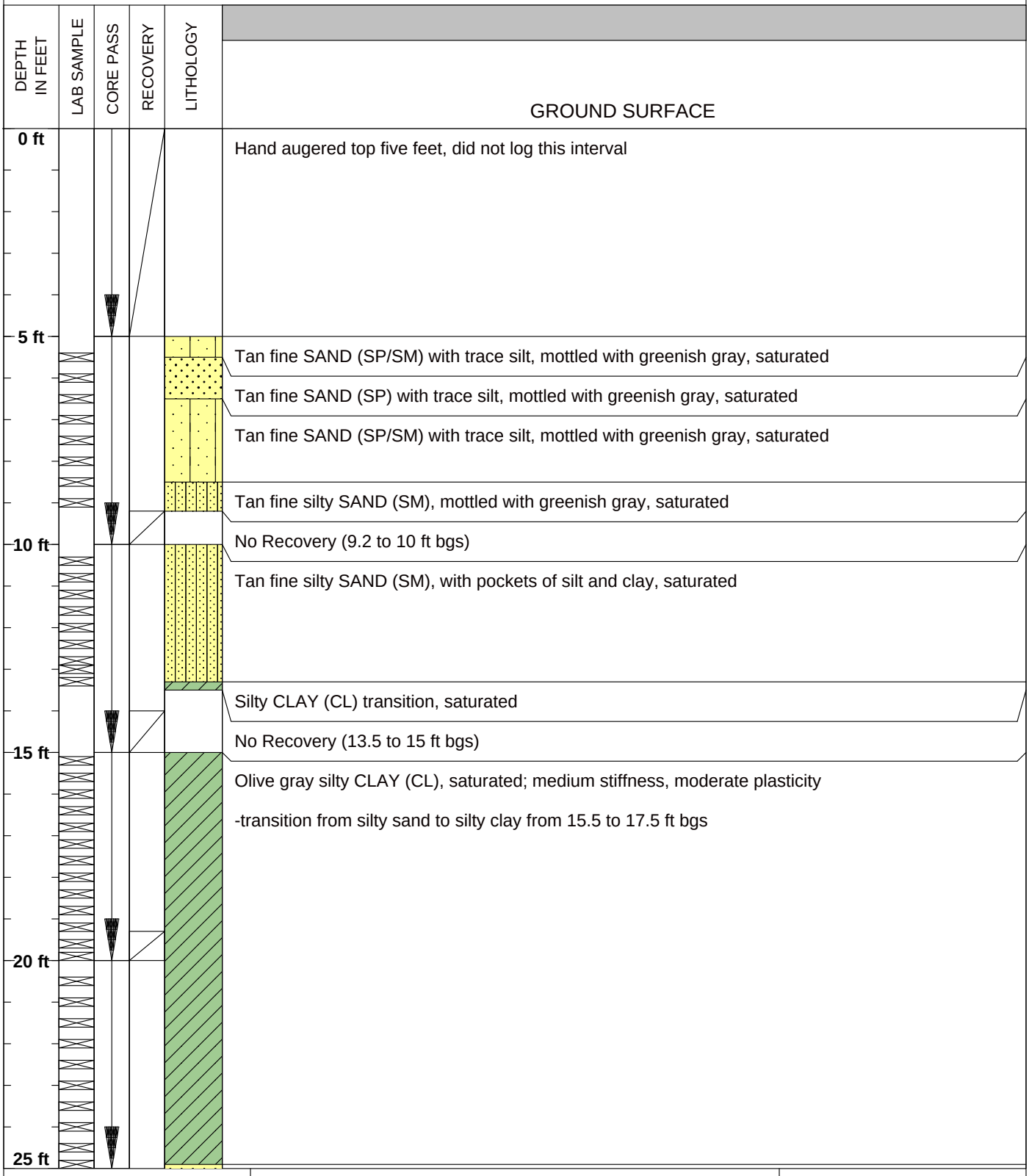
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 15 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-5

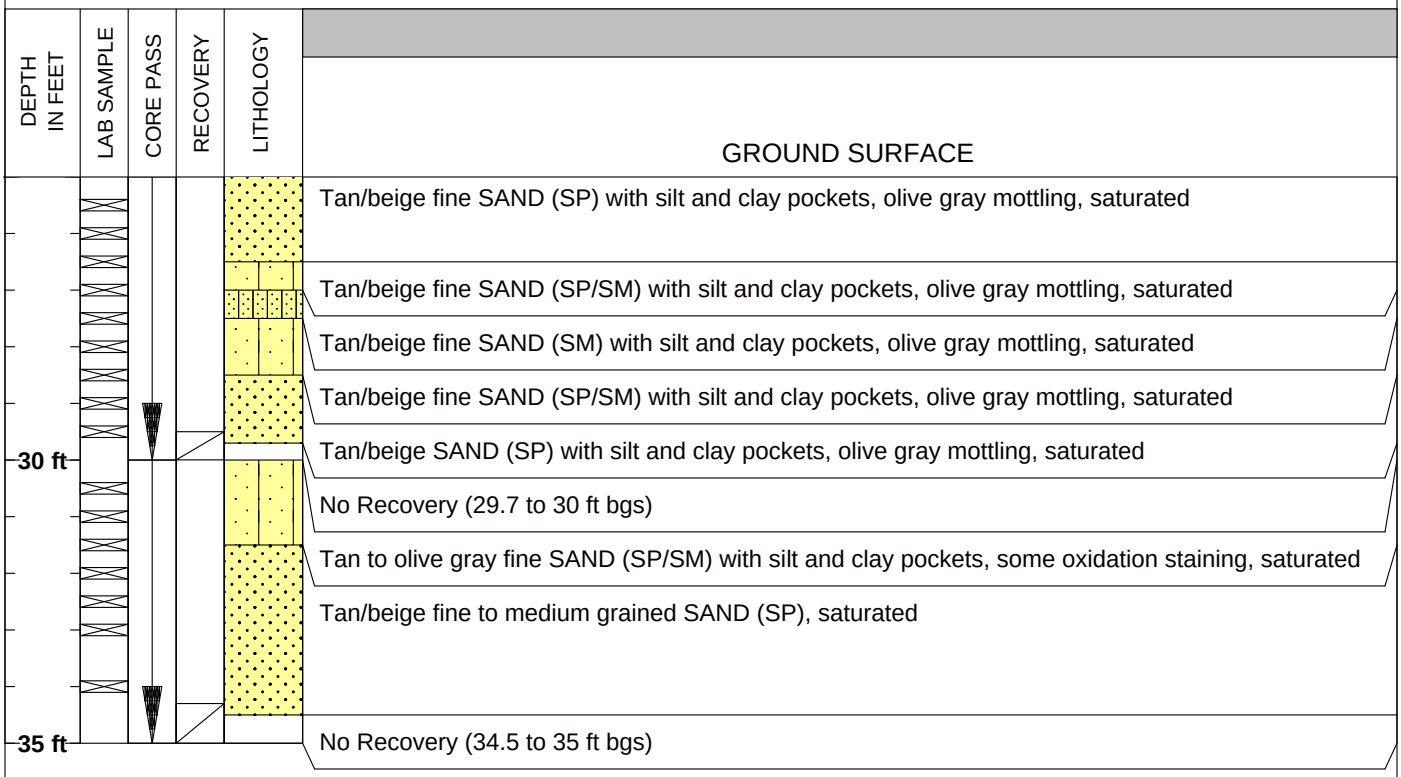
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 15 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-5

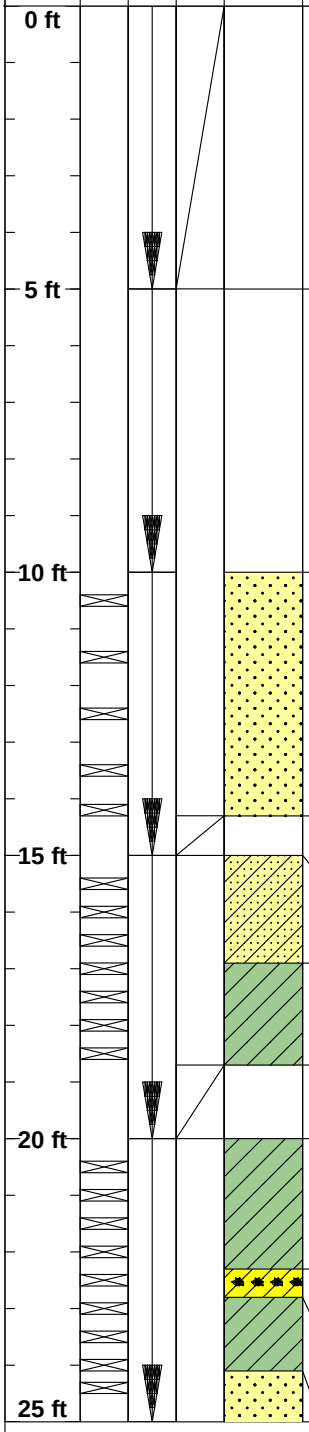
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 19 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Hand augered top five feet, did not log this interval

Core not logged from 5 to 10 ft bgs

Greenish gray silty clayey SAND (SP), saturated

No Recovery (14.3 to 15 ft bgs)

Greenish gray with light brown layers clayey SAND to silty CLAY (SC/CL), mottled with oxidative staining, damp; soft, low plasticity

Greenish gray with light brown layers silty CLAY (CL) with few sand pockets, damp; stiff, moderate plasticity

No Recovery (18.7 to 20 ft bgs)

Olive gray with light brown layers silty CLAY (CL), few sand laminations, damp; stiff, moderate plasticity

Light brown silty clayey GRAVEL (GC), gravel less than 1/4 inch diameter, saturated

Olive gray with light brown layers silty CLAY (CL) with some fine sand laminations, damp; medium stiffness

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-5 Dup

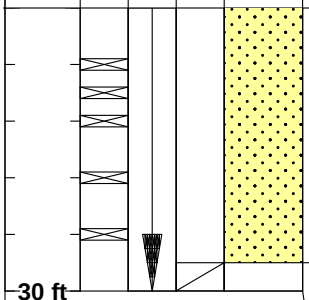
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 19 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Greenish gray fine SAND (SP), few silty clay laminations, saturated

-Oxidative staining from 24.1 to 24.8 ft bgs

No Recovery (29.5 to 30 ft bgs)

Total Depth = 30.5 ft bgs

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-5 Dup

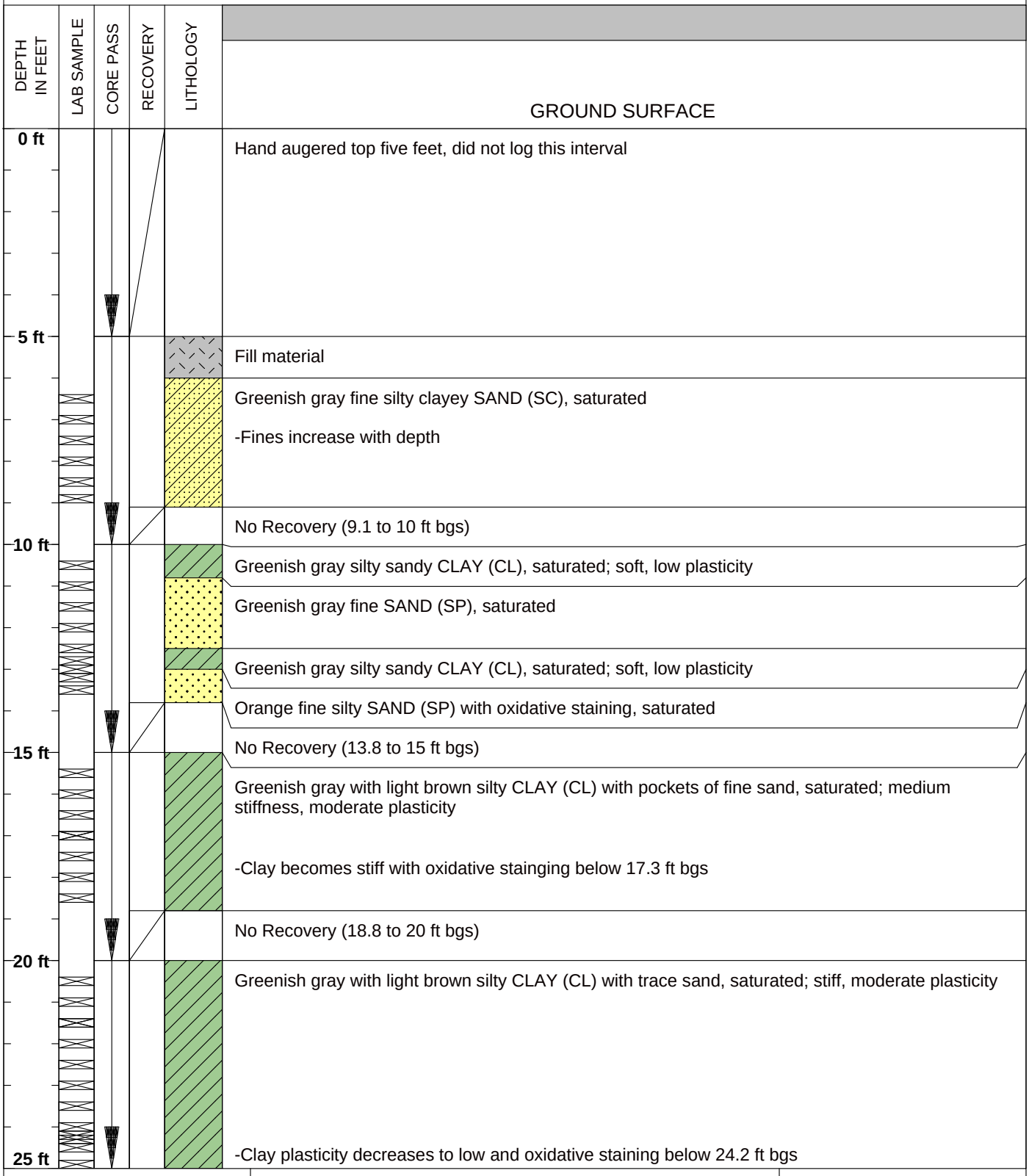
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 18 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-6

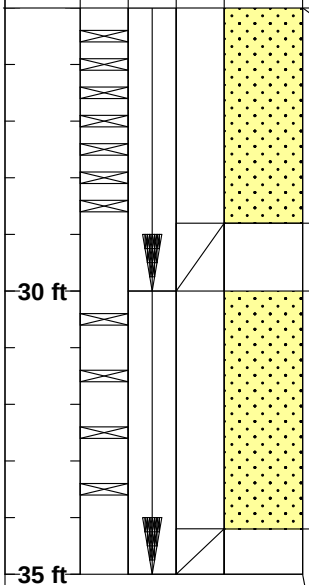
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 18 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Greenish gray with light brown fine SAND (SP) with silty clay laminations, oxidative staining, saturated

-Color changes to greenish gray with yellowish orange below 26.2 ft bgs

No Recovery (28.8 to 30 ft bgs)

Greenish gray and yellowish orange fine sand, few silty clay laminations, oxidative staining throughout, saturated

No Recovery (34.2 to 35 ft bgs)

Total Depth = 35 ft bgs

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-6

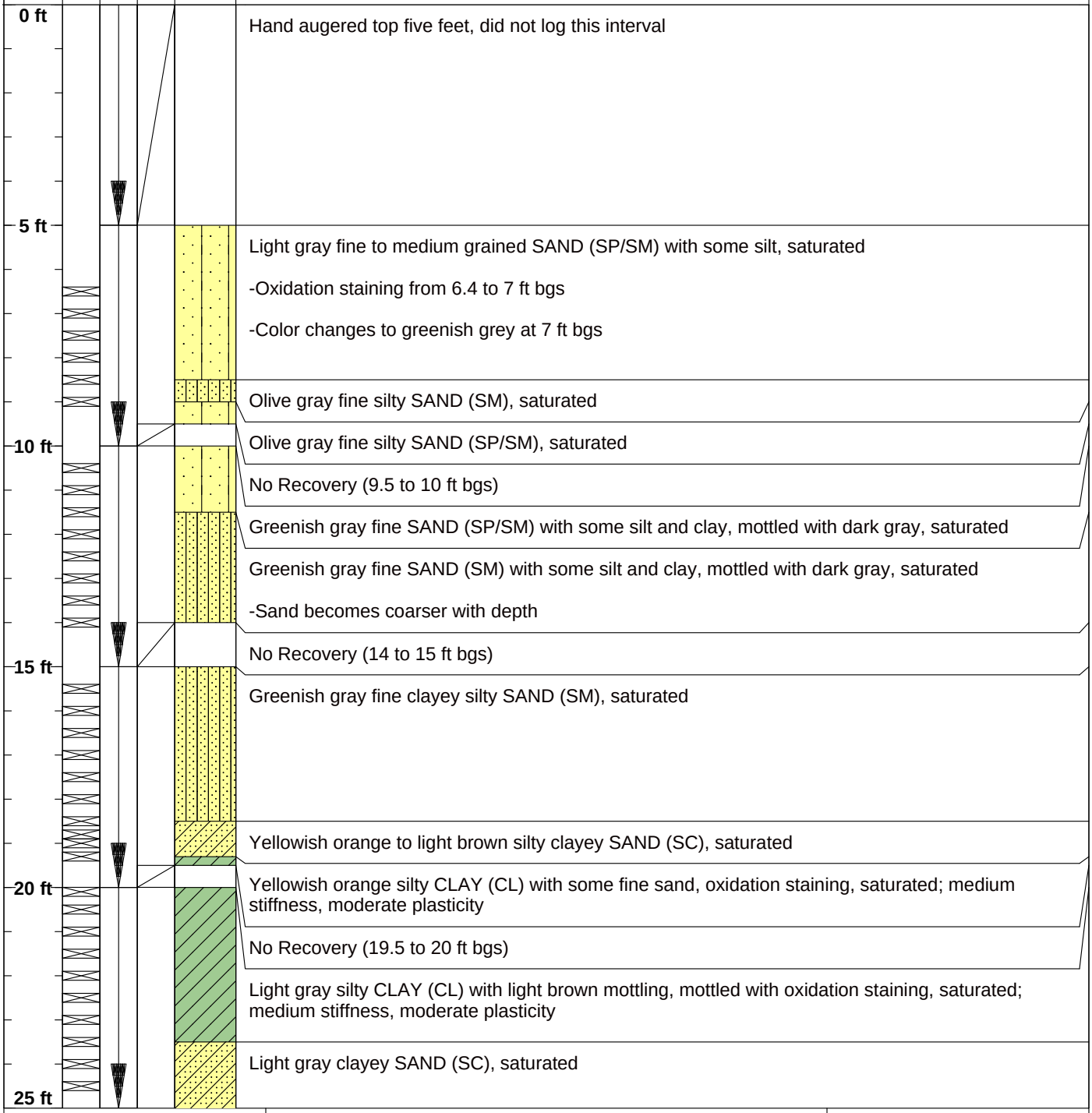
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 16 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-9

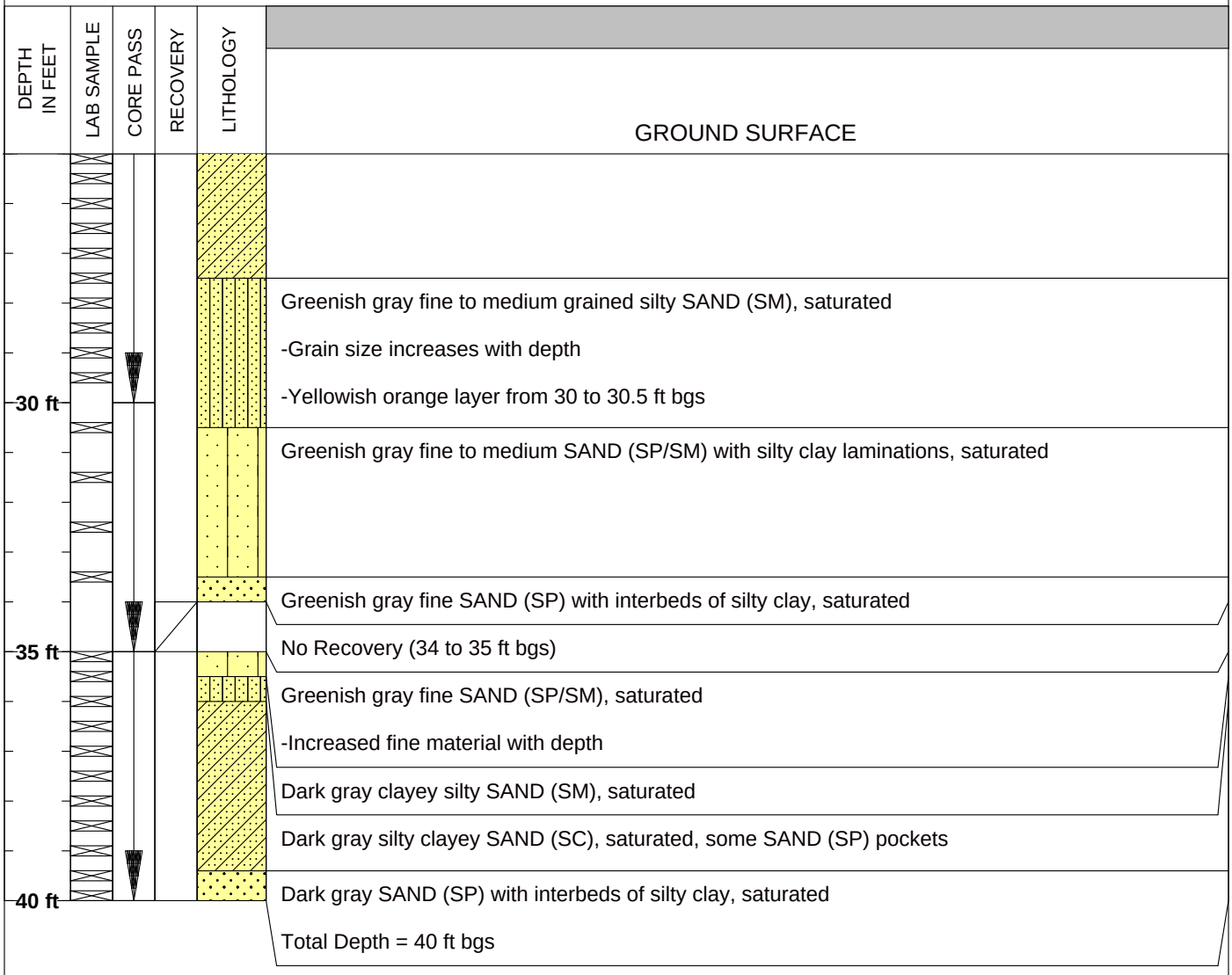
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 16 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-9

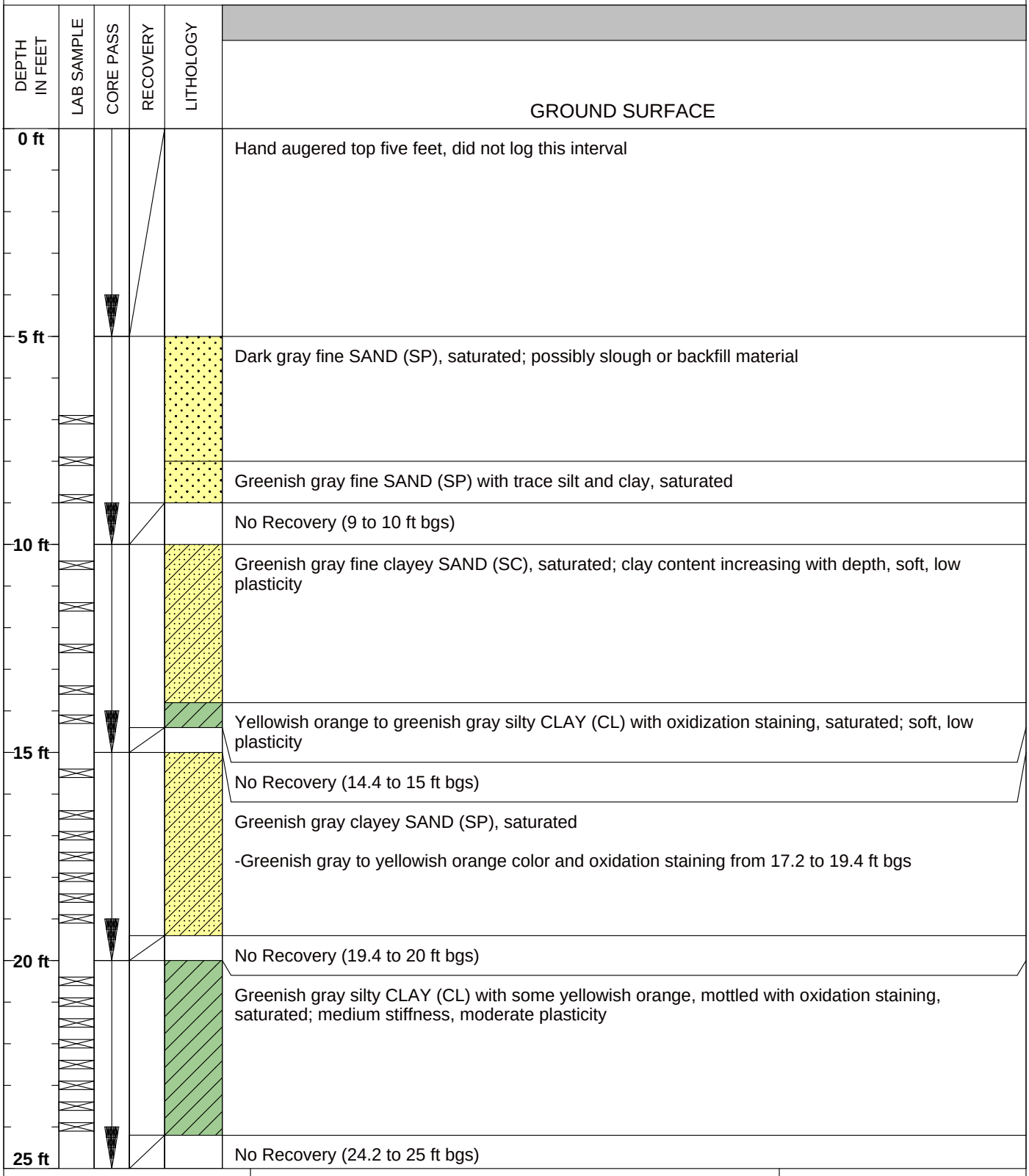
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 16 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-10

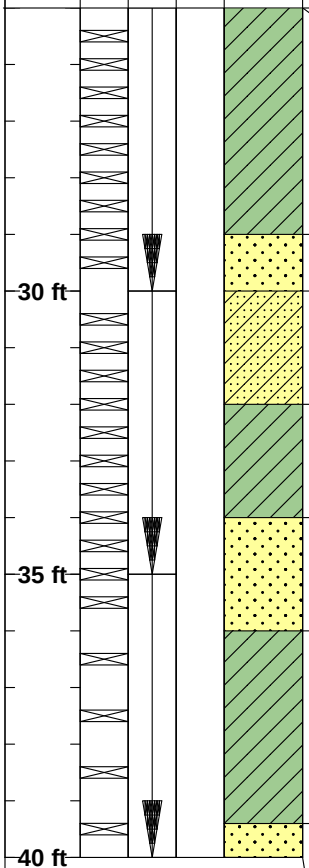
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 16 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Greenish gray silty CLAY (CL) with some yellowish orange, mottled with oxidation staining, saturated; medium stiffness, moderate plasticity

-Sand content increases with depth

Greenish graiy fine SAND (SP) with some silt and clay, saturated

Greenish gray clayey SAND (SC) with silty clay interbeds, mottled with yellowish orange oxidative staining, saturated

Greenish gray silty, sandy CLAY (CL), saturated; soft, low plasticity

Greenish gray fine SAND (SP) with some silt and clay, some oxidation staining, saturated

Greenish gray silty CLAY (CL) with fine sand, saturated; soft, low plasticity

Greenish gray fine SAND (SP) with some silt and clay, saturated

Total Depth = 40 ft

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-10

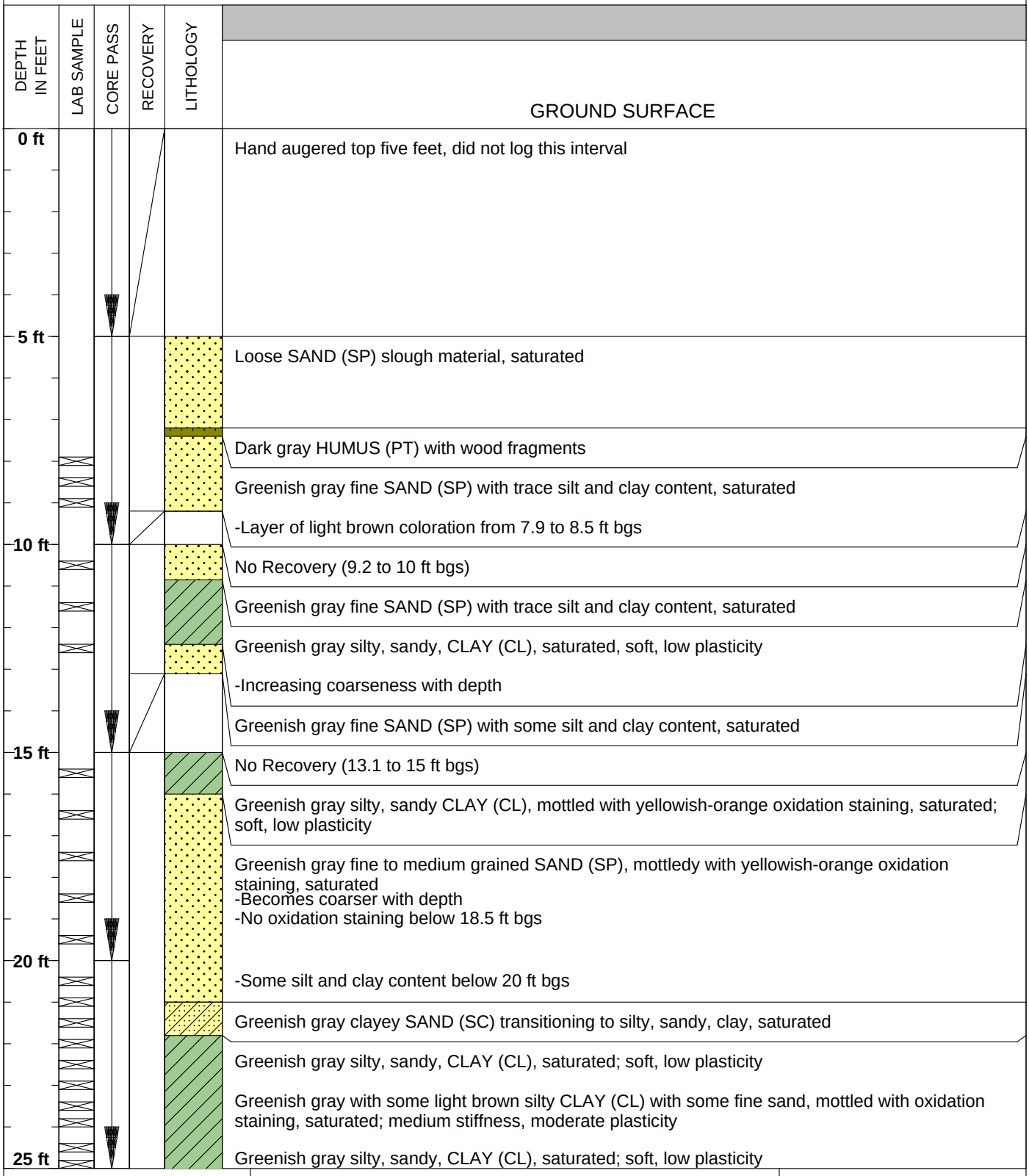
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 17 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-11

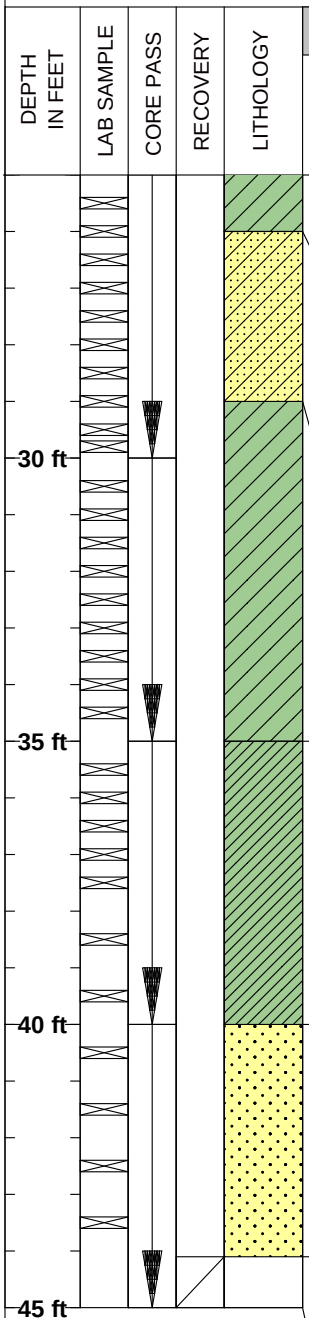
Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

GEOLOGIST: Steve Chapman / Nicholas Mahler
DRILLER: Josh Chaney / Probe Domain
DRILLING METHOD: Dual Tube
HOLE DIAMETER: ~5 inches

COMPLETION DATE: 17 August 2011
GROUND SURFACE ELEV.: NM
LATITUDE AND LONGITUDE: NM



GROUND SURFACE

Greenish gray with some light brown silty CLAY (CL), mottled with oxidation staining, saturated; medium stiffness, moderate plasticity

Greenish gray with some light brown silty CLAY to fine SAND (SP/CL), oxidation staining, saturated; medium stiffness, moderate plasticity

-Increasing coarseness with depth

-Color changes to light brown below 27.4 ft bgs

Olive gray silty CLAY (CL) with fine sand, saturated; soft, medium stiffness

-Dark gray layer from 29.5 to 30 ft bgs
Olive gray with light brown silty CLAY (CL) with some fine sand, oxidation staining, saturated; medium stiffness, moderate plasticity

-Decreasing sand content with depth

-Color changes to dark gray and plasticity increases to high below 34 ft bgs

Dark gray silty CLAY (CH), moderate moisture content; soft, high plasticity

Greenish gray fine SAND (SP) with trace silt and clay, saturated

No Recovery (44.1 to 45 ft bgs)

Total Depth = 45 ft bgs

GSI ENVIRONMENTAL

LOG OF MONITORING WELL
OU3-11

Source Attenuation History
Jacksonville Naval Air Station

GSI Job No. G-3544

Issued: 16 August 2012

APPENDIX H

Soil Volatile Organic Compound (VOC) Concentration Results from Demonstration Project

GSI ENVIRONMENTAL

TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-328	OU3-3	5.50		0.0215	J	UB	ND	U		0.0936			ND	U		0.2282			ND	U		ND	U	
NAS-SC-VOC-329	OU3-3	6.50		0.0181	J	UB	ND	U		0.4031			ND	U		1.8461			ND	U		ND	U	
NAS-SC-VOC-330	OU3-3	7.50		0.0108	J	UB	ND	U		0.4014			ND	U		2.0003			ND	U		ND	U	
NAS-SC-VOC-331	OU3-3	8.50		0.0057	J	UB	ND	U		0.2970			ND	U		0.9776			ND	U		ND	U	
NAS-SC-VOC-332	OU3-3	10.50		0.0664			ND	U		0.4303			ND	U		1.8343			ND	U		ND	U	
NAS-SC-VOC-333	OU3-3	11.00		0.0321		UB	ND	U		0.2111			ND	U		3.1827			ND	U		ND	U	
NAS-SC-VOC-334	OU3-3	11.50		0.0182		UB	ND	U		0.0134	J		ND	U		0.5305			ND	U		ND	U	
NAS-SC-VOC-335	OU3-3	12.00		0.0088	J	UB	ND	U		ND	U		ND	U		0.3479			ND	U		ND	U	
NAS-SC-VOC-336	OU3-3	12.50		0.0049	J	UB	ND	U		0.0132	J		ND	U		0.3478			ND	U		ND	U	
NAS-SC-VOC-339	OU3-3	12.50	D	0.0033	J	UB	ND	U		ND	U		ND	U		0.1755			ND	U		ND	U	
NAS-SC-VOC-337	OU3-3	13.00		0.0084	J	UB	ND	U		0.0589			ND	U		0.3228			ND	U		ND	U	
NAS-SC-VOC-338	OU3-3	13.40		ND	U		ND	U		0.0619			ND	U		0.1565			ND	U		ND	U	
NAS-SC-VOC-340	OU3-3	15.50		0.0054	J	UB	ND	U		0.1579			ND	U		0.2463			ND	U		ND	U	
NAS-SC-VOC-341	OU3-3	16.00		ND	U		ND	U		0.0796			ND	U		0.1137			ND	U		ND	U	
NAS-SC-VOC-342	OU3-3	16.50		0.1010	J	UB	ND	U		0.4059			ND	U		0.7296			ND	U		ND	U	
NAS-SC-VOC-343	OU3-3	17.00		ND	U		ND	U		0.1931	J		ND	U		0.4903			ND	U		ND	U	
NAS-SC-VOC-344	OU3-3	17.50		ND	U		ND	U		ND	U		ND	U		0.2651			ND	U		ND	U	
NAS-SC-VOC-345	OU3-3	17.70		ND	U		ND	U		ND	U		ND	U		0.1922	J		ND	U		ND	U	
NAS-SC-VOC-346	OU3-3	18.00		ND	U		ND	U		ND	U		ND	U		0.1155			ND	U		ND	U	
NAS-SC-VOC-347	OU3-3	18.40		0.0295	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-348	OU3-3	18.70		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-349	OU3-3	18.70	D	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-350	OU3-3	19.00		0.0490		UB	ND	U		ND	U		ND	U		0.0219	J		ND	U		ND	U	
NAS-SC-VOC-351	OU3-3	20.33		0.3230		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-352	OU3-3	20.67		0.0684		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-353	OU3-3	21.00		0.1048		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-354	OU3-3	21.33		0.1803		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-355	OU3-3	21.67		0.1756		UB	ND	U		ND	U		ND	U		0.0093	J		ND	U		ND	U	
NAS-SC-VOC-356	OU3-3	21.67	D	0.1818		UB	ND	U		ND	U		ND	U		0.0100	J		ND	U		ND	U	
NAS-SC-VOC-357	OU3-3	22.00		0.2652		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-358	OU3-3	22.33		0.1374		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-359	OU3-3	22.67		0.1320		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-360	OU3-3	23.00		0.1486		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-361	OU3-3	23.33		0.1666		UB	ND	U		ND	U		ND	U		0.0217	J		ND	U		ND	U	
NAS-SC-VOC-362	OU3-3	23.67		0.4390		UB	ND	U		ND	U		ND	U		0.0202	J		ND	U		ND	U	
NAS-SC-VOC-363	OU3-3	24.00		0.1541		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-364	OU3-3	24.33		0.1616		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-365	OU3-3	24.50		0.0824		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-366	OU3-3	24.90		0.1034		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-367	OU3-3	25.50		0.0690		UB	ND	U		ND	U		ND	U		0.0097	J		ND	U		ND	U	
NAS-SC-VOC-368	OU3-3	26.00		0.0549		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-369	OU3-3	27.00		0.0401		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-370	OU3-3	28.00		0.0688		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-371	OU3-3	29.00		0.0678		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-372	OU3-3	30.50		0.2192		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-373	OU3-3	31.50		0.0711		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-374	OU3-3	32.50		0.0443		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-375	OU3-3	33.50		0.0277		UB	ND	U		ND	U		ND	U		0.0170	J		ND	U		ND	U	
NAS-SC-VOC-001	OU3-4	5.50		ND	U		ND	U		0.0293			ND	U		0.1015			ND	U		ND	U	
NAS-SC-VOC-002	OU3-4	6.00		0.0063	J		0.023533454			0.2543			ND	U		0.8074			ND	U		ND	U	
NAS-SC-VOC-003	OU3-4	6.50		ND	U		ND	U		0.3954			ND	U		1.3282			ND	U		ND	U	
NAS-SC-VOC-004	OU3-4	7.00		0.0039	J		ND	U		0.4617			ND	U		1.4790			ND	U		ND	U	
NAS-SC-VOC-005	OU3-4	7.50		0.0236			ND	U		0.6576			ND	U		1.9731			ND	U		ND	U	
NAS-SC-VOC-006	OU3-4	8.00		0.0209			0.018446837	J		0.7237			ND	U		2.1452			ND	U		ND	U	
NAS-SC-VOC-007	OU3-4	8.50		0.0544		UB	ND	U		0.3905			ND	U		2.1461			ND	U		ND	U	
NAS-SC-VOC-008	OU3-4	9.00		0.0101	J		ND	U		0.9754			ND	U		2.3723			ND	U		ND	U	
NAS-SC-VOC-009	OU3-4	10.50		0.0104	J		ND	U		1.0035			ND	U		2.0573			0.00156588	J		ND	U	
NAS-SC-VOC-010	OU3-4	11.00		ND	U		ND	U		1.0264			ND	U		2.0919			ND	U		ND	U	
NAS-SC-VOC-011	OU3-4	11.50		ND	U		ND	U		0.9860			ND	U		1.8737			ND	U		ND	U	
NAS-SC-VOC-012	OU3-4	12.00		ND	U		ND	U		1.1385			ND	U		1.9289			ND	U		ND	U	
NAS-SC-VOC-013	OU3-4	12.50		ND	U		ND	U		1.5495			ND	U		2.6465			ND	U		ND	U	
NAS-SC-VOC-014	OU3-4	13.00		ND	U		ND	U		1.1532			ND	U		2.2861			ND	U		ND	U	
NAS-SC-VOC-015	OU3-4	13.50		ND	U		ND	U		1.1116			ND	U		2.1356			ND	U		ND	U	
NAS-SC-VOC-016	OU3-4	14.00		ND	U		ND	U		0.8720			ND	U		1.8538			ND	U		ND	U	
NAS-SC-VOC-017	OU3-4	15.20		ND	U		ND	U		0.5073			ND	U		1.5282			ND	U		ND	U	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-018	OU3-4	15.40		ND	U		ND	U		0.4814			ND	U		1.6330			ND	U		ND	U	
NAS-SC-VOC-019	OU3-4	15.70		ND	U		ND	U		0.4402			ND	U		1.7435			ND	U		ND	U	
NAS-SC-VOC-020	OU3-4	16.00		ND	U		ND	U		0.4556			ND	U		1.8396			ND	U		ND	U	
NAS-SC-VOC-021	OU3-4	16.00	D	ND	U		ND	U		0.3755			ND	U		1.5208			ND	U		ND	U	
NAS-SC-VOC-022	OU3-4	16.40		ND	U		ND	U		0.3664			ND	U		1.5296			ND	U		ND	U	
NAS-SC-VOC-023	OU3-4	16.80		ND	U		ND	U		0.2896			ND	U		1.2093			ND	U		ND	U	
NAS-SC-VOC-024	OU3-4	17.20		ND	U		ND	U		0.2524			ND	U		1.0611			ND	U		ND	U	
NAS-SC-VOC-025	OU3-4	17.50		ND	U		ND	U		0.2338			ND	U		0.9370			ND	U		ND	U	
NAS-SC-VOC-026	OU3-4	17.80		ND	U		ND	U		0.2227	J		ND	U		0.9279			ND	U		ND	U	
NAS-SC-VOC-027	OU3-4	18.10		ND	U		ND	U		0.1970			ND	U		0.7162			0.001597552	J		ND	U	
NAS-SC-VOC-028	OU3-4	18.40		0.0254	J	UB	ND	U		0.0858			ND	U		0.3049			0.001438436	J		ND	U	
NAS-SC-VOC-029	OU3-4	18.70		0.0084	J	UB	ND	U		0.0548			ND	U		0.2184			ND	U		ND	U	
NAS-SC-VOC-030	OU3-4	18.70	D	0.0506	J	UB	ND	U		0.0630			ND	U		0.2285			0.001431015	J		ND	U	
NAS-SC-VOC-031	OU3-4	19.00		ND	U	UB	ND	U		0.0197	J		ND	U		0.0799			ND	U		ND	U	
NAS-SC-VOC-032	OU3-4	20.20		0.0153	J	UB	0.028741318	J		0.0090	J		ND	U		0.0452			ND	U		ND	U	
NAS-SC-VOC-033	OU3-4	20.50		0.0183	J	UB	ND	U		ND	U		ND	U		0.0282			ND	U		ND	U	
NAS-SC-VOC-034	OU3-4	21.00		0.0417		UB	ND	U		ND	U		ND	U		0.0258			ND	U		ND	U	
NAS-SC-VOC-035	OU3-4	21.50		0.0720		UB	ND	U		ND	U		ND	U		0.0228	J		ND	U		ND	U	
NAS-SC-VOC-036	OU3-4	22.00		0.1230		UB	ND	U		ND	U		ND	U		0.0163	J		ND	U		ND	U	
NAS-SC-VOC-037	OU3-4	22.50		0.1587		UB	ND	U		ND	U		ND	U		0.0168	J		ND	U		ND	U	
NAS-SC-VOC-038	OU3-4	23.00		0.1386		UB	ND	U		ND	U		ND	U		0.0157	J		ND	U		ND	U	
NAS-SC-VOC-039	OU3-4	23.50		0.1380		UB	ND	U		ND	U		ND	U		0.0215	J		ND	U		ND	U	
NAS-SC-VOC-040	OU3-4	24.00		0.1244		UB	ND	U		ND	U		ND	U		0.0325			ND	U		ND	U	
NAS-SC-VOC-041	OU3-4	24.40		0.1328		UB	ND	U		ND	U		ND	U		0.0123	J		ND	U		ND	U	
NAS-SC-VOC-042	OU3-4	24.70		0.1336		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-043	OU3-4	25.50		0.1021		UB	ND	U		ND	U		ND	U		0.0230			ND	U		ND	U	
NAS-SC-VOC-044	OU3-4	26.00		0.0392		UB	0.046251755			ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-045	OU3-4	27.00		0.0237		UB	0.010612721	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-046	OU3-4	28.00		0.0567		UB	ND	U		ND	U		ND	U		0.0099	J		ND	U		ND	U	
NAS-SC-VOC-047	OU3-4	29.00		0.0230		UB	ND	U		ND	U		ND	U		0.0142			ND	U		ND	U	
NAS-SC-VOC-048	OU3-4	30.30		0.0315	J	UB	ND	U		ND	U		ND	U		0.0312			ND	U		ND	U	
NAS-SC-VOC-049	OU3-4	30.50		0.0762		UB	ND	U		ND	U		ND	U		0.0185			ND	U		ND	U	
NAS-SC-VOC-050	OU3-4	31.00		0.0526		UB	ND	U		ND	U		ND	U		0.0244			ND	U		ND	U	
NAS-SC-VOC-051	OU3-4	31.50		0.0684		UB	ND	U		ND	U		ND	U		0.0243			ND	U		ND	U	
NAS-SC-VOC-052	OU3-4	32.00		0.0564		UB	ND	U		ND	U		ND	U		0.0323			ND	U		ND	U	
NAS-SC-VOC-053	OU3-4	33.00		0.0393		UB	ND	U		ND	U		ND	U		0.0289			ND	U		ND	U	
NAS-SC-VOC-054	OU3-4	34.00		0.0075	J	UB	ND	U		ND	U		ND	U		0.0306			ND	U		ND	U	
NAS-SC-VOC-055	OU3-5	5.50		0.0146		UB	ND	U		0.2823			ND	U		0.8992			ND	U		ND	U	
NAS-SC-VOC-056	OU3-5	6.00		0.0283		UB	ND	U		0.6781			ND	U		1.9373			ND	U		ND	U	
NAS-SC-VOC-057	OU3-5	6.50		0.0813		UB	0.028748261	J		1.3118			ND	U		3.9240			0.01453935			0.0235	J	
NAS-SC-VOC-058	OU3-5	7.00		0.0225	J	UB	ND	U		1.1723			ND	U		3.3800			ND	U		ND	U	
NAS-SC-VOC-059	OU3-5	7.50		0.0198	J	UB	ND	U		1.2676			ND	U		3.9045			ND	U		ND	U	
NAS-SC-VOC-060	OU3-5	8.00		0.0261	J	UB	ND	U		0.9275			ND	U		4.5052			ND	U		ND	U	
NAS-SC-VOC-061	OU3-5	8.00	D	0.0421	J	UB	ND	U		1.3279			ND	U		5.3624			ND	U		ND	U	
NAS-SC-VOC-062	OU3-5	8.50		0.0488	J	UB	ND	U		1.2587			ND	U		5.1041			ND	U		ND	U	
NAS-SC-VOC-063	OU3-5	9.00		0.0601	J	UB	ND	U		1.6987			ND	U		6.8650			ND	U		ND	U	
NAS-SC-VOC-064	OU3-5	10.40		0.0596	J	UB	ND	U		1.6013			ND	U		6.9595			ND	U		ND	U	
NAS-SC-VOC-065	OU3-5	10.80		0.0481	J	UB	ND	U		1.4234			ND	U		5.9090			ND	U		ND	U	
NAS-SC-VOC-066	OU3-5	11.20		0.0407	J	UB	ND	U		1.3417			ND	U		5.0097			ND	U		ND	U	
NAS-SC-VOC-067	OU3-5	11.60		0.0455	J	UB	ND	U		1.3498			ND	U		4.4274			ND	U		ND	U	
NAS-SC-VOC-068	OU3-5	12.00		0.0428	J	UB	ND	U		1.2343			ND	U		4.4308			ND	U		ND	U	
NAS-SC-VOC-069	OU3-5	12.40		0.0452	J	UB	ND	U		1.1028			ND	U		4.1660			ND	U		ND	U	
NAS-SC-VOC-070	OU3-5	12.80		0.0593	J	UB	ND	U		0.8094			ND	U		3.0079			ND	U		ND	U	
NAS-SC-VOC-071	OU3-5	13.00		ND	U	UB	ND	U		0.2971			ND	U		1.7938			0.003792441	J		ND	U	
NAS-SC-VOC-072	OU3-5	13.30		0.2951		UB	ND	U		0.5750			ND	U		2.3134			ND	U		ND	U	
NAS-SC-VOC-073	OU3-5	15.20		ND	U	UB	ND	U		0.3542			ND	U		1.5188			ND	U		ND	U	
NAS-SC-VOC-074	OU3-5	15.60		ND	U	UB	ND	U		0.2728			ND	U		1.2341			ND	U		ND	U	
NAS-SC-VOC-075	OU3-5	16.00		ND	U	UB	ND	U		0.2707			ND	U		1.3787			ND	U		ND	U	
NAS-SC-VOC-076	OU3-5	16.40		0.0539	J	UB	ND	U		0.1804			ND	U		1.0158			ND	U		ND	U	
NAS-SC-VOC-077	OU3-5	16.80		0.0775	J	UB	ND	U		0.1311			ND	U		0.8201			ND	U		ND	U	
NAS-SC-VOC-078	OU3-5	17.20		0.1797		UB	ND	U		0.0967			ND	U		0.7325			ND	U		ND	U	
NAS-SC-VOC-079	OU3-5	17.60		0.0688		UB	ND	U		0.1100			ND	U		0.7946			0.004874945	J		ND	U	
NAS-SC-VOC-080	OU3-5	18.00		0.1089		UB	ND	U		0.0598			ND	U		0.5516			ND	U		ND	U	
NAS-SC-VOC-081	OU3-5	18.00	D	0.1667		UB	ND	U		0.0466			ND	U		0.4697			ND	U		ND	U	
NAS-SC-VOC-082	OU3-5	18.40		0.0649		UB	ND	U		0.0254			ND	U		0.2620			ND	U		ND	U	

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NAS-SC-VOC-083	OU3-5	18.80		0.1256		UB	ND	U		0.0193	J		ND	U		0.2201			ND	U		ND	U	
NAS-SC-VOC-084	OU3-5	19.20		0.1086		UB	ND	U		ND	U		ND	U		0.1077			ND	U		ND	U	
NAS-SC-VOC-085	OU3-5	19.60		0.0747		UB	ND	U		ND	U		ND	U		0.0596			ND	U		ND	U	
NAS-SC-VOC-086	OU3-5	19.90		0.1049		UB	ND	U		ND	U		ND	U		0.0314			ND	U		ND	U	
NAS-SC-VOC-087	OU3-5	20.50		0.0987		UB	ND	U		ND	U		ND	U		0.0308			ND	U		ND	U	
NAS-SC-VOC-088	OU3-5	21.00		0.1110		UB	ND	U		ND	U		ND	U		0.0292			ND	U		ND	U	
NAS-SC-VOC-089	OU3-5	21.50		0.0966		UB	ND	U		ND	U		ND	U		0.0314			ND	U		ND	U	
NAS-SC-VOC-090	OU3-5	22.00		0.0656		UB	ND	U		ND	U		ND	U		0.0312			ND	U		ND	U	
NAS-SC-VOC-091	OU3-5	22.50		0.1013		UB	ND	U		ND	U		ND	U		0.0349			ND	U		ND	U	
NAS-SC-VOC-092	OU3-5	23.00		0.1387		UB	ND	U		ND	U		ND	U		0.0364			ND	U		ND	U	
NAS-SC-VOC-093	OU3-5	23.50		0.0362		UB	ND	U		ND	U		ND	U		0.0417			ND	U		ND	U	
NAS-SC-VOC-094	OU3-5	24.00		0.1550		UB	ND	U		ND	U		ND	U		0.0449			ND	U		ND	U	
NAS-SC-VOC-095	OU3-5	24.00	D	0.1866		UB	ND	U		ND	U		ND	U		0.0397			ND	U		ND	U	
NAS-SC-VOC-096	OU3-5	24.50		0.1994		UB	ND	U		ND	U		ND	U		0.0557			ND	U		ND	U	
NAS-SC-VOC-097	OU3-5	24.90		0.1238		UB	ND	U		ND	U		ND	U		0.0679			ND	U		ND	U	
NAS-SC-VOC-098	OU3-5	25.50		0.0831		UB	ND	U		ND	U		ND	U		0.0775			ND	U		ND	U	
NAS-SC-VOC-099	OU3-5	26.00		0.0106	J	UB	ND	U		0.0087	J		ND	U		0.0732			ND	U		ND	U	
NAS-SC-VOC-100	OU3-5	26.50		0.0375		UB	ND	U		ND	U		ND	U		0.1399			ND	U		ND	U	
NAS-SC-VOC-101	OU3-5	27.00		0.0607		UB	ND	U		ND	U		ND	U		0.1719			ND	U		ND	U	
NAS-SC-VOC-102	OU3-5	27.50		0.0333		UB	ND	U		ND	U		ND	U		0.2076			ND	U		ND	U	
NAS-SC-VOC-103	OU3-5	28.00		0.1491		UB	ND	U		ND	U		ND	U		0.2643			ND	U		ND	U	
NAS-SC-VOC-104	OU3-5	28.50		0.0583		UB	ND	U		ND	U		ND	U		0.2720			ND	U		ND	U	
NAS-SC-VOC-105	OU3-5	29.00		0.0564		UB	ND	U		ND	U		ND	U		0.2365			ND	U		ND	U	
NAS-SC-VOC-106	OU3-5	29.50		0.1093		UB	ND	U		ND	U		ND	U		0.2051			ND	U		ND	U	
NAS-SC-VOC-107	OU3-5	30.50		0.0791		UB	ND	U		ND	U		ND	U		0.1339			ND	U		ND	U	
NAS-SC-VOC-108	OU3-5	31.00		0.1079		UB	ND	U		ND	U		ND	U		0.1401			ND	U		ND	U	
NAS-SC-VOC-109	OU3-5	31.50		0.0933		UB	ND	U		ND	U		ND	U		0.1004			ND	U		ND	U	
NAS-SC-VOC-110	OU3-5	32.00		0.0839		UB	ND	U		ND	U		ND	U		0.0508			ND	U		ND	U	
NAS-SC-VOC-111	OU3-5	32.50		0.0593		UB	ND	U		ND	U		ND	U		0.0295			ND	U		ND	U	
NAS-SC-VOC-112	OU3-5	33.00		0.0272		UB	ND	U		ND	U		ND	U		0.0266			ND	U		ND	U	
NAS-SC-VOC-113	OU3-5	34.00		0.0238		UB	ND	U		ND	U		ND	U		0.0235			ND	U		ND	U	
NAS-SC-VOC-114	OU3-5	34.00	D	0.0432		UB	ND	U		ND	U		ND	U		0.0214			ND	U		ND	U	
NAS-SC-VOC-376	OU3-5D	10.50		0.1732		UB	ND	U		1.5586			ND	U		6.4449			ND	U		ND	U	
NAS-SC-VOC-377	OU3-5D	11.50		ND	U		ND	U		1.5541			ND	U		7.5335			ND	U		ND	U	
NAS-SC-VOC-378	OU3-5D	12.50		ND	U		ND	U		1.1319			ND	U		4.4185			ND	U		ND	U	
NAS-SC-VOC-379	OU3-5D	13.50		0.0932		UB	ND	U		0.7764			ND	U		3.0692			ND	U		ND	U	
NAS-SC-VOC-380	OU3-5D	14.20		ND	U		ND	U		0.6026			ND	U		2.4793			ND	U		ND	U	
NAS-SC-VOC-381	OU3-5D	15.50		ND	U		ND	U		0.4061			ND	U		2.2920			ND	U		ND	U	
NAS-SC-VOC-382	OU3-5D	16.00		0.0641		UB	ND	U		0.3095			ND	U		5.4179			ND	U		ND	U	
NAS-SC-VOC-383	OU3-5D	16.50		0.1124		UB	ND	U		0.1562			ND	U		2.7395			ND	U		ND	U	
NAS-SC-VOC-384	OU3-5D	17.00		0.0876		UB	ND	U		0.0852			ND	U		1.5163			ND	U		ND	U	
NAS-SC-VOC-385	OU3-5D	17.50		0.1510		UB	ND	U		0.0434			ND	U		0.9197			ND	U		ND	U	
NAS-SC-VOC-386	OU3-5D	17.50	D	0.1997		UB	ND	U		0.0479			ND	U		0.9636			ND	U		ND	U	
NAS-SC-VOC-387	OU3-5D	18.00		0.1062		UB	ND	U		0.0174	J		ND	U		0.4010			ND	U		ND	U	
NAS-SC-VOC-388	OU3-5D	18.50		0.0599		UB	ND	U		ND	U		ND	U		0.1421			ND	U		ND	U	
NAS-SC-VOC-389	OU3-5D	20.50		0.0860		UB	ND	U		ND	U		ND	U		0.0511			ND	U		ND	U	
NAS-SC-VOC-390	OU3-5D	21.00		0.0696		UB	ND	U		ND	U		ND	U		0.0528			ND	U		ND	U	
NAS-SC-VOC-391	OU3-5D	21.50		0.0574		UB	ND	U		ND	U		ND	U		0.0544			ND	U		ND	U	
NAS-SC-VOC-392	OU3-5D	22.00		0.0691		UB	ND	U		ND	U		ND	U		0.0574			ND	U		ND	U	
NAS-SC-VOC-393	OU3-5D	22.50		0.0455		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-394	OU3-5D	23.00		0.0611		UB	ND	U		ND	U		ND	U		0.0728			ND	U		ND	U	
NAS-SC-VOC-395	OU3-5D	23.50		0.0814		UB	ND	U		ND	U		ND	U		0.0885			ND	U		ND	U	
NAS-SC-VOC-396	OU3-5D	23.50	D	0.1386		UB	ND	U		ND	U		ND	U		0.0961			ND	U		ND	U	
NAS-SC-VOC-397	OU3-5D	24.00		ND	U	UB	ND	U		ND	U		ND	U		0.0842			ND	U		ND	U	
NAS-SC-VOC-398	OU3-5D	24.40		0.0579		UB	ND	U		ND	U		ND	U		0.0903			ND	U		ND	U	
NAS-SC-VOC-399	OU3-5D	26.00		0.0587		UB	ND	U		ND	U		ND	U		0.0716			ND	U		ND	U	
NAS-SC-VOC-400	OU3-5D	26.50		0.0207	J	UB	ND	U		ND	U		ND	U		0.1076			ND	U		ND	U	
NAS-SC-VOC-401	OU3-5D	27.00		0.0356		UB	ND	U		ND	U		ND	U		0.1163			ND	U		ND	U	
NAS-SC-VOC-402	OU3-5D	28.00		0.0375		UB	ND	U		ND	U		ND	U		0.1927			ND	U		ND	U	
NAS-SC-VOC-403	OU3-5D	28.00	D	0.0403		UB	ND	U		ND	U		ND	U		0.2196			ND	U		ND	U	
NAS-SC-VOC-404	OU3-5D	29.00		0.0931		UB	ND	U		ND	U		ND	U		0.2109			ND	U		ND	U	
NAS-SC-VOC-281	OU3-6	6.50		0.0092	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-282	OU3-6	7.00		0.0149	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-283	OU3-6	7.50		0.0183	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-284	OU3-6	8.00		0.0147	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-285	OU3-6	8.50		0.0064	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-286	OU3-6	8.90		0.0260		UB	ND	U		ND	U		ND	U		0.0129			ND	U		ND	U	
NAS-SC-VOC-287	OU3-6	10.50		0.0476		UB	ND	U		ND	U		ND	U		0.0525			ND	U		ND	U	
NAS-SC-VOC-288	OU3-6	11.00		0.0677		UB	ND	U		0.0855			ND	U		0.3429			ND	U		ND	U	
NAS-SC-VOC-289	OU3-6	11.50		0.0217		UB	ND	U		0.1421			ND	U		0.5959			ND	U		ND	U	
NAS-SC-VOC-290	OU3-6	12.00		0.0665		UB	ND	U		0.2078			ND	U		0.8770			ND	U		ND	U	
NAS-SC-VOC-291	OU3-6	12.50		0.0289		UB	ND	U		0.4063			ND	U		3.0039			ND	U		ND	U	
NAS-SC-VOC-292	OU3-6	12.80		0.0207	J	UB	ND	U		0.4830			ND	U		3.7110			ND	U		ND	U	
NAS-SC-VOC-293	OU3-6	13.00		0.0178	J	UB	ND	U		0.4345			ND	U		3.6749			ND	U		ND	U	
NAS-SC-VOC-294	OU3-6	13.20		0.0142	J	UB	ND	U		0.4910			ND	U		4.3590			ND	U		ND	U	
NAS-SC-VOC-295	OU3-6	13.50		0.0206	J	UB	ND	U		0.4633			ND	U		4.3107			ND	U		ND	U	
NAS-SC-VOC-296	OU3-6	15.50		0.0218	J	UB	ND	U		0.2449			ND	U		2.6584			ND	U		ND	U	
NAS-SC-VOC-297	OU3-6	16.00		0.1381		UB	ND	U		0.1413			ND	U		2.2176			ND	U		ND	U	
NAS-SC-VOC-298	OU3-6	16.50		0.1088		UB	ND	U		0.0917			ND	U		1.2162			ND	U		ND	U	
NAS-SC-VOC-299	OU3-6	17.00		0.1262		UB	ND	U		0.0379			ND	U		0.4773			ND	U		ND	U	
NAS-SC-VOC-300	OU3-6	17.00	D	0.0865		UB	ND	U		0.0379			ND	U		0.4722			ND	U		ND	U	
NAS-SC-VOC-301	OU3-6	17.50		0.1165		UB	ND	U		0.0208	J		ND	U		0.2312			ND	U		ND	U	
NAS-SC-VOC-302	OU3-6	18.00		0.0438		UB	ND	U		0.0143	J		ND	U		0.1376			ND	U		ND	U	
NAS-SC-VOC-303	OU3-6	18.50		0.1308		UB	ND	U		ND	U		ND	U		0.0714			ND	U		ND	U	
NAS-SC-VOC-304	OU3-6	20.50		0.1276		UB	ND	U		ND	U		ND	U		0.0529			ND	U		ND	U	
NAS-SC-VOC-305	OU3-6	21.00		0.0972		UB	ND	U		ND	U		ND	U		0.0467			ND	U		ND	U	
NAS-SC-VOC-306	OU3-6	21.50		0.0844		UB	ND	U		ND	U		ND	U		0.0435			ND	U		ND	U	
NAS-SC-VOC-307	OU3-6	21.50	D	0.0717		UB	ND	U		ND	U		ND	U		0.0424			ND	U		ND	U	
NAS-SC-VOC-308	OU3-6	22.00		0.0376		UB	ND	U		ND	U		ND	U		0.0469			ND	U		ND	U	
NAS-SC-VOC-309	OU3-6	22.50		ND	U	UB	ND	U		ND	U		ND	U		0.0502			ND	U		ND	U	
NAS-SC-VOC-310	OU3-6	23.00		0.0187	J	UB	ND	U		ND	U		ND	U		0.0397			ND	U		ND	U	
NAS-SC-VOC-311	OU3-6	23.50		0.0195	J	UB	ND	U		ND	U		ND	U		0.0526			ND	U		ND	U	
NAS-SC-VOC-312	OU3-6	24.00		0.0488		UB	ND	U		ND	U		ND	U		0.0607			ND	U		ND	U	
NAS-SC-VOC-313	OU3-6	24.20		0.0241	J	UB	ND	U		ND	U		ND	U		0.0502			ND	U		ND	U	
NAS-SC-VOC-314	OU3-6	24.30		0.0092	J	UB	ND	U		ND	U		ND	U		0.0402			ND	U		ND	U	
NAS-SC-VOC-315	OU3-6	24.50		0.0307		UB	ND	U		ND	U		ND	U		0.0468			ND	U		ND	U	
NAS-SC-VOC-316	OU3-6	24.90		0.0251	J	UB	ND	U		ND	U		ND	U		0.0693			ND	U		ND	U	
NAS-SC-VOC-317	OU3-6	25.50		0.0236	J	UB	ND	U		ND	U		ND	U		0.0868			ND	U		ND	U	
NAS-SC-VOC-318	OU3-6	26.00		0.0061	J	UB	ND	U		ND	U		ND	U		0.1102			ND	U		ND	U	
NAS-SC-VOC-319	OU3-6	26.50		0.0133	J	UB	ND	U		ND	U		ND	U		0.0823			ND	U		ND	U	
NAS-SC-VOC-320	OU3-6	27.00		0.0166	J	UB	ND	U		ND	U		0.215873923			0.0854			0.000856643	J	UB	ND	U	
NAS-SC-VOC-321	OU3-6	27.50		0.0260		UB	ND	U		ND	U		ND	U		0.0553			ND	U		ND	U	
NAS-SC-VOC-322	OU3-6	28.00		0.0748		UB	ND	U		ND	U		ND	U		0.0523			ND	U		ND	U	
NAS-SC-VOC-323	OU3-6	28.50		0.1045		UB	ND	U		ND	U		ND	U		0.0466			ND	U		ND	U	
NAS-SC-VOC-324	OU3-6	30.50		0.1131		UB	ND	U		ND	U		ND	U		0.0398			ND	U		ND	U	
NAS-SC-VOC-325	OU3-6	31.50		0.2178		UB	ND	U		ND	U		ND	U		0.0255			ND	U		ND	U	
NAS-SC-VOC-326	OU3-6	32.50		0.1756		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-327	OU3-6	33.50		0.0228	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-115	OU3-9	6.50		0.0504		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-116	OU3-9	7.00		0.0734			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-119	OU3-9	7.50		0.1520			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-117	OU3-9	8.00		0.1505			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-120	OU3-9	8.50		0.0569			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-118	OU3-9	9.00		0.0840			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-121	OU3-9	10.50		0.0247	J		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-122	OU3-9	11.00		0.0142	J		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-123	OU3-9	11.50		0.0599			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-124	OU3-9	12.00		0.0552			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-125	OU3-9	12.50		0.0335			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-126	OU3-9	13.00		0.0861			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-127	OU3-9	13.50		0.2090			ND	U		ND	U		0.345468175			0.2621			ND	U		ND	U	
NAS-SC-VOC-128	OU3-9	13.50	D	0.1619			ND	U		ND	U		0.302008542			0.2236			ND	U		ND	U	
NAS-SC-VOC-129	OU3-9	14.00		0.3258			ND	U		ND	U		0.51540654			0.4645			ND	U		ND	U	
NAS-SC-VOC-130	OU3-9	15.50		0.6132			ND	U		ND	U		0.933518679			0.8606			ND	U		ND	U	
NAS-SC-VOC-131	OU3-9	16.00		0.5782			ND	U		ND	U		0.96937799			0.9775			ND	U		ND	U	
NAS-SC-VOC-132	OU3-9	16.50		0.7670			ND	U		ND	U		1.127203752			1.3610			ND	U		0.0230	J	
NAS-SC-VOC-133	OU3-9	17.00		0.6421			ND	U		ND	U		0.997914651			1.3393			ND	U		0.0093	J	
NAS-SC-VOC-134	OU3-9	17.50		0.6606			ND	U		ND	U		0.939856562			1.3435			ND	U		0.0085	J	
NAS-SC-VOC-135	OU3-9	18.00		0.3948			ND	U		ND	U		0.60627032			1.0960			ND	U		ND	U	
NAS-SC-VOC-136	OU3-9	18.50		0.4791			ND	U		ND	U		0.341606068			2.0197			ND	U		0.0447		

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NAS-SC-VOC-137	OU3-9	18.80		0.6348			ND	U		ND	U		0.280596616			3.0277			ND	U		0.0969		
NAS-SC-VOC-138	OU3-9	19.00		0.8256			ND	U		ND	U		0.340994063			3.5583			0.000681534	J		0.2145		
NAS-SC-VOC-139	OU3-9	19.30		0.5969			ND	U		ND	U		0.205917257			3.0914			0.00095887	J		0.2783		
NAS-SC-VOC-140	OU3-9	20.10		0.3951			ND	U		ND	U		0.110888006			3.2095			0.001440104	J		0.5511		
NAS-SC-VOC-141	OU3-9	20.50		0.2765			ND	U		ND	U		0.072354815			3.3346			0.001722734	J		0.6905		
NAS-SC-VOC-142	OU3-9	21.00		0.2613			ND	U		ND	U		0.055351433	J		4.3438			0.002635783	J		1.0500		
NAS-SC-VOC-143	OU3-9	21.50		0.1749			ND	U		ND	U		0.025460551	J		4.0482			0.002518076	J		1.0190		
NAS-SC-VOC-144	OU3-9	22.00		0.1251			ND	U		ND	U		0.022750465	J		4.0408			0.002843808			1.0690		
NAS-SC-VOC-145	OU3-9	22.00	D	0.1343			ND	U		ND	U		0.024557707	J		4.1353			0.002870381	J		1.1083		
NAS-SC-VOC-146	OU3-9	22.50		0.0930			ND	U		ND	U		0.021148696	J		3.6682			ND	U		1.0321		
NAS-SC-VOC-147	OU3-9	23.00		0.0592		UB	ND	U		ND	U		ND	U		4.0971			0.003316357			1.2053		
NAS-SC-VOC-148	OU3-9	23.50		0.0393		UB	ND	U		ND	U		ND	U		3.1341			0.002563685			0.9054		
NAS-SC-VOC-149	OU3-9	24.00		0.0363		UB	ND	U		ND	U		ND	U		3.2136			0.002686972			0.9463		
NAS-SC-VOC-150	OU3-9	24.00	D	0.0396		UB	ND	U		ND	U		ND	U		3.2816			0.002639721			0.9840		
NAS-SC-VOC-151	OU3-9	24.50		0.0269	J	UB	ND	U		ND	U		ND	U		3.7089			0.003275823			1.1262		
NAS-SC-VOC-152	OU3-9	25.10		ND	U	UB	ND	U		ND	U		ND	U		1.0427			ND	U		0.3575		
NAS-SC-VOC-153	OU3-9	25.50		0.0092	J	UB	ND	U		ND	U		ND	U		0.8402			0.00104215	J	UB	0.2666		
NAS-SC-VOC-154	OU3-9	26.00		0.0324		UB	ND	U		ND	U		ND	U		0.5150			ND	U		0.1647		
NAS-SC-VOC-155	OU3-9	26.50		0.0490		UB	ND	U		ND	U		ND	U		0.4443			ND	U		0.1408		
NAS-SC-VOC-156	OU3-9	27.00		0.1016		UB	ND	U		ND	U		ND	U		0.2858			ND	U		0.0905		
NAS-SC-VOC-157	OU3-9	27.50		0.0865		UB	ND	U		ND	U		ND	U		0.2087			0.000536048	J	UB	0.0636		
NAS-SC-VOC-158	OU3-9	28.00		0.1225		UB	ND	U		ND	U		ND	U		0.1130			ND	U		0.0285	J	
NAS-SC-VOC-159	OU3-9	28.50		0.1194		UB	ND	U		ND	U		ND	U		0.0479			ND	U		ND	U	
NAS-SC-VOC-160	OU3-9	29.00		0.1915		UB	ND	U		ND	U		ND	U		0.0164			ND	U		ND	U	
NAS-SC-VOC-161	OU3-9	29.50		0.4639		UB	ND	U		ND	U		ND	U		0.0119	J		ND	U		ND	U	
NAS-SC-VOC-162	OU3-9	30.50		ND	U		ND	U		ND	U		ND	U		0.0061	J		ND	U		ND	U	
NAS-SC-VOC-163	OU3-9	31.50		0.0476		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-164	OU3-9	32.50		0.0335		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-165	OU3-9	33.50		0.0452		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-166	OU3-9	35.10		0.0498		UB	ND	U		ND	U		ND	U		ND	U		0.00070757	J		ND	U	
NAS-SC-VOC-167	OU3-9	35.50		0.0148	J	UB	ND	U		ND	U		ND	U		0.0053	J		0.000457419	J		ND	U	
NAS-SC-VOC-168	OU3-9	36.00		0.0228		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-169	OU3-9	36.50		0.0504		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-170	OU3-9	36.50	D	0.0741		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-171	OU3-9	37.00		0.0526		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-172	OU3-9	37.50		0.0129	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-173	OU3-9	38.00		0.0703		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-174	OU3-9	38.50		0.0147	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-175	OU3-9	39.00		0.0097	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-176	OU3-9	39.50		0.0049	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-177	OU3-9	39.90		ND	U	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-178	OU3-10	7.00		0.0081	J	UB	ND	U		ND	U		ND	U		ND	U		0.003317209			ND	U	
NAS-SC-VOC-179	OU3-10	8.00		ND	U	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-180	OU3-10	8.90		ND	U	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-181	OU3-10	10.50		ND	U	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-182	OU3-10	11.50		0.0085	J	UB	ND	U		ND	U		0.013682668	J		ND	U		ND	U		ND	U	
NAS-SC-VOC-183	OU3-10	12.50		0.1068			ND	U		ND	U		0.217451346			0.0695			ND	U		ND	U	
NAS-SC-VOC-184	OU3-10	13.50		0.2035			ND	U		ND	U		0.551021305			0.1394			ND	U		ND	U	
NAS-SC-VOC-185	OU3-10	14.20		0.1017			ND	U		ND	U		0.386229504			0.0735			ND	U		ND	U	
NAS-SC-VOC-186	OU3-10	15.50		0.0486			ND	U		ND	U		0.110248908			0.0405			ND	U		ND	U	
NAS-SC-VOC-187	OU3-10	16.50		0.0450			ND	U		ND	U		0.033648436			0.0314			ND	U		ND	U	
NAS-SC-VOC-188	OU3-10	17.00		0.0099	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-189	OU3-10	17.50		0.0169	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-190	OU3-10	18.00		0.1369			ND	U		ND	U		ND	U		0.0319			ND	U		ND	U	
NAS-SC-VOC-191	OU3-10	18.50		0.6907			ND	U		ND	U		0.016531058	J		0.1355			ND	U		ND	U	
NAS-SC-VOC-192	OU3-10	19.00		2.6301			ND	U		ND	U		0.045817629	J		0.6082			ND	U		ND	U	
NAS-SC-VOC-193	OU3-10	19.00	D	3.4625			ND	U		ND	U		0.053125203	J		0.7128			ND	U		ND	U	
NAS-SC-VOC-194	OU3-10	20.50		5.6489			ND	U		ND	U		0.241331741			1.9029			ND	U		ND	U	
NAS-SC-VOC-195	OU3-10	21.00		6.6395			ND	U		ND	U		0.204192431	J		1.2625			ND	U		ND	U	
NAS-SC-VOC-196	OU3-10	21.50		4.0391			ND	U		ND	U		0.067517615	J		0.5906			ND	U		ND	U	
NAS-SC-VOC-197	OU3-10	22.00		5.2661			ND	U		ND	U		ND	U		0.3634			ND	U		ND	U	
NAS-SC-VOC-198	OU3-10	22.50		4.0642			ND	U		ND	U		ND	U		0.1441			ND	U		ND	U	
NAS-SC-VOC-199	OU3-10	23.00		3.2684			ND	U		ND	U		ND	U		0.0761			0.0008	J		0.0292	J	
NAS-SC-VOC-200	OU3-10	23.50		2.4446			ND	U		ND	U		ND	U		0.0562			0.0007	J		0.0288	J	
NAS-SC-VOC-201	OU3-10	24.00		0.9121			ND	U		ND	U		ND	U		0.0473			0.0007	J		0.0204	J	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-202	OU3-10	25.50		0.6093			ND	U		ND	U		ND	U		0.0672			ND	U		0.0119	J	
NAS-SC-VOC-203	OU3-10	25.50	D	0.6389			ND	U		ND	U		ND	U		0.0668			ND	U		0.0241	J	
NAS-SC-VOC-204	OU3-10	26.00		0.4724			ND	U		ND	U		ND	U		0.0856			0.0006	J		ND	U	
NAS-SC-VOC-205	OU3-10	26.50		0.2579			ND	U		ND	U		ND	U		0.0770			0.0005	J		0.0240	J	
NAS-SC-VOC-206	OU3-10	27.00		0.2319			ND	U		ND	U		ND	U		0.0807			0.0004	J		0.0258	J	
NAS-SC-VOC-207	OU3-10	27.50		0.2146			ND	U		ND	U		ND	U		0.0870			ND	U		0.0292	J	
NAS-SC-VOC-208	OU3-10	28.00		0.2026			ND	U		ND	U		ND	U		0.0902			0.0005	J	UB	0.0317		
NAS-SC-VOC-209	OU3-10	28.50		0.1399			ND	U		ND	U		ND	U		0.0885			0.0005	J	UB	ND	U	
NAS-SC-VOC-210	OU3-10	29.00		0.0575		UB	ND	U		ND	U		ND	U		0.0735			0.0008	J	UB	0.0189	J	
NAS-SC-VOC-211	OU3-10	29.50		0.0345		UB	ND	U		ND	U		ND	U		0.0628			ND	U		ND	U	
NAS-SC-VOC-212	OU3-10	30.50		0.0279		UB	ND	U		ND	U		ND	U		0.0426			ND	U		ND	U	
NAS-SC-VOC-213	OU3-10	31.00		0.0356		UB	ND	U		ND	U		ND	U		0.0345			ND	U		ND	U	
NAS-SC-VOC-214	OU3-10	31.50		0.0312		UB	ND	U		ND	U		ND	U		0.0226			ND	U		ND	U	
NAS-SC-VOC-215	OU3-10	32.00		0.3026			ND	U		ND	U		ND	U		0.0242			ND	U		ND	U	
NAS-SC-VOC-216	OU3-10	32.50		0.0138	J	UB	ND	U		ND	U		ND	U		0.0228	J		ND	U		ND	U	
NAS-SC-VOC-217	OU3-10	33.00		0.0188	J	UB	ND	U		ND	U		ND	U		0.0279			ND	U		ND	U	
NAS-SC-VOC-218	OU3-10	33.50		0.0628		UB	ND	U		ND	U		ND	U		0.0246			0.0006	J	UB	ND	U	
NAS-SC-VOC-219	OU3-10	34.00		0.0592		UB	ND	U		ND	U		ND	U		0.0300			ND	U		ND	U	
NAS-SC-VOC-220	OU3-10	34.50		0.0653		UB	ND	U		ND	U		ND	U		0.0283			ND	U		ND	U	
NAS-SC-VOC-222	OU3-10	35.00		0.0266		UB	ND	U		ND	U		ND	U		0.0364			ND	U		ND	U	
NAS-SC-VOC-221	OU3-10	35.50		0.0395		UB	ND	U		ND	U		ND	U		0.0195			ND	U		ND	U	
NAS-SC-VOC-223	OU3-10	36.50		0.1250		UB	ND	U		ND	U		ND	U		0.0789			ND	U		ND	U	
NAS-SC-VOC-224	OU3-10	37.50		0.1391		UB	ND	U		ND	U		ND	U		0.3531			ND	U		ND	U	
NAS-SC-VOC-225	OU3-10	38.50		0.1353		UB	ND	U		ND	U		ND	U		0.1728			0.0012	J	UB	ND	U	
NAS-SC-VOC-226	OU3-10	39.50		0.0726		UB	ND	U		ND	U		ND	U		0.0943			0.0011	J	UB	ND	U	
NAS-SC-VOC-227	OU3-11	8.00		0.0772		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-228	OU3-11	8.50		0.0403		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-229	OU3-11	9.00		0.0186	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-230	OU3-11	10.50		0.0049	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-231	OU3-11	11.50		0.0048	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-232	OU3-11	12.50		0.0241	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-233	OU3-11	15.50		0.0076	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-234	OU3-11	16.50		0.0055	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-235	OU3-11	17.50		0.0170		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-236	OU3-11	18.50		0.0063	J	UB	ND	U		ND	U		ND	U		0.0065	J		ND	U		ND	U	
NAS-SC-VOC-237	OU3-11	19.50		0.0056	J	UB	ND	U		ND	U		ND	U		0.0082	J		ND	U		ND	U	
NAS-SC-VOC-238	OU3-11	20.50		0.0102	J	UB	ND	U		ND	U		ND	U		0.0175			ND	U		ND	U	
NAS-SC-VOC-239	OU3-11	21.00		0.0071	J	UB	ND	U		ND	U		ND	U		0.0148	J		ND	U		ND	U	
NAS-SC-VOC-240	OU3-11	21.50		ND	U	UB	ND	U		ND	U		ND	U		0.0240	J		ND	U		ND	U	
NAS-SC-VOC-241	OU3-11	22.00		0.0071	J	UB	ND	U		ND	U		ND	U		0.0263			ND	U		ND	U	
NAS-SC-VOC-242	OU3-11	22.50		0.0429			ND	U		ND	U		ND	U		0.0298			ND	U		ND	U	
NAS-SC-VOC-243	OU3-11	22.50	D	0.0056	J	UB	ND	U		ND	U		ND	U		0.0271			ND	U		ND	U	
NAS-SC-VOC-244	OU3-11	23.00		ND	U		ND	U		ND	U		ND	U		0.0307			ND	U		ND	U	
NAS-SC-VOC-245	OU3-11	23.50		0.0043	J	UB	ND	U		ND	U		ND	U		0.0362			ND	U		ND	U	
NAS-SC-VOC-246	OU3-11	23.90		0.0038	J	UB	ND	U		ND	U		ND	U		0.0315			ND	U		ND	U	
NAS-SC-VOC-247	OU3-11	24.50		ND	U		ND	U		ND	U		ND	U		0.0341			ND	U		ND	U	
NAS-SC-VOC-248	OU3-11	24.90		ND	U		ND	U		ND	U		ND	U		0.0339			ND	U		ND	U	
NAS-SC-VOC-249	OU3-11	25.50		0.0121	J	UB	ND	U		ND	U		ND	U		0.0415			ND	U		ND	U	
NAS-SC-VOC-250	OU3-11	26.00		0.0244			ND	U		ND	U		ND	U		0.0457			ND	U		ND	U	
NAS-SC-VOC-251	OU3-11	26.50		ND	U		ND	U		ND	U		ND	U		0.0488			ND	U		ND	U	
NAS-SC-VOC-252	OU3-11	27.00		0.0117	J	UB	ND	U		ND	U		ND	U		0.0440			ND	U		ND	U	
NAS-SC-VOC-253	OU3-11	27.00	D	ND	U		ND	U		ND	U		ND	U		0.0446			ND	U		ND	U	
NAS-SC-VOC-254	OU3-11	27.50		ND	U		ND	U		ND	U		ND	U		0.0508			ND	U		ND	U	
NAS-SC-VOC-255	OU3-11	28.00		0.0346			ND	U		ND	U		ND	U		0.0505			ND	U		ND	U	
NAS-SC-VOC-256	OU3-11	28.50		ND	U		ND	U		ND	U		ND	U		0.0294			ND	U		ND	U	
NAS-SC-VOC-257	OU3-11	29.00		ND	U		ND	U		ND	U		ND	U		0.0265			ND	U		ND	U	
NAS-SC-VOC-258	OU3-11	29.50		0.0428			ND	U		ND	U		ND	U		0.0230			ND	U		ND	U	
NAS-SC-VOC-259	OU3-11	29.80		ND	U		ND	U		ND	U		ND	U		0.0250			ND	U		ND	U	
NAS-SC-VOC-260	OU3-11	30.50		ND	U		ND	U		ND	U		ND	U		0.0318			ND	U		ND	U	
NAS-SC-VOC-261	OU3-11	31.00		0.0064	J	UB	ND	U		ND	U		ND	U		0.0252			ND	U		ND	U	
NAS-SC-VOC-262	OU3-11	31.50		0.0249		UB	ND	U		ND	U		ND	U		0.0214			ND	U		ND	U	
NAS-SC-VOC-263	OU3-11	32.00		0.0317		UB	ND	U		ND	U		ND	U		0.0202			ND	U		ND	U	
NAS-SC-VOC-264	OU3-11	32.50		0.0533		UB	ND	U		ND	U		ND	U		0.0199			ND	U		ND	U	
NAS-SC-VOC-265	OU3-11	33.00		0.0478		UB	ND	U		ND	U		ND	U		0.0127	J		ND	U		ND	U	
NAS-SC-VOC-266	OU3-11	33.50		0.0312	J	UB	ND	U		ND	U		ND	U		0.0120	J		ND	U		ND	U	

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Field ID	Borhole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-267	OU3-11	33.50	D	0.0520		UB	ND	U		ND	U		ND	U		0.0114	J		ND	U		ND	U	
NAS-SC-VOC-268	OU3-11	34.00		0.0351		UB	ND	U		ND	U		ND	U		0.0175	J		ND	U		ND	U	
NAS-SC-VOC-269	OU3-11	34.50		0.0509		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-270	OU3-11	35.50		0.1894		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-271	OU3-11	36.00		0.0334	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-272	OU3-11	36.50		0.0052	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-273	OU3-11	37.00		0.1752			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-274	OU3-11	37.50		0.2465			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-275	OU3-11	38.50		0.1518			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	

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Field ID	Borhole ID	Depth (ft bgs)	Duplicates	1,1-DCE	Flag	QA/QC flag	DCM	Flag	QA/QC flag	t-DCE	Flag	QA/QC flag	1.1-DCA	Flag	QA/QC flag	c-DCE	Flag	QA/QC flag	CF	Flag	QA/QC flag	1,2-DCA	Flag	QA/QC flag
NAS-SC-VOC-276	OU3-11	39.50		0.2643			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-277	OU3-11	40.50		0.1849			ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-278	OU3-11	41.50		0.0168	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-279	OU3-11	42.50		0.0080	J	UB	ND	U		ND	U		ND	U		ND	U		0.0015	J	UB	ND	U	
NAS-SC-VOC-280	OU3-11	43.50		0.0459			ND	U		ND	U		ND	U		ND	U		0.0027			ND	U	
ENC-01	OU3-6	12.00		0.0401		UB	ND	U		0.0841			ND	U		0.4533			ND	U		ND	U	
ENC-02	OU3-6	13.50		0.0497		UB	ND	U		0.0755			ND	U		2.0769			0.0007	J		ND	U	
ENC-03	OU3-6	16.00		0.0786		UB	ND	U		ND	U		ND	U		1.1255			0.0006	J		0.020339562	J	R
ENC-04	OU3-6	17.00		0.0867		UB	ND	U		ND	U		ND	U		0.1620			ND	U		ND	U	
ENC-05	OU3-6	17.50		0.0745		UB	ND	U		ND	U		ND	U		0.1458			ND	U		ND	U	
ENC-06	OU3-6	18.00		0.0205		UB	ND	U		ND	U		ND	U		0.0540			ND	U		ND	U	
ENC-07	OU3-6	18.50		0.0046	J	UB	ND	U		ND	U		ND	U		0.0291			ND	U		ND	U	
ENC-08	OU3-6	21.00		0.0055	J	UB	ND	U		ND	U		ND	U		0.0251			ND	U		ND	U	
ENC-09	OU3-6	23.00		ND	U	UB	ND	U		ND	U		ND	U		0.0200			ND	U		ND	U	
ENC-10	OU3-6	24.00		0.0046	J	UB	ND	U		ND	U		ND	U		0.0377			ND	U		ND	U	
ENC-11	OU3-6	24.50		0.0081	J	UB	ND	U		ND	U		ND	U		0.0164			ND	U		ND	U	
ENC-12	OU3-6	26.00		0.0130	J	UB	ND	U		ND	U		ND	U		0.0500			ND	U		ND	U	
ENC-13	OU3-6	28.00		0.0629		UB	ND	U		ND	U		ND	U		0.0235			ND	U		ND	U	
ENC-14	OU3-3	8.50		0.1132		UB	ND	U		0.1131			ND	U		0.7230			0.0006	J		ND	U	
ENC-15	OU3-3	11.50		0.0395		UB	ND	U		ND	U		ND	U		1.9227			ND	U		0.513841106		R
ENC-16	OU3-3	13.00		0.1112		UB	ND	U		ND	U		ND	U		0.4787			ND	U		1.138465995		R
ENC-17	OU3-3	16.50		ND	U	UB	ND	U		0.1129	J		ND	U		0.3687			ND	U		ND	U	
ENC-18	OU3-3	18.00		0.1294		UB	ND	U		ND	U		ND	U		0.0826			ND	U		ND	U	
ENC-19	OU3-3	19.00		0.0127	J	UB	ND	U		ND	U		ND	U		0.0142	J		ND	U		ND	U	
ENC-20	OU3-3	21.00		0.1218		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
ENC-21	OU3-3	22.00		0.0746		UB	ND	U		ND	U		ND	U		ND	U		ND	U		0.010045024	J	R
ENC-22	OU3-3	23.00		0.0663		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
ENC-23	OU3-3	24.00		0.0554		UB	ND	U		ND	U		ND	U		ND	U		ND	U		0.021121919	J	R
ENC-24	OU3-3	24.50		0.0255		UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
ENC-25	OU3-3	26.00		0.0391		UB	ND	U		ND	U		ND	U		ND	U		0.0013	J		ND	U	
ENC-26	OU3-3	29.00		0.0154	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
ENC-27	OU3-5D	14.20		0.1306		UB	ND	U		0.0959			ND	U		1.1087			ND	U		0.219822258		R
ENC-28	OU3-5D	16.00		0.0495		UB	ND	U		0.0262	J		ND	U		3.1994			0.0009	J		0.07331566		R
ENC-29	OU3-5D	17.50		0.0094	J	UB	ND	U		ND	U		ND	U		0.4127			ND	U		ND	U	
ENC-30	OU3-5D	21.50		0.0778		UB	ND	U		ND	U		ND	U		0.0306			ND	U		0.011419979	J	UB
ENC-31	OU3-5D	23.50		0.0737		UB	ND	U		ND	U		ND	U		0.0566			ND	U		ND	U	
ENC-32	OU3-5D	27.00		0.0562		UB	ND	U		ND	U		ND	U		0.0447			ND	U		0.011143831	J	UB

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-328	OU3-3	5.50		ND	U		ND	U		ND	U		ND	U		0.000259282	J	UB	ND	U		ND	U	
NAS-SC-VOC-329	OU3-3	6.50		ND	U		ND	U		0.000963139	J		ND	U		0.000240785	J	UB	ND	U		ND	U	
NAS-SC-VOC-330	OU3-3	7.50		ND	U		ND	U		1.153936045			ND	U		0.3060224			ND	U		ND	U	
NAS-SC-VOC-331	OU3-3	8.50		ND	U		ND	U		0.000546437	J		ND	U		0.000546437	J	UB	ND	U		ND	U	
NAS-SC-VOC-332	OU3-3	10.50		ND	U		0.0006	J		0.000567365	J	UB	ND	U		0.001512974	J	UB	ND	U		ND	U	
NAS-SC-VOC-333	OU3-3	11.00		ND	U		0.0003	J		0.657479169			ND	U		0.082391703			ND	U		ND	U	
NAS-SC-VOC-334	OU3-3	11.50		ND	U		0.0001	J		0.55439841			ND	U		0.522556039			ND	U		ND	U	
NAS-SC-VOC-335	OU3-3	12.00		ND	U		ND	U		0.543301824			ND	U		0.99772896			ND	U		ND	U	
NAS-SC-VOC-336	OU3-3	12.50		ND	U		0.0002	J		0.707184853			ND	U		1.577412543			ND	U		ND	U	
NAS-SC-VOC-339	OU3-3	12.50	D	ND	U		ND	U		0.353649742			ND	U		0.765151741			ND	U		ND	U	
NAS-SC-VOC-337	OU3-3	13.00		ND	U		ND	U		0.685741493			ND	U		3.368246129			ND	U		ND	U	
NAS-SC-VOC-338	OU3-3	13.40		ND	U		ND	U		0.326460814			ND	U		1.739677468			ND	U		ND	U	
NAS-SC-VOC-340	OU3-3	15.50		ND	U		ND	U		0.582105307			ND	U		3.258369949			ND	U		ND	U	
NAS-SC-VOC-341	OU3-3	16.00		ND	U		ND	U		0.328575701			ND	U		3.323844504			ND	U		ND	U	
NAS-SC-VOC-342	OU3-3	16.50		ND	U		0.0056	J		1.848248571			ND	U		28.95838853			ND	U		ND	U	
NAS-SC-VOC-343	OU3-3	17.00		ND	U		0.0051	J		1.148287451			ND	U		25.07432996			ND	U		ND	U	
NAS-SC-VOC-344	OU3-3	17.50		ND	U		0.0046	J		0.654769955			ND	U		18.12145016			ND	U		ND	U	
NAS-SC-VOC-345	OU3-3	17.70		ND	U		ND	U		0.566291412			ND	U		18.46421722			ND	U		ND	U	
NAS-SC-VOC-346	OU3-3	18.00		ND	U		0.0022	J		0.306564519			ND	U		10.72975815			ND	U		ND	U	
NAS-SC-VOC-347	OU3-3	18.40		ND	U		ND	U		0.16395112			ND	U		6.876980972			ND	U		ND	U	
NAS-SC-VOC-348	OU3-3	18.70		ND	U		0.0021	J		0.099615129			ND	U		4.753798274			ND	U		ND	U	
NAS-SC-VOC-349	OU3-3	18.70	D	ND	U		0.0008	J		0.085443309			ND	U		4.16536133			ND	U		ND	U	
NAS-SC-VOC-350	OU3-3	19.00		ND	U		0.0005	J		0.064845139			ND	U		3.201631095			ND	U		ND	U	
NAS-SC-VOC-351	OU3-3	20.33		ND	U		0.0007	J		0.058247398			ND	U		0.98702864			ND	U		ND	U	
NAS-SC-VOC-352	OU3-3	20.67		ND	U		0.0010	J		0.042518664			ND	U		0.577926765			ND	U		ND	U	
NAS-SC-VOC-353	OU3-3	21.00		ND	U		0.0005	J		0.050299522			ND	U		0.347093038			ND	U		ND	U	
NAS-SC-VOC-354	OU3-3	21.33		ND	U		0.0005	J		0.070671379			ND	U		0.170856858			ND	U		ND	U	
NAS-SC-VOC-355	OU3-3	21.67		ND	U		0.0005	J		0.084613825			ND	U		0.092621442			ND	U		ND	U	
NAS-SC-VOC-356	OU3-3	21.67	D	ND	U		0.0005	J		0.088070577			ND	U		0.09173002			ND	U		ND	U	
NAS-SC-VOC-357	OU3-3	22.00		ND	U		0.0007	J		0.078509627			ND	U		0.0377735			ND	U		ND	U	
NAS-SC-VOC-358	OU3-3	22.33		ND	U		0.0006	J		0.129832652			ND	U		0.035514761			ND	U		ND	U	
NAS-SC-VOC-359	OU3-3	22.67		ND	U		ND	U		0.136654617			ND	U		0.056258626			ND	U		ND	U	
NAS-SC-VOC-360	OU3-3	23.00		ND	U		0.0003	J		0.144609075			ND	U		0.076895302			ND	U		ND	U	
NAS-SC-VOC-361	OU3-3	23.33		ND	U		0.0006	J		0.344826003			ND	U		0.265695078			ND	U		ND	U	
NAS-SC-VOC-362	OU3-3	23.67		ND	U		0.0008	J		0.324180252			ND	U		0.456149693			ND	U		ND	U	
NAS-SC-VOC-363	OU3-3	24.00		ND	U		0.0003	J		0.082396567			ND	U		0.221339799			ND	U		ND	U	
NAS-SC-VOC-364	OU3-3	24.33		ND	U		0.0004	J		0.048452495			ND	U		0.186888195			ND	U		ND	U	
NAS-SC-VOC-365	OU3-3	24.50		ND	U		ND	U		0.033842829			ND	U		0.193790487			ND	U		ND	U	
NAS-SC-VOC-366	OU3-3	24.90		ND	U		ND	U		0.019154844			ND	U		0.183277028			ND	U		ND	U	
NAS-SC-VOC-367	OU3-3	25.50		ND	U		ND	U		0.01008693			ND	U		0.079309094			ND	U		ND	U	
NAS-SC-VOC-368	OU3-3	26.00		ND	U		ND	U		0.009284837			ND	U		0.098310041			ND	U		ND	U	
NAS-SC-VOC-369	OU3-3	27.00		ND	U		ND	U		0.006954005			ND	U		0.03556477			ND	U		ND	U	
NAS-SC-VOC-370	OU3-3	28.00		ND	U		ND	U		0.005456905			ND	U		0.015421688			ND	U		ND	U	
NAS-SC-VOC-371	OU3-3	29.00		ND	U		ND	U		0.003804161			ND	U		0.011888004			ND	U		ND	U	
NAS-SC-VOC-372	OU3-3	30.50		ND	U		0.0008	J		0.004117008			ND	U		0.023930108			ND	U		ND	U	
NAS-SC-VOC-373	OU3-3	31.50		ND	U		0.0002	J		0.000917574	J		ND	U		0.001146968	J	UB	ND	U		ND	U	
NAS-SC-VOC-374	OU3-3	32.50		ND	U		ND	U		0.000468463	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-375	OU3-3	33.50		ND	U		ND	U		0.000593921	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-001	OU3-4	5.50		ND	U		0.0008	J	UB	0.009773043			ND	U		0.062589064			ND	U		ND	U	
NAS-SC-VOC-002	OU3-4	6.00		ND	U		0.0005	J	UB	0.005343345			ND	U		0.004206463			ND	U		ND	U	
NAS-SC-VOC-003	OU3-4	6.50		ND	U		0.0006	J	UB	0.009191124			ND	U		0.00093787	J	UB	ND	U		ND	U	
NAS-SC-VOC-004	OU3-4	7.00		ND	U		0.0005	J	UB	0.00165263			ND	U		0.000508502	J	UB	ND	U		ND	U	
NAS-SC-VOC-005	OU3-4	7.50		ND	U		0.0004	J	UB	0.000283885	J		ND	U		0.000283885	J	UB	ND	U		ND	U	
NAS-SC-VOC-006	OU3-4	8.00		ND	U		0.0004	J	UB	0.026066183			ND	U		0.007084655			ND	U		ND	U	
NAS-SC-VOC-007	OU3-4	8.50		ND	U		0.0005	J	UB	2.051485283			ND	U		1.714364259			ND	U		0.006759627	J	
NAS-SC-VOC-008	OU3-4	9.00		ND	U		0.0009	J	UB	3.688187839			ND	U		3.420407734			ND	U		ND	U	
NAS-SC-VOC-009	OU3-4	10.50		0.0013	J		0.0018	J		3.483299184			ND	U		3.475208806			ND	U		ND	U	
NAS-SC-VOC-010	OU3-4	11.00		ND	U		0.0007	J	UB	3.721468176			ND	U		4.697310713			ND	U		ND	U	
NAS-SC-VOC-011	OU3-4	11.50		ND	U		ND	U		3.915364628			ND	U		6.143082112			ND	U		ND	U	
NAS-SC-VOC-012	OU3-4	12.00		ND	U		ND	U		4.079985654			ND	U		6.767644388			ND	U		ND	U	
NAS-SC-VOC-013	OU3-4	12.50		ND	U		ND	U		4.346115005			ND	U		7.519000323			ND	U		ND	U	
NAS-SC-VOC-014	OU3-4	13.00		ND	U		ND	U		3.629011908			ND	U		9.710791386			ND	U		ND	U	
NAS-SC-VOC-015	OU3-4	13.50		ND	U		ND	U		3.716284161			ND	U		10.98457666			ND	U		ND	U	
NAS-SC-VOC-016	OU3-4	14.00		ND	U		ND	U		3.374712608			ND	U		11.49365877			ND	U		ND	U	
NAS-SC-VOC-017	OU3-4	15.20		ND	U		ND	U		2.80381523			ND	U		13.07542426			ND	U		ND	U	

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NAS-SC-VOC-018	OU3-4	15.40		ND	U		ND	U		2.869650763			ND	U		14.59932232			ND	U		ND	U	
NAS-SC-VOC-019	OU3-4	15.70		ND	U		ND	U		2.813050765			ND	U		16.56740154			ND	U		ND	U	
NAS-SC-VOC-020	OU3-4	16.00		ND	U		ND	U		2.756560743			ND	U		19.98790135			ND	U		ND	U	
NAS-SC-VOC-021	OU3-4	16.00	D	ND	U		ND	U		2.301860038			ND	U		17.43292859			ND	U		ND	U	
NAS-SC-VOC-022	OU3-4	16.40		ND	U		ND	U		1.86077534			ND	U		12.94222848			ND	U		ND	U	
NAS-SC-VOC-023	OU3-4	16.80		ND	U		ND	U		1.352807163			ND	U		10.8955115			ND	U		ND	U	
NAS-SC-VOC-024	OU3-4	17.20		ND	U		ND	U		1.138187101			ND	U		10.48855285			ND	U		ND	U	
NAS-SC-VOC-025	OU3-4	17.50		ND	U		ND	U		1.102007596			ND	U		11.39526928			ND	U		ND	U	
NAS-SC-VOC-026	OU3-4	17.80		ND	U		ND	U		1.447524596			ND	U		21.37545062			ND	U		ND	U	
NAS-SC-VOC-027	OU3-4	18.10		ND	U		0.0027	J	UB	0.885576424			ND	U		8.530396113			ND	U		ND	U	
NAS-SC-VOC-028	OU3-4	18.40		ND	U		0.0024	J	UB	0.416666955			ND	U		4.27407277			ND	U		ND	U	
NAS-SC-VOC-029	OU3-4	18.70		ND	U		0.0008	J	UB	0.316169386			ND	U		3.498113203			ND	U		ND	U	
NAS-SC-VOC-030	OU3-4	18.70	D	ND	U		0.0024	J		0.33628863			ND	U		3.861833689			ND	U		ND	U	
NAS-SC-VOC-031	OU3-4	19.00		ND	U		0.0010	J	UB	0.10733795			ND	U		1.213126253			ND	U		ND	U	
NAS-SC-VOC-032	OU3-4	20.20		ND	U		0.0007	J	UB	0.063775114			ND	U		0.5040785			ND	U		ND	U	
NAS-SC-VOC-033	OU3-4	20.50		ND	U		0.0008	J	UB	0.039989008			ND	U		0.309445144			ND	U		ND	U	
NAS-SC-VOC-034	OU3-4	21.00		ND	U		0.0007	J	UB	0.04285404			ND	U		0.217461457			ND	U		0.018691656	J	
NAS-SC-VOC-035	OU3-4	21.50		ND	U		0.0008	J	UB	0.048912572			ND	U		0.171067286			ND	U		ND	U	
NAS-SC-VOC-036	OU3-4	22.00		ND	U		0.0007	J	UB	0.04631619			ND	U		0.076638299			ND	U		ND	U	
NAS-SC-VOC-037	OU3-4	22.50		ND	U		0.0004	J	UB	0.053868381			ND	U		0.044216962			ND	U		ND	U	
NAS-SC-VOC-038	OU3-4	23.00		ND	U		0.0006	J	UB	0.073305192			ND	U		0.011167588			ND	U		ND	U	
NAS-SC-VOC-039	OU3-4	23.50		ND	U		0.0005	J	UB	0.164975564			ND	U		0.015044941			ND	U		0.014785546	J	
NAS-SC-VOC-040	OU3-4	24.00		ND	U		ND	U		0.39676976			ND	U		0.134265344			ND	U		ND	U	
NAS-SC-VOC-041	OU3-4	24.40		ND	U		0.0004	J	UB	0.14449205			ND	U		0.151637261			ND	U		0.014290423	J	
NAS-SC-VOC-042	OU3-4	24.70		ND	U		0.0005	J	UB	0.042083892			ND	U		0.083159787			ND	U		ND	U	
NAS-SC-VOC-043	OU3-4	25.50		ND	U		0.0003	J	UB	0.035938166			ND	U		0.128400439			ND	U		ND	U	
NAS-SC-VOC-044	OU3-4	26.00		ND	U		0.0004	J	UB	0.004256297			ND	U		0.016741433			ND	U		ND	U	
NAS-SC-VOC-045	OU3-4	27.00		ND	U		ND	U		0.003859171			ND	U		0.003996999			ND	U		ND	U	
NAS-SC-VOC-046	OU3-4	28.00		ND	U		0.0003	J	UB	0.001097761	J		ND	U		0.000548881	J	UB	ND	U		ND	U	
NAS-SC-VOC-047	OU3-4	29.00		ND	U		ND	U		0.00024961	J		ND	U		0.000124805	J	UB	ND	U		ND	U	
NAS-SC-VOC-048	OU3-4	30.30		ND	U		0.0006	J		0.001404379	J		ND	U		0.002527883	J	UB	ND	U		ND	U	
NAS-SC-VOC-049	OU3-4	30.50		ND	U		ND	U		0.000533929	J		ND	U		0.000533929	J	UB	ND	U		ND	U	
NAS-SC-VOC-050	OU3-4	31.00		ND	U		0.0004	J		0.00091653	J		ND	U		0.00091653	J	UB	ND	U		ND	U	
NAS-SC-VOC-051	OU3-4	31.50		ND	U		ND	U		0.001006251	J	UB	ND	U		0.001293752	J	UB	ND	U		ND	U	
NAS-SC-VOC-052	OU3-4	32.00		ND	U		0.0005	J		0.00084168	J	UB	ND	U		0.001346689	J	UB	ND	U		ND	U	
NAS-SC-VOC-053	OU3-4	33.00		ND	U		0.0004	J		0.000639283	J	UB	ND	U		0.00038357	J	UB	ND	U		ND	U	
NAS-SC-VOC-054	OU3-4	34.00		ND	U		0.0004	J		0.001346606	J	UB	ND	U		0.000384744	J	UB	ND	U		ND	U	
NAS-SC-VOC-055	OU3-5	5.50		ND	U		0.0003	J		0.009756075			ND	U		0.01170729			ND	U		ND	U	
NAS-SC-VOC-056	OU3-5	6.00		ND	U		0.0003	J		0.011426187			ND	U		0.008719985			ND	U		ND	U	
NAS-SC-VOC-057	OU3-5	6.50		0.0142			0.0215			0.068070594			0.009913193	J		0.082609945			ND	U		ND	U	
NAS-SC-VOC-058	OU3-5	7.00		ND	U		0.0007	J		0.002535897	J	UB	ND	U		0.002173626	J	UB	ND	U		ND	U	
NAS-SC-VOC-059	OU3-5	7.50		ND	U		0.0004	J		0.000218094	J	UB	ND	U		0.000436187	J	UB	ND	U		ND	U	
NAS-SC-VOC-060	OU3-5	8.00		ND	U		0.0006	J		0.001931645	J	UB	ND	U		0.001609704	J	UB	ND	U		ND	U	
NAS-SC-VOC-061	OU3-5	8.00	D	ND	U		ND	U		0.002478565	J	UB	ND	U		0.000619641	J	UB	ND	U		ND	U	
NAS-SC-VOC-062	OU3-5	8.50		ND	U		0.0018	J		0.006320347	J	UB	ND	U		0.000902907	J	UB	ND	U		ND	U	
NAS-SC-VOC-063	OU3-5	9.00		ND	U		0.0011	J		ND	U		ND	U		0.001133207	J	UB	ND	U		ND	U	
NAS-SC-VOC-064	OU3-5	10.40		ND	U		ND	U		ND	U		ND	U		0.001242316	J	UB	ND	U		ND	U	
NAS-SC-VOC-065	OU3-5	10.80		ND	U		0.0007	J		1.140836635			ND	U		0.428801761			ND	U		ND	U	
NAS-SC-VOC-066	OU3-5	11.20		ND	U		0.0008	J		2.312048034			ND	U		1.64952252			ND	U		ND	U	
NAS-SC-VOC-067	OU3-5	11.60		ND	U		0.0009	J		2.886032337			ND	U		3.385223998			ND	U		ND	U	
NAS-SC-VOC-068	OU3-5	12.00		ND	U		0.0007	J		2.815525677			ND	U		5.448187315			ND	U		ND	U	
NAS-SC-VOC-069	OU3-5	12.40		ND	U		0.0007	J		2.651806733			ND	U		7.398081277			ND	U		ND	U	
NAS-SC-VOC-070	OU3-5	12.80		ND	U		ND	U		2.393653491			ND	U		10.14863159			ND	U		ND	U	
NAS-SC-VOC-071	OU3-5	13.00		ND	U		0.0013	J		1.656032598			ND	U		8.855349883			ND	U		ND	U	
NAS-SC-VOC-072	OU3-5	13.30		ND	U		ND	U		2.122388144			ND	U		11.30048732			ND	U		ND	U	
NAS-SC-VOC-073	OU3-5	15.20		ND	U		ND	U		1.687768658			ND	U		9.964549115			ND	U		ND	U	
NAS-SC-VOC-074	OU3-5	15.60		ND	U		ND	U		1.58376669			ND	U		10.82763267			ND	U		ND	U	
NAS-SC-VOC-075	OU3-5	16.00		ND	U		ND	U		1.552920613			ND	U		12.08969682			ND	U		ND	U	
NAS-SC-VOC-076	OU3-5	16.40		ND	U		ND	U		1.009981085			ND	U		7.653360146			ND	U		ND	U	
NAS-SC-VOC-077	OU3-5	16.80		ND	U		ND	U		0.762523878			ND	U		4.797346246			ND	U		ND	U	
NAS-SC-VOC-078	OU3-5	17.20		ND	U		ND	U		0.597116134			ND	U		3.245862061			ND	U		ND	U	
NAS-SC-VOC-079	OU3-5	17.60		0.0043	J		0.0060			0.632659477			ND	U		3.239129854			ND	U		ND	U	
NAS-SC-VOC-080	OU3-5	18.00		ND	U		0.0006	J		0.406296001			ND	U		1.942481832			ND	U		ND	U	
NAS-SC-VOC-081	OU3-5	18.00	D	ND	U		0.0007	J		0.30158814			ND	U		1.381182796			ND	U		ND	U	
NAS-SC-VOC-082	OU3-5	18.40		ND	U		0.0006	J		0.168401302			ND	U		0.562649211			ND	U		ND	U	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-083	OU3-5	18.80		ND	U		0.0006	J		0.146471237			ND	U		0.43087948			ND	U		ND	U	
NAS-SC-VOC-084	OU3-5	19.20		ND	U		0.0005	J		0.066535593			ND	U		0.119670024			ND	U		ND	U	
NAS-SC-VOC-085	OU3-5	19.60		ND	U		ND	U		0.039839293			ND	U		0.032030791			ND	U		ND	U	
NAS-SC-VOC-086	OU3-5	19.90		ND	U		ND	U		0.027985402			ND	U		0.006914041			ND	U		ND	U	
NAS-SC-VOC-087	OU3-5	20.50		ND	U		0.0005	J		0.050910651			ND	U		0.001566482	J	UB	ND	U		ND	U	
NAS-SC-VOC-088	OU3-5	21.00		ND	U		0.0005	J		0.05988726			ND	U		0.002711876		UB	ND	U		ND	U	
NAS-SC-VOC-089	OU3-5	21.50		ND	U		ND	U		0.076309526			ND	U		0.002510182	J	UB	ND	U		ND	U	
NAS-SC-VOC-090	OU3-5	22.00		ND	U		0.0003	J		0.087023939			ND	U		0.00259773			ND	U		ND	U	
NAS-SC-VOC-091	OU3-5	22.50		ND	U		0.0004	J		0.111541942			ND	U		0.006057521			ND	U		ND	U	
NAS-SC-VOC-092	OU3-5	23.00		ND	U		ND	U		0.125556376			ND	U		0.009152708			ND	U		ND	U	
NAS-SC-VOC-093	OU3-5	23.50		ND	U		0.0011	J		0.148731319			ND	U		0.018868899			ND	U		ND	U	
NAS-SC-VOC-094	OU3-5	24.00		ND	U		0.0007	J		0.167134007			ND	U		0.038514522			ND	U		ND	U	
NAS-SC-VOC-095	OU3-5	24.00	D	ND	U		0.0007	J		0.158078894			ND	U		0.036100286			ND	U		ND	U	
NAS-SC-VOC-096	OU3-5	24.50		ND	U		0.0006	J		0.235488266			ND	U		0.098717563			ND	U		ND	U	
NAS-SC-VOC-097	OU3-5	24.90		ND	U		0.0007	J		0.221773323			ND	U		0.114196711			ND	U		ND	U	
NAS-SC-VOC-098	OU3-5	25.50		ND	U		0.0004	J		0.023647565			ND	U		0.051982034			ND	U		0.012143344	J	
NAS-SC-VOC-099	OU3-5	26.00		ND	U		ND	U		0.023973045			ND	U		0.051894591			ND	U		ND	U	
NAS-SC-VOC-100	OU3-5	26.50		ND	U		ND	U		0.028863439			ND	U		0.030035559			ND	U		ND	U	
NAS-SC-VOC-101	OU3-5	27.00		ND	U		0.0005	J		0.000539839	J		ND	U		0.001079679	J	UB	ND	U		ND	U	
NAS-SC-VOC-102	OU3-5	27.50		ND	U		0.0005	J		0.001495354			ND	U		0.004214179			ND	U		0.006797062	J	
NAS-SC-VOC-103	OU3-5	28.00		ND	U		0.0003	J		0.000151705	J		ND	U		0.000303409	J	UB	ND	U		ND	U	
NAS-SC-VOC-104	OU3-5	28.50		ND	U		0.0004	J		0.000269296	J		ND	U		0.001346478	J	UB	ND	U		ND	U	
NAS-SC-VOC-105	OU3-5	29.00		ND	U		ND	U		ND	U		ND	U		0.000288262	J	UB	ND	U		ND	U	
NAS-SC-VOC-106	OU3-5	29.50		ND	U		ND	U		ND	U		ND	U		0.00014972	J	UB	ND	U		ND	U	
NAS-SC-VOC-107	OU3-5	30.50		ND	U		ND	U		0.015798998			ND	U		0.037119977			ND	U		ND	U	
NAS-SC-VOC-108	OU3-5	31.00		ND	U		ND	U		0.001019661	J		ND	U		0.002767651			ND	U		ND	U	
NAS-SC-VOC-109	OU3-5	31.50		ND	U		ND	U		0.000321166	J		ND	U		0.000321166	J	UB	ND	U		ND	U	
NAS-SC-VOC-110	OU3-5	32.00		ND	U		ND	U		ND	U		ND	U		0.000261732	J	UB	ND	U		ND	U	
NAS-SC-VOC-111	OU3-5	32.50		ND	U		ND	U		ND	U		ND	U		0.000218645	J	UB	ND	U		ND	U	
NAS-SC-VOC-112	OU3-5	33.00		ND	U		ND	U		ND	U		ND	U		ND	U	UB	ND	U		ND	U	
NAS-SC-VOC-113	OU3-5	34.00		ND	U		ND	U		0.000254478	J		ND	U		0.000254478	J	UB	ND	U		ND	U	
NAS-SC-VOC-114	OU3-5	34.00	D	ND	U		ND	U		0.000220403	J		ND	U		0.000220403	J	UB	ND	U		ND	U	
NAS-SC-VOC-376	OU3-5D	10.50		ND	U		ND	U		0.310630261			ND	U		0.000687235	J	UB	ND	U		ND	U	
NAS-SC-VOC-377	OU3-5D	11.50		ND	U		0.0009	J		0.868687739			ND	U		0.375095785			ND	U		ND	U	
NAS-SC-VOC-378	OU3-5D	12.50		ND	U		0.0006	J		2.486658301			ND	U		5.238678657			ND	U		ND	U	
NAS-SC-VOC-379	OU3-5D	13.50		ND	U		0.0006	J		2.385992536			ND	U		9.989079379			ND	U		ND	U	
NAS-SC-VOC-380	OU3-5D	14.20		ND	U		ND	U		2.117121064			ND	U		11.50069794			ND	U		ND	U	
NAS-SC-VOC-381	OU3-5D	15.50		ND	U		ND	U		1.695880415			ND	U		9.703793175			ND	U		ND	U	
NAS-SC-VOC-382	OU3-5D	16.00		ND	U		0.0009	J		0.33083369			ND	U		0.582209507			ND	U		ND	U	
NAS-SC-VOC-383	OU3-5D	16.50		ND	U		0.0005	J		0.246894471			ND	U		1.033522986			ND	U		ND	U	
NAS-SC-VOC-384	OU3-5D	17.00		ND	U		ND	U		0.238318344			ND	U		0.964962664			ND	U		ND	U	
NAS-SC-VOC-385	OU3-5D	17.50		ND	U		0.0006	J		0.12348836			ND	U		0.312856874			ND	U		ND	U	
NAS-SC-VOC-386	OU3-5D	17.50	D	ND	U		ND	U		0.137593803			ND	U		0.379740015			ND	U		ND	U	
NAS-SC-VOC-387	OU3-5D	18.00		ND	U		ND	U		0.020386283			ND	U		0.041845529			ND	U		ND	U	
NAS-SC-VOC-388	OU3-5D	18.50		ND	U		0.0005	J		0.018149225			ND	U		0.016499295			ND	U		ND	U	
NAS-SC-VOC-389	OU3-5D	20.50		ND	U		ND	U		0.023213996			ND	U		0.00216664	J	UB	ND	U		ND	U	
NAS-SC-VOC-390	OU3-5D	21.00		ND	U		ND	U		0.041878185			ND	U		0.002064418	J	UB	ND	U		ND	U	
NAS-SC-VOC-391	OU3-5D	21.50		ND	U		ND	U		0.07576013			ND	U		0.003052606		UB	ND	U		ND	U	
NAS-SC-VOC-392	OU3-5D	22.00		ND	U		0.0009	J		0.103260144			ND	U		0.007850186			ND	U		ND	U	
NAS-SC-VOC-393	OU3-5D	22.50		ND	U		ND	U		0.10681214			ND	U		0.045124749			ND	U		ND	U	
NAS-SC-VOC-394	OU3-5D	23.00		ND	U		ND	U		0.192363757			ND	U		0.094558556			ND	U		ND	U	
NAS-SC-VOC-395	OU3-5D	23.50		ND	U		ND	U		0.218618352			ND	U		0.132281062			ND	U		ND	U	
NAS-SC-VOC-396	OU3-5D	23.50	D	ND	U		ND	U		0.25508559			ND	U		0.161106689			ND	U		ND	U	
NAS-SC-VOC-397	OU3-5D	24.00		ND	U		0.0011	J		0.110737989			ND	U		0.087483011			ND	U		ND	U	
NAS-SC-VOC-398	OU3-5D	24.40		ND	U		0.0005	J		0.109946082			ND	U		0.09345417			ND	U		ND	U	
NAS-SC-VOC-399	OU3-5D	26.00		ND	U		0.0003	J		0.039970808			ND	U		0.075258843			ND	U		ND	U	
NAS-SC-VOC-400	OU3-5D	26.50		ND	U		0.0005	J		0.112601611			ND	U		0.110834322			ND	U		ND	U	
NAS-SC-VOC-401	OU3-5D	27.00		ND	U		0.0005	J		0.132688874			ND	U		0.124224668			ND	U		ND	U	
NAS-SC-VOC-402	OU3-5D	28.00		ND	U		0.0005	J		0.100391313			ND	U		0.065610071			ND	U		ND	U	
NAS-SC-VOC-403	OU3-5D	28.00	D	ND	U		ND	U		0.110444688			ND	U		0.071442769			ND	U		ND	U	
NAS-SC-VOC-404	OU3-5D	29.00		ND	U		0.0005	J		0.001732691	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-281	OU3-6	6.50		ND	U		0.0005	J		ND	U		ND	U		0.000519679	J	UB	ND	U		ND	U	
NAS-SC-VOC-282	OU3-6	7.00		ND	U		0.0004	J		ND	U		ND	U		0.000177788	J	UB	ND	U		ND	U	
NAS-SC-VOC-283	OU3-6	7.50		ND	U		0.0004	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-284	OU3-6	8.00		ND	U		0.0003	J		ND	U		ND	U		ND	U		ND	U		ND	U	

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NAS-SC-VOC-285	OU3-6	8.50		ND	U		0.0003	J		ND	U		ND	U		0.000163382	J	UB	ND	U		ND	U	
NAS-SC-VOC-286	OU3-6	8.90		ND	U		0.0003	J		ND	U		ND	U		0.000105408	J	UB	ND	U		ND	U	
NAS-SC-VOC-287	OU3-6	10.50		ND	U		ND	U		ND	U		ND	U		0.000215291	J	UB	ND	U		ND	U	
NAS-SC-VOC-288	OU3-6	11.00		ND	U		ND	U		0.000335154	J		ND	U		0.000167577	J	UB	ND	U		ND	U	
NAS-SC-VOC-289	OU3-6	11.50		ND	U		ND	U		0.000445459	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-290	OU3-6	12.00		ND	U		0.0003	J		0.000170593	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-291	OU3-6	12.50		ND	U		ND	U		0.000238706	J	UB	ND	U		0.000238706	J	UB	ND	U		ND	U	
NAS-SC-VOC-292	OU3-6	12.80		ND	U		0.0013	J		0.002668584	J	UB	ND	U		0.000667146	J	UB	ND	U		ND	U	
NAS-SC-VOC-293	OU3-6	13.00		ND	U		0.0008	J		0.014799671		UB	ND	U		0.01821498			ND	U		ND	U	
NAS-SC-VOC-294	OU3-6	13.20		ND	U		0.0007	J		0.102303993			ND	U		0.175472868			ND	U		ND	U	
NAS-SC-VOC-295	OU3-6	13.50		ND	U		0.0007	J		0.172220874			ND	U		0.387864961			ND	U		ND	U	
NAS-SC-VOC-296	OU3-6	15.50		ND	U		0.0005	J		0.729497967			ND	U		1.667752365			ND	U		ND	U	
NAS-SC-VOC-297	OU3-6	16.00		ND	U		0.0005	J		0.022719314		UB	ND	U		0.031598126			ND	U		ND	U	
NAS-SC-VOC-298	OU3-6	16.50		ND	U		0.0005	J		0.016305486		UB	ND	U		0.023789971			ND	U		ND	U	
NAS-SC-VOC-299	OU3-6	17.00		ND	U		0.0005	J		0.024912478		UB	ND	U		0.035513533			ND	U		ND	U	
NAS-SC-VOC-300	OU3-6	17.00	D	ND	U		ND	U		0.034247876			ND	U		0.0333346			ND	U		ND	U	
NAS-SC-VOC-301	OU3-6	17.50		ND	U		0.0005	J		0.012407482		UB	ND	U		0.004045918			ND	U		ND	U	
NAS-SC-VOC-302	OU3-6	18.00		ND	U		0.0008	J		0.015316183			ND	U		0.003168866		UB	ND	U		ND	U	
NAS-SC-VOC-303	OU3-6	18.50		ND	U		0.0005	J		0.011050599			ND	U		0.001381325	J	UB	ND	U		ND	U	
NAS-SC-VOC-304	OU3-6	20.50		ND	U		ND	U		0.021050165			ND	U		0.001578762	J	UB	ND	U		ND	U	
NAS-SC-VOC-305	OU3-6	21.00		ND	U		0.0004	J		0.031640024			ND	U		0.00165438	J	UB	ND	U		ND	U	
NAS-SC-VOC-306	OU3-6	21.50		ND	U		0.0005	J		0.046846906			ND	U		0.002151133	J	UB	ND	U		ND	U	
NAS-SC-VOC-307	OU3-6	21.50	D	ND	U		ND	U		0.042076118			ND	U		0.002112608		UB	ND	U		ND	U	
NAS-SC-VOC-308	OU3-6	22.00		ND	U		ND	U		0.078536383			ND	U		0.003490506		UB	ND	U		ND	U	
NAS-SC-VOC-309	OU3-6	22.50		ND	U		0.0011	J		0.112279711			ND	U		0.005667966			ND	U		ND	U	
NAS-SC-VOC-310	OU3-6	23.00		ND	U		0.0005	J		0.147106839			ND	U		0.011148129			ND	U		ND	U	
NAS-SC-VOC-311	OU3-6	23.50		ND	U		0.0005	J		0.233862139			ND	U		0.030892565			ND	U		ND	U	
NAS-SC-VOC-312	OU3-6	24.00		ND	U		0.0005	J		0.312573731			ND	U		0.092905364			ND	U		ND	U	
NAS-SC-VOC-313	OU3-6	24.20		ND	U		0.0007	J		0.219163532			ND	U		0.077012572			ND	U		ND	U	
NAS-SC-VOC-314	OU3-6	24.30		ND	U		ND	U		0.111569171			ND	U		0.034225325			ND	U		ND	U	
NAS-SC-VOC-315	OU3-6	24.50		ND	U		0.0005	J		0.096234336			ND	U		0.035703648			ND	U		ND	U	
NAS-SC-VOC-316	OU3-6	24.90		ND	U		0.0005	J		0.080351648			ND	U		0.036158242			ND	U		ND	U	
NAS-SC-VOC-317	OU3-6	25.50		ND	U		ND	U		0.031984562			ND	U		0.009175899			ND	U		ND	U	
NAS-SC-VOC-318	OU3-6	26.00		ND	U		ND	U		0.007299642		UB	ND	U		0.000486643	J	UB	ND	U		ND	U	
NAS-SC-VOC-319	OU3-6	26.50		ND	U		0.0005	J		0.000492704	J	UB	ND	U		0.000492704	J	UB	ND	U		ND	U	
NAS-SC-VOC-320	OU3-6	27.00		ND	U		0.0006	J		ND	U		ND	U		0.00114219	J	UB	ND	U		0.046544245	J	
NAS-SC-VOC-321	OU3-6	27.50		ND	U		0.0004	J		ND	U		ND	U		0.000368871	J	UB	ND	U		ND	U	
NAS-SC-VOC-322	OU3-6	28.00		ND	U		0.0005	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-323	OU3-6	28.50		ND	U		0.0003	J		ND	U		ND	U		0.000148905	J	UB	ND	U		ND	U	
NAS-SC-VOC-324	OU3-6	30.50		ND	U		0.0003	J		ND	U		ND	U		0.000140281	J	UB	ND	U		ND	U	
NAS-SC-VOC-325	OU3-6	31.50		ND	U		0.0005	J		0.000918212	J		ND	U		0.000229553	J	UB	ND	U		ND	U	
NAS-SC-VOC-326	OU3-6	32.50		ND	U		0.0004	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-327	OU3-6	33.50		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-115	OU3-9	6.50		0.0013	J		0.0002	J		0.000221905	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-116	OU3-9	7.00		ND	U		0.0003	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-119	OU3-9	7.50		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-117	OU3-9	8.00		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-120	OU3-9	8.50		ND	U		0.0009	J		0.002599284	J		0.005198567	J		0.004620949			ND	U		ND	U	
NAS-SC-VOC-118	OU3-9	9.00		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-121	OU3-9	10.50		ND	U		0.0002	J		ND	U		ND	U		0.000216797	J		ND	U		ND	U	
NAS-SC-VOC-122	OU3-9	11.00		ND	U		0.0007	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-123	OU3-9	11.50		ND	U		0.0004	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-124	OU3-9	12.00		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-125	OU3-9	12.50		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-126	OU3-9	13.00		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-127	OU3-9	13.50		ND	U		ND	U		0.010064452			ND	U		ND	U		ND	U		0.028320901	J	
NAS-SC-VOC-128	OU3-9	13.50	D	ND	U		ND	U		0.001695487	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-129	OU3-9	14.00		ND	U		0.0003	J		0.006708967			ND	U		0.000131548	J	UB	ND	U		0.019074515	J	
NAS-SC-VOC-130	OU3-9	15.50		ND	U		ND	U		0.011722813			ND	U		ND	U		ND	U		0.021770938	J	
NAS-SC-VOC-131	OU3-9	16.00		ND	U		ND	U		0.014207504			ND	U		ND	U		ND	U		0.025573507	J	
NAS-SC-VOC-132	OU3-9	16.50		ND	U		0.0009	J		0.01987456			ND	U		0.000225847	J	UB	ND	U		0.023713964	J	
NAS-SC-VOC-133	OU3-9	17.00		ND	U		0.0004	J		0.019949743			0.001994974	J		0.000284996	J	UB	ND	U		0.034057061		
NAS-SC-VOC-134	OU3-9	17.50		ND	U		0.0003	J		0.016661662			0.001388472	J		0.000138847	J	UB	ND	U		0.024992492	J	
NAS-SC-VOC-135	OU3-9	18.00		ND	U		0.0004	J		0.037991349			ND	U		0.000397815	J	UB	ND	U		0.023471095	J	
NAS-SC-VOC-136	OU3-9	18.50		ND	U		0.0003	J		0.210306295			ND	U		0.000647594	J	UB	ND	U		0.023637197	J	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-137	OU3-9	18.80		ND	U		0.0005	J		0.352920456			ND	U		0.001491213	J	UB	ND	U		ND	U	
NAS-SC-VOC-138	OU3-9	19.00		ND	U		0.0005	J		0.530006095			ND	U		0.002953313		UB	ND	U		0.012721964	J	
NAS-SC-VOC-139	OU3-9	19.30		ND	U		ND	U		0.650593056			ND	U		0.0055135			ND	U		0.015102197	J	
NAS-SC-VOC-140	OU3-9	20.10		ND	U		ND	U		1.196726406			0.002880208	J		0.011040797			ND	U		ND	U	
NAS-SC-VOC-141	OU3-9	20.50		ND	U		0.0006	J		1.500501045			0.004019712	J		0.015504603			ND	U		ND	U	
NAS-SC-VOC-142	OU3-9	21.00		ND	U		0.0007	J		2.463138785			0.006259984	J		0.035912537			ND	U		ND	U	
NAS-SC-VOC-143	OU3-9	21.50		ND	U		0.0006	J		2.549412557			0.006155298	J		0.03833072			ND	U		ND	U	
NAS-SC-VOC-144	OU3-9	22.00		ND	U		0.0006	J		2.49032282			0.006256378	J		0.031566271			ND	U		ND	U	
NAS-SC-VOC-145	OU3-9	22.00	D	ND	U		ND	U		2.427704723			0.006378625	J		0.028703813			ND	U		ND	U	
NAS-SC-VOC-146	OU3-9	22.50		ND	U		ND	U		2.438048162			0.006388669	J		0.033265137			ND	U		ND	U	
NAS-SC-VOC-147	OU3-9	23.00		ND	U		ND	U		2.681037989			0.007343363	J		0.032452925			ND	U		ND	U	
NAS-SC-VOC-148	OU3-9	23.50		ND	U		ND	U		2.078721172			0.005554651	J		0.024995928			ND	U		ND	U	
NAS-SC-VOC-149	OU3-9	24.00		ND	U		ND	U		2.148009867			0.005821772	J		0.025302316			ND	U		ND	U	
NAS-SC-VOC-150	OU3-9	24.00	D	ND	U		0.0004	J		2.220005741			0.005939373	J		0.027057145			ND	U		ND	U	
NAS-SC-VOC-151	OU3-9	24.50		ND	U		ND	U		2.53267916			0.006551646	J		0.029482407			ND	U		ND	U	
NAS-SC-VOC-152	OU3-9	25.10		ND	U		0.0006	J		0.849366104			ND	U		0.004520195			ND	U		ND	U	
NAS-SC-VOC-153	OU3-9	25.50		ND	U		ND	U		0.708870299			ND	U		0.003126449			ND	U		ND	U	
NAS-SC-VOC-154	OU3-9	26.00		ND	U		ND	U		0.499867003			ND	U		0.002008739		UB	ND	U		ND	U	
NAS-SC-VOC-155	OU3-9	26.50		ND	U		ND	U		0.50884556			ND	U		0.002286946		UB	ND	U		ND	U	
NAS-SC-VOC-156	OU3-9	27.00		ND	U		ND	U		0.385862624			ND	U		0.00173812		UB	ND	U		ND	U	
NAS-SC-VOC-157	OU3-9	27.50		ND	U		ND	U		0.380415702			ND	U		0.002501559		UB	ND	U		ND	U	
NAS-SC-VOC-158	OU3-9	28.00		ND	U		ND	U		0.330485478			ND	U		0.004042636			ND	U		ND	U	
NAS-SC-VOC-159	OU3-9	28.50		ND	U		ND	U		0.282083079			ND	U		0.006863335			ND	U		ND	U	
NAS-SC-VOC-160	OU3-9	29.00		ND	U		0.0003	J		0.204556764			ND	U		0.006709337			ND	U		0.012638519	J	
NAS-SC-VOC-161	OU3-9	29.50		ND	U		0.0006	J		0.208725786			ND	U		0.007257503			ND	U		ND	U	
NAS-SC-VOC-162	OU3-9	30.50		ND	U		0.0003	J		0.102898941			ND	U		0.003201947			ND	U		ND	U	
NAS-SC-VOC-163	OU3-9	31.50		ND	U		0.0007	J	UB	0.096768707			ND	U		0.001968177	J	UB	ND	U		ND	U	
NAS-SC-VOC-164	OU3-9	32.50		ND	U		0.0005	J	UB	0.055212508			ND	U		0.000774007	J	UB	ND	U		ND	U	
NAS-SC-VOC-165	OU3-9	33.50		ND	U		0.0003	J	UB	0.010698761			ND	U		0.00014265	J	UB	ND	U		ND	U	
NAS-SC-VOC-166	OU3-9	35.10		ND	U		0.0002	J	UB	0.021698824			ND	U		0.00070757	J	UB	ND	U		ND	U	
NAS-SC-VOC-167	OU3-9	35.50		ND	U		0.0003	J	UB	0.01722944			ND	U		0.000609892	J	UB	ND	U		ND	U	
NAS-SC-VOC-168	OU3-9	36.00		ND	U		0.0003	J	UB	0.000321536	J		ND	U		0.000160768	J	UB	ND	U		ND	U	
NAS-SC-VOC-169	OU3-9	36.50		ND	U		0.0002	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-170	OU3-9	36.50	D	ND	U		0.0002	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-171	OU3-9	37.00		ND	U		0.0002	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-172	OU3-9	37.50		ND	U		0.0004	J		ND	U		ND	U		0.000201683	J	UB	ND	U		ND	U	
NAS-SC-VOC-173	OU3-9	38.00		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-174	OU3-9	38.50		ND	U		0.0003	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-175	OU3-9	39.00		ND	U		0.0002	J		0.000231585	J		ND	U		0.000231585	J	UB	ND	U		ND	U	
NAS-SC-VOC-176	OU3-9	39.50		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-177	OU3-9	39.90		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-178	OU3-10	7.00		0.106861505			0.0002	J		0.012084117			ND	U		0.002132491	J	UB	ND	U		ND	U	
NAS-SC-VOC-179	OU3-10	8.00		0.115524868			0.0002	J		0.002265193			ND	U		0.001132597	J	UB	ND	U		ND	U	
NAS-SC-VOC-180	OU3-10	8.90		ND	U		0.0003	J		0.000257796	J		ND	U		0.000257796	J	UB	ND	U		ND	U	
NAS-SC-VOC-181	OU3-10	10.50		ND	U		0.0002	J		0.000195133	J		ND	U		0.000780531	J	UB	ND	U		0.019318148	J	
NAS-SC-VOC-182	OU3-10	11.50		ND	U		0.0002	J		0.000556206	J	UB	ND	U		0.000333724	J	UB	ND	U		0.005784543	J	
NAS-SC-VOC-183	OU3-10	12.50		0.006780907			0.0002	J		0.013870036			ND	U		ND	U		ND	U		0.014024148	J	
NAS-SC-VOC-184	OU3-10	13.50		0.000640722	J		0.0001	J		0.054333264			ND	U		ND	U		ND	U		0.031651689		
NAS-SC-VOC-185	OU3-10	14.20		ND	U		0.0002	J		0.01778278			ND	U		ND	U		ND	U		0.038217378		
NAS-SC-VOC-186	OU3-10	15.50		ND	U		0.0002	J		0.003186385		UB	ND	U		ND	U		ND	U		0.034412954		
NAS-SC-VOC-187	OU3-10	16.50		ND	U		0.0002	J		0.002112458		UB	ND	U		0.00015089	J	UB	ND	U		0.012976527	J	
NAS-SC-VOC-188	OU3-10	17.00		ND	U		0.0002	J		0.001585401	J	UB	ND	U		0.000176156	J	UB	ND	U		ND	U	
NAS-SC-VOC-189	OU3-10	17.50		ND	U		0.0002	J		0.004496499		UB	ND	U		0.000749416	J	UB	ND	U		0.010679184	J	
NAS-SC-VOC-190	OU3-10	18.00		ND	U		0.0002	J		0.021607707			ND	U		0.000154341	J	UB	ND	U		ND	U	
NAS-SC-VOC-191	OU3-10	18.50		ND	U		0.0002	J		0.102226543			0.001900122	J		0.000570036	J	UB	ND	U		ND	U	
NAS-SC-VOC-192	OU3-10	19.00		ND	U		0.0003	J		0.480261047			0.009888697	J		0.002307363	J	UB	ND	U		ND	U	
NAS-SC-VOC-193	OU3-10	19.00	D	ND	U		0.0003	J		0.574718107			0.009981099	J		0.002575767	J		ND	U		ND	U	
NAS-SC-VOC-194	OU3-10	20.50		ND	U		0.0011	J		2.635428036			0.020288952	J		0.021356791			ND	U		ND	U	
NAS-SC-VOC-195	OU3-10	21.00		ND	U		ND	U		3.027756586			0.015369323	J		0.02634741			ND	U		ND	U	
NAS-SC-VOC-196	OU3-10	21.50		ND	U		0.0009	J		2.938298224			0.011965147	J		0.026494254			ND	U		ND	U	
NAS-SC-VOC-197	OU3-10	22.00		ND	U		0.0012	J		4.539304722			0.012731349	J		0.046295816			ND	U		ND	U	
NAS-SC-VOC-198	OU3-10	22.50		ND	U		0.0005	J		3.830099474			0.011651298	J		0.037072312			ND	U		ND	U	
NAS-SC-VOC-199	OU3-10	23.00		ND	U		0.0003	J		3.377430567			0.009202808	J		0.031397816			ND	U		ND	U	
NAS-SC-VOC-200	OU3-10	23.50		ND	U		0.0002	J		2.892261603			0.007253321	J		0.024026625			ND	U		ND	U	
NAS-SC-VOC-201	OU3-10	24.00		ND	U		0.0002	J		1.813182153			0.004609991	J		0.011888924			ND	U		ND	U	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
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Field ID	Borehole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-202	OU3-10	25.50		ND	U		0.0002	J		1.868988331			0.003036889	J		0.008459905			ND	U		ND	U	
NAS-SC-VOC-203	OU3-10	25.50	D	ND	U		0.0002	J		1.982100934			0.003034215	J		0.008913006			ND	U		ND	U	
NAS-SC-VOC-204	OU3-10	26.00		ND	U		0.0002	J		2.199096326			0.003136821	J		0.009225945			ND	U		ND	U	
NAS-SC-VOC-205	OU3-10	26.50		ND	U		0.0002	J		1.84719401			0.002532021	J		0.007764866			ND	U		ND	U	
NAS-SC-VOC-206	OU3-10	27.00		ND	U		0.0001	J		1.820814084			0.002476505	J		0.008303577			ND	U		ND	U	
NAS-SC-VOC-207	OU3-10	27.50		ND	U		0.0002	J		1.99090001			0.002330635	J		0.010756776			ND	U		ND	U	
NAS-SC-VOC-208	OU3-10	28.00		ND	U		0.0003	J		2.098736368			0.002910019	J		0.012405871			ND	U		ND	U	
NAS-SC-VOC-209	OU3-10	28.50		ND	U		0.0005	J		1.961871368			0.002228676	J		0.016874259			ND	U		ND	U	
NAS-SC-VOC-210	OU3-10	29.00		ND	U		0.0004	J		1.163395332			0.002857061	J		0.014856718			ND	U		0.021142253	J	
NAS-SC-VOC-211	OU3-10	29.50		ND	U		0.0004	J		0.597814584			ND	U		0.011848577			ND	U		ND	U	
NAS-SC-VOC-212	OU3-10	30.50		ND	U		0.0003	J		0.175070359			ND	U		0.004942788			ND	U		ND	U	
NAS-SC-VOC-213	OU3-10	31.00		ND	U		0.0003	J		0.096484069			ND	U		0.002330533			ND	U		ND	U	
NAS-SC-VOC-214	OU3-10	31.50		ND	U		0.0002	J		0.019688776			ND	U		0.000302904	J	UB	ND	U		ND	U	
NAS-SC-VOC-215	OU3-10	32.00		ND	U		0.0004	J		0.003072768			ND	U		0.000180751	J	UB	ND	U		ND	U	
NAS-SC-VOC-216	OU3-10	32.50		ND	U		0.0003	J		0.004169154			ND	U		0.000320704	J	UB	ND	U		ND	U	
NAS-SC-VOC-217	OU3-10	33.00		ND	U		0.0003	J		0.003596886			ND	U		0.000276684	J	UB	ND	U		ND	U	
NAS-SC-VOC-218	OU3-10	33.50		ND	U		0.0004	J		0.004749615			0.003886049	J		0.001079458	J	UB	ND	U		0.080095784		
NAS-SC-VOC-219	OU3-10	34.00		ND	U		0.0001	J		0.006291542			ND	U		0.000149799	J	UB	ND	U		ND	U	
NAS-SC-VOC-220	OU3-10	34.50		ND	U		0.0002	J		0.005487686			ND	U		0.00017149	J	UB	ND	U		ND	U	
NAS-SC-VOC-222	OU3-10	35.00		ND	U		0.0002	J		0.001908107			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-221	OU3-10	35.50		ND	U		0.0002	J		0.000846766	J		ND	U		0.000169353	J	UB	ND	U		ND	U	
NAS-SC-VOC-223	OU3-10	36.50		ND	U		0.0002	J		0.006260825			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-224	OU3-10	37.50		ND	U		0.0002	J		0.059850979			ND	U		0.000220852	J	UB	ND	U		0.034673815	J	
NAS-SC-VOC-225	OU3-10	38.50		ND	U		0.0002	J		0.055656787			ND	U		0.000234839	J	UB	ND	U		0.184818106		
NAS-SC-VOC-226	OU3-10	39.50		ND	U		0.0003	J		0.010863537			ND	U		ND	U		ND	U		0.119213022		
NAS-SC-VOC-227	OU3-11	8.00		ND	U		0.0001	J		0.000140439	J		ND	U		0.000140439	J		ND	U		ND	U	
NAS-SC-VOC-228	OU3-11	8.50		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-229	OU3-11	9.00		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-230	OU3-11	10.50		ND	U		0.0002	J		0.000159083	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-231	OU3-11	11.50		ND	U		0.0002	J		0.000239352	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-232	OU3-11	12.50		ND	U		0.0002	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-233	OU3-11	15.50		ND	U		0.0002	J		0.000201151	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-234	OU3-11	16.50		ND	U		0.0002	J		0.000382489	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-235	OU3-11	17.50		ND	U		0.0001	J		0.001201707	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-236	OU3-11	18.50		ND	U		0.0002	J		0.004350129			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-237	OU3-11	19.50		ND	U		0.0002	J		0.007512665			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-238	OU3-11	20.50		ND	U		0.0002	J		0.024004361			ND	U		0.000162192	J	UB	ND	U		ND	U	
NAS-SC-VOC-239	OU3-11	21.00		ND	U		0.0002	J		0.03405445			ND	U		0.000374225	J	UB	ND	U		ND	U	
NAS-SC-VOC-240	OU3-11	21.50		ND	U		0.0003	J		0.071548278			ND	U		0.000792047	J	UB	ND	U		ND	U	
NAS-SC-VOC-241	OU3-11	22.00		ND	U		0.0002	J		0.064473684			ND	U		0.000589698	J	UB	ND	U		ND	U	
NAS-SC-VOC-242	OU3-11	22.50		ND	U		0.0005	J		0.073470083			ND	U		0.000501502	J	UB	ND	U		ND	U	
NAS-SC-VOC-243	OU3-11	22.50	D	ND	U		0.0005	J		0.063841116			ND	U		0.00160944	J	UB	ND	U		ND	U	
NAS-SC-VOC-244	OU3-11	23.00		ND	U		0.0004	J		0.077787222			ND	U		0.000554303	J	UB	ND	U		ND	U	
NAS-SC-VOC-245	OU3-11	23.50		ND	U		0.0004	J		0.094143754			ND	U		0.000560379	J	UB	ND	U		ND	U	
NAS-SC-VOC-246	OU3-11	23.90		ND	U		0.0002	J		0.086681848			ND	U		0.00052218	J	UB	ND	U		ND	U	
NAS-SC-VOC-247	OU3-11	24.50		ND	U		0.0002	J		0.091218754			ND	U		0.000568932	J	UB	ND	U		ND	U	
NAS-SC-VOC-248	OU3-11	24.90		ND	U		0.0002	J		0.092536761			ND	U		0.00063273	J	UB	ND	U		ND	U	
NAS-SC-VOC-249	OU3-11	25.50		ND	U		0.0002	J		0.116661874			ND	U		0.000765498	J	UB	ND	U		ND	U	
NAS-SC-VOC-250	OU3-11	26.00		ND	U		0.0002	J		0.13078849			ND	U		0.000926483	J	UB	ND	U		ND	U	
NAS-SC-VOC-251	OU3-11	26.50		ND	U		0.0002	J		0.143002996			ND	U		0.00099538	J	UB	ND	U		ND	U	
NAS-SC-VOC-252	OU3-11	27.00		ND	U		0.0002	J		0.11940432			ND	U		0.000872839	J	UB	ND	U		ND	U	
NAS-SC-VOC-253	OU3-11	27.00	D	ND	U		0.0002	J		0.121532982			ND	U		0.000756743	J	UB	ND	U		ND	U	
NAS-SC-VOC-254	OU3-11	27.50		ND	U		0.0002	J		0.157553164			ND	U		0.001039955	J	UB	ND	U		ND	U	
NAS-SC-VOC-255	OU3-11	28.00		ND	U		0.0001	J		0.16422382			ND	U		0.001010164	J	UB	ND	U		ND	U	
NAS-SC-VOC-256	OU3-11	28.50		ND	U		0.0002	J		0.069544567			ND	U		0.000884791	J	UB	ND	U		ND	U	
NAS-SC-VOC-257	OU3-11	29.00		ND	U		0.0002	J		0.023743251			ND	U		0.000989302	J	UB	ND	U		ND	U	
NAS-SC-VOC-258	OU3-11	29.50		ND	U		0.0002	J		0.00680896			ND	U		0.000523766	J	UB	ND	U		0.012046621	J	
NAS-SC-VOC-259	OU3-11	29.80		ND	U		0.0002	J		0.007110952			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-260	OU3-11	30.50		ND	U		0.0002	J		0.025321187			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-261	OU3-11	31.00		ND	U		0.0002	J		0.019321688			ND	U		0.000184016	J	UB	ND	U		ND	U	
NAS-SC-VOC-262	OU3-11	31.50		ND	U		0.0003	J		0.012723162			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-263	OU3-11	32.00		ND	U		0.0003	J		0.009154748			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-264	OU3-11	32.50		ND	U		0.0002	J		0.008981169			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-265	OU3-11	33.00		ND	U		0.0002	J		0.007758785			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-266	OU3-11	33.50		ND	U		0.0003	J		0.012337611			ND	U		ND	U		ND	U		ND	U	

TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Field ID	Borhole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-267	OU3-11	33.50	D	ND	U		0.0002	J		0.011216187			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-268	OU3-11	34.00		ND	U		0.0002	J		0.014033874			ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-269	OU3-11	34.50		ND	U		0.0003	J		0.000297495	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-270	OU3-11	35.50		ND	U		0.0003	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-271	OU3-11	36.00		ND	U		0.0004	J		ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-272	OU3-11	36.50		ND	U		0.0007	J	UB	0.000224698	J		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-273	OU3-11	37.00		ND	U		0.0008	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-274	OU3-11	37.50		ND	U		0.0007	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-275	OU3-11	38.50		ND	U		0.0005	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	

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TABLE H.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Field ID	Borhole ID	Depth (ft bgs)	Duplicates	1,1,1-TCA	Flag	QA/QC flag	CT	Flag	QA/QC flag	TCE	Flag	QA/QC flag	1,1,2-TCA	Flag	QA/QC flag	PCE	Flag	QA/QC flag	1,1,1,2 PCA	Flag	QA/QC flag	1,1,2,2 PCA	Flag	QA/QC flag
NAS-SC-VOC-276	OU3-11	39.50		ND	U		0.0006	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-277	OU3-11	40.50		ND	U		0.0003	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-278	OU3-11	41.50		ND	U		0.0002	J	UB	ND	U		ND	U		ND	U		ND	U		ND	U	
NAS-SC-VOC-279	OU3-11	42.50		ND	U		0.0002	J	UB	ND	U		ND	U		ND	U		ND	U		0.317488718		
NAS-SC-VOC-280	OU3-11	43.50		ND	U		0.0001	J	UB	0.00014157	J		ND	U		ND	U		ND	U		0.801005369		
ENC-01	OU3-6	12.00		ND	U		0.0003	J		0.000301486	J	UB	ND	U		0.000301486	J		ND	U		ND	U	
ENC-02	OU3-6	13.50		ND	U		0.0003	J		0.060385417			ND	U		0.095646974			ND	U		ND	U	
ENC-03	OU3-6	16.00		0.000931583	J		0.0003	J		0.068160821			ND	U		0.083066148			ND	U		ND	U	
ENC-04	OU3-6	17.00		ND	U		0.0001	J		0.005672689			ND	U		0.005963596			ND	U		ND	U	
ENC-05	OU3-6	17.50		ND	U		0.0001	J		0.006064382			ND	U		0.001479117	J	UB	ND	U		ND	U	
ENC-06	OU3-6	18.00		ND	U		0.0003	J		0.00507555			ND	U		0.001492809	J	UB	ND	U		ND	U	
ENC-07	OU3-6	18.50		ND	U		0.0003	J		0.004451357			ND	U		0.000593514	J	UB	ND	U		ND	U	
ENC-08	OU3-6	21.00		ND	U		0.0002	J		0.0137644			ND	U		0.000764689	J	UB	ND	U		ND	U	
ENC-09	OU3-6	23.00		ND	U		0.0002	J		0.082484369			ND	U		0.007398407			ND	U		ND	U	
ENC-10	OU3-6	24.00		0.000795805	J		0.0002	J		0.18271692			ND	U		0.059207922			ND	U		ND	U	
ENC-11	OU3-6	24.50		ND	U		0.0001	J		0.038102755			ND	U		0.01148686			ND	U		ND	U	
ENC-12	OU3-6	26.00		ND	U		0.0001	J		0.002779483			ND	U		0.000292577	J	UB	ND	U		ND	U	
ENC-13	OU3-6	28.00		ND	U		0.0001	J		0.000147039	J	UB	ND	U		0.000147039	J	UB	ND	U		ND	U	
ENC-14	OU3-3	8.50		ND	U		0.0002	J		0.000381931	J	UB	ND	U		0.000572897	J	UB	ND	U		ND	U	
ENC-15	OU3-3	11.50		0.032827881		R	ND	U		0.967574824			ND	U		0.490568758			ND	U		ND	U	
ENC-16	OU3-3	13.00		ND	U		ND	U		0.801859757			ND	U		3.157478919			ND	U		ND	U	
ENC-17	OU3-3	16.50		ND	U		ND	U		0.94214677			ND	U		12.05676961			ND	U		ND	U	
ENC-18	OU3-3	18.00		ND	U		0.0008	J		0.219780772			ND	U		7.405520917			ND	U		ND	U	
ENC-19	OU3-3	19.00		ND	U		0.0003	J		0.037158777			ND	U		1.642927377			ND	U		ND	U	
ENC-20	OU3-3	21.00		ND	U		0.0002	J		0.029723064			ND	U		0.245215276			ND	U		ND	U	
ENC-21	OU3-3	22.00		ND	U		0.0002	J		0.037628979			ND	U		0.020249493			ND	U		ND	U	
ENC-22	OU3-3	23.00		ND	U		0.0002	J		0.079827215			ND	U		0.046758137			ND	U		ND	U	
ENC-23	OU3-3	24.00		ND	U		0.0002	J		0.015404708			ND	U		0.045896501			ND	U		ND	U	
ENC-24	OU3-3	24.50		ND	U		0.0002	J		0.0076847			ND	U		0.048519087			ND	U		ND	U	
ENC-25	OU3-3	26.00		ND	U		0.0002	J		0.0038644			ND	U		0.019160984			ND	U		ND	U	
ENC-26	OU3-3	29.00		ND	U		0.0001	J		0.001476918			ND	U		0.003544603			ND	U		ND	U	
ENC-27	OU3-5D	14.20		ND	U		ND	U		0.80257254			ND	U		3.072348006			ND	U		ND	U	
ENC-28	OU3-5D	16.00		ND	U		0.0003	J		0.22454718			ND	U		0.406255012			ND	U		ND	U	
ENC-29	OU3-5D	17.50		ND	U		0.0001	J		0.033707865			ND	U		0.072486825			ND	U		ND	U	
ENC-30	OU3-5D	21.50		ND	U		0.0002	J		0.031019131			ND	U		0.00154324	J	UB	ND	U		ND	U	
ENC-31	OU3-5D	23.50		0.000792365	J		0.0002	J		0.122816545			ND	U		0.069411157			ND	U		ND	U	
ENC-32	OU3-5D	27.00		ND	U		0.0003	J		0.037198422			ND	U		0.024641993			ND	U		0.035628869		

Notes:

1. All analyses completed at the University of Guelph with the following reporting limits:

1,1-DCE RL =	12	µg/L
DCM RL =	20	µg/L
t-DCE RL =	10	µg/L
1,1-DCA RL =	20	µg/L
c-DCE RL =	10	µg/L
CF RL =	1	µg/L
1,2-DCA RL =	20	µg/L
1,1,1-TCA RL=	1	µg/L
CT RL =	1	µg/L
TCE RL =	1	µg/L
1,1,2-TCA RL =	5	µg/L
PCE RL =	1.1	µg/L
1,1,1,2-PCA RL =	5	µg/L
1,1,2,2-PCA RL =	20	µg/L

2. The following QA/QC flags apply:

<mdl	-less than method detection limit
ND	-not deteced
U	-The analyte was not detected above the reporting limit
B	-The analyte was detected in the blank
J	-The analyte positevly identified, aproximate concentration of the analyte
U/B	-non-detect at the level of blank contamination
U/J	-Estimated non-detect, the concentration is less than elevated RL due to analytical deficiencies
R	-the sample results are rejected due to presence of front-end interference
E	-analyte concentration exceeds calibration range

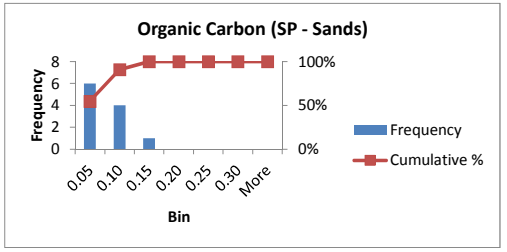
APPENDIX I

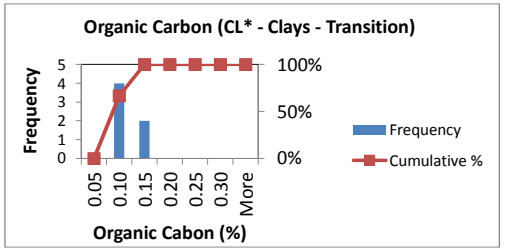
Soil Organic Carbon Data from Demonstration Project

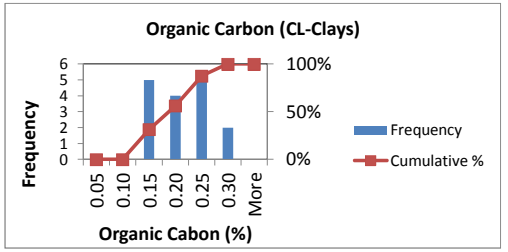
TABLE I.1
SUMMARY OF ORGANIC CARBON ANALYSES OF SOIL SAMPLES

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Sample ID	Borhole ID	Depth (ft bgs)	Lithology	Carbon Package			Walkley-Black
				Total C (% dry)	Inorganic C (% dry)	Organic C (% dry)	Organic Matter (% dry)
NAS-SC-MC-284	OU3-6	8.0	SP	0.107	<0.05	0.107	<0.1
NAS-SC-MC-290	OU3-6	12.0	SP	<0.05	<0.05	<0.05	<0.1
NAS-SC-MC-295	OU3-6	13.5	SP	0.0574	<0.05	0.0574	<0.1
NAS-SC-MC-297	OU3-6	16.0	CL*	0.0679	<0.05	0.0679	<0.1
NAS-SC-MC-299	OU3-6	17.0	CL*	0.0808	<0.05	0.0808	<0.1
NAS-SC-MC-301	OU3-6	17.5	CL	0.162	<0.05	0.162	<0.1
NAS-SC-MC-303	OU3-6	18.5	CL	0.123	<0.05	0.123	<0.1
NAS-SC-MC-305	OU3-6	21.0	CL	0.131	<0.05	0.131	<0.1
NAS-SC-MC-310	OU3-6	23.0	CL	0.18	<0.05	0.18	<0.1
NAS-SC-MC-312	OU3-6	24.0	CL	0.267	<0.05	0.267	0.1
NAS-SC-MC-315	OU3-6	24.5	CL*	0.0563	<0.05	0.0563	<0.1
NAS-SC-MC-318	OU3-6	26.0	SP	<0.05	<0.05	<0.05	<0.1
NAS-SC-MC-322	OU3-6	28.0	SP	0.0536	<0.05	0.0536	<0.1
NAS-SC-MC-331	OU3-3	8.5	SP	<0.05	<0.05	<0.05	<0.1
NAS-SC-MC-334	OU3-3	11.5	SP	<0.05	<0.05	<0.05	<0.1
NAS-SC-MC-337	OU3-3	13.0	CL*	0.0524	<0.05	0.0524	<0.1
NAS-SC-MC-342	OU3-3	16.5	CL*	0.148	<0.05	0.148	0.1
NAS-SC-MC-346	OU3-3	18.0	CL	0.219	<0.05	0.219	0.1
NAS-SC-MC-350	OU3-3	19.0	CL	0.225	<0.05	0.225	0.1
NAS-SC-MC-353	OU3-3	21.0	CL	0.258	<0.05	0.258	0.2
NAS-SC-MC-357	OU3-3	22.0	CL	0.224	<0.05	0.224	0.2
NAS-SC-MC-360	OU3-3	23.0	CL	0.214	<0.05	0.214	0.2
NAS-SC-MC-368	OU3-3	26.0	SP	0.0596	<0.05	0.0596	<0.1
NAS-SC-MC-371	OU3-3	29.0	SP	<0.05	<0.05	<0.05	<0.1
NAS-SC-MC-380	OU3-5D	14.2	SP	0.0546	<0.05	0.0546	<0.1
NAS-SC-MC-382	OU3-5D	16.0	CL*	0.118	<0.05	0.118	0.1
NAS-SC-MC-384	OU3-5D	17.0	CL	0.141	<0.05	0.141	0.1
NAS-SC-MC-385	OU3-5D	17.5	CL	0.141	<0.05	0.141	0.1
NAS-SC-MC-388	OU3-5D	18.5	CL	0.131	<0.05	0.131	0.1
NAS-SC-MC-390	OU3-5D	21.0	CL	0.156	<0.05	0.156	0.1
NAS-SC-MC-391	OU3-5D	21.5	CL	0.176	<0.05	0.176	0.1
NAS-SC-MC-395	OU3-5D	23.5	CL	0.21	<0.05	0.21	0.3
NAS-SC-MC-401	OU3-5D	27.0	SP	<0.05	<0.05	<0.05	<0.1







Notes:
1. All analyses completed at the University of Guelph Agricultural and Food Laboratory.

APPENDIX J

Results of Alternate Soil Sampling and Analyses Methods

Table J.1 Comparison of Results Obtained with Different Soil Collection and Analyses Methods: EnCore Sampling and Field Preservation

Table J.2 Comparison of Results Obtained with Different Soil Collection and Analyses Methods: Field Extraction Methods and Field Duplicates at Different Laboratories

Table J.3 Comparison of Results Obtained with Different Soil Collection and Analyses Methods: Field Extraction Methods and Field Duplicates at Different Laboratories

Table J.4 Comparison of Results Obtained with Different Soil Collection and Analyses Methods: Field Duplicates at Same Laboratory

Figure J.5 Plots of Time-Series Extractions of Soil VOC Concentrations

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TABLE J.1
COMPARISON OF RESULTS OBTAINED WITH DIFFERENT SOIL COLLECTION AND ANALYSES METHODS:
EnCore Sampling and Field Preservation

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

				UG Results (mg / kg wet soil) -- Field Methanol Preservation						UG Results (mg / kg wet soil) -- EnCore w/ Delayed Methanol Preservation (24 - 72 hr)							Test America Results (mg / kg wet soil) - EnCore No Preservation					
Borehole ID	Depth (ft bgs)	Lithology	UG Field ID	PCE	Flag	TCE	Flag	cis-DCE	Flag	PCE	Flag	TCE	Flag	cis-DCE	Flag	Encore Field ID	PCE	Flag	TCE	Flag	cis-DCE	Flag
OU3-6	12.0	SP	NAS-SC-VOC-290		U	0.00012	J	0.59480		0.000301486	J	0.000301486	J	0.45328434		NAS-ENC-VOC-01		U		U	0.26000	E
OU3-6	13.5	SP	NAS-SC-VOC-295	0.26481		0.11758		2.94302		0.095646974		0.060385417		2.07690573		NAS-ENC-VOC-02	0.06000		0.03300		0.85000	E
OU3-6	16.0	CL	NAS-SC-VOC-297	0.02238		0.01609		1.57070		0.083066148		0.068160821		1.125507492		NAS-ENC-VOC-03	0.01600		0.01100		0.28000	E
OU3-6	17.0	CL	NAS-SC-VOC-299	0.02599		0.01823		0.34934		0.005963596		0.005672689		0.162035262		NAS-ENC-VOC-04	0.00450		0.00380	J	0.07500	
OU3-6	17.5	CL	NAS-SC-VOC-301	0.00271		0.00832		0.15494		0.001479117	J	0.006064382		0.145840982		NAS-ENC-VOC-05		U	0.00210	J	0.04800	
OU3-6	18.0	CL	NAS-SC-VOC-302	0.00214		0.01035		0.09301		0.001492809	J	0.00507555		0.054039681		NAS-ENC-VOC-06	0.00140	J	0.00410	J	0.04200	
OU3-6	18.5	CL	NAS-SC-VOC-303	0.00097	J	0.00779		0.05029		0.000593514	J	0.004451357		0.029082202		NAS-ENC-VOC-07		U	0.00240	J	0.01400	
OU3-6	21.0	CL	NAS-SC-VOC-305	0.00111	J	0.02132		0.03149		0.000764689	J	0.0137644		0.025081796		NAS-ENC-VOC-08		U	0.00640		0.01000	
OU3-6	23.0	CL	NAS-SC-VOC-310	0.00746		0.09848		0.02661		0.007398407		0.082484369		0.019991441		NAS-ENC-VOC-09	0.00570		0.02600		0.00820	
OU3-6	24.0	CL	NAS-SC-VOC-312	0.05730		0.19280		0.03742		0.059207922		0.18271692		0.037721176		NAS-ENC-VOC-10	0.00950		0.03300		0.00730	
OU3-6	24.5	CL	NAS-SC-VOC-315	0.02585		0.06967		0.03389		0.01148686		0.038102755		0.016389788		NAS-ENC-VOC-11	0.00630		0.01800		0.00760	
OU3-6	26.0	SP	NAS-SC-VOC-318	0.00035	J	0.00518		0.07822		0.000292577	J	0.002779483		0.050030703		NAS-ENC-VOC-12		U	0.00170	J	0.02300	
OU3-6	28.0	SP	NAS-SC-VOC-322		U		U	0.03738		0.000147039	J	0.000147039	J	0.02352632		NAS-ENC-VOC-13		U		U	0.01400	
OU3-3	8.5	SP	NAS-SC-VOC-331	0.00041	J	0.00041	J	0.73585		0.000572897	J	0.000381931	J	0.722996119		NAS-ENC-VOC-14		U		U	0.29000	E
OU3-3	11.5	SP	NAS-SC-VOC-334	0.33558		0.35603		0.34069		0.490568758		0.967574824		1.922665805		NAS-ENC-VOC-15	0.28000	E	0.49000	E	0.59000	E
OU3-3	13.0	CL	NAS-SC-VOC-337	2.52238		0.51353		0.24170		3.157478919		0.801859757		0.478680299		NAS-ENC-VOC-16	3.50000	E	0.86000	E	0.44000	E
OU3-3	16.5	CL	NAS-SC-VOC-342	20.15838		1.28659		0.50787		12.05676961		0.94214677		0.368731563		NAS-ENC-VOC-17	3.10000	E	0.26000	E	0.10000	
OU3-3	18.0	CL	NAS-SC-VOC-346	7.73939		0.22113		0.08332		7.405520917		0.219780772		0.082612631		NAS-ENC-VOC-18	3.70000	E	0.10000		0.03700	
OU3-3	19.0	CL	NAS-SC-VOC-350	2.31497		0.04689		0.01582	J	1.642927377		0.037158777		0.014234209	J	NAS-ENC-VOC-19	0.70000	E	0.01400		0.00440	J
OU3-3	21.0	CL	NAS-SC-VOC-353	0.24472		0.03546			U	0.245215276		0.029723064			U	NAS-ENC-VOC-20	0.04200		0.00580		0.00120	J
OU3-3	22.0	CL	NAS-SC-VOC-357	0.02816		0.05854			U	0.020249493		0.037628979			U	NAS-ENC-VOC-21	0.00470	J	0.01100		0.00160	J
OU3-3	23.0	CL	NAS-SC-VOC-360	0.05166		0.09715			U	0.046758137		0.079827215			U	NAS-ENC-VOC-22	0.01000		0.02300		0.00220	J
OU3-3	24.0	CL	NAS-SC-VOC-363	0.15465		0.05757			U	0.045896501		0.015404708			U	NAS-ENC-VOC-23	0.01800		0.00440	J		U
OU3-3	24.5	CL	NAS-SC-VOC-365	0.13790		0.02410			U	0.048519087		0.0076847			U	NAS-ENC-VOC-24	0.00930			U		U
OU3-3	26.0	SP	NAS-SC-VOC-368	0.07331		0.00692			U	0.019160984		0.0038644			U	NAS-ENC-VOC-25	0.01300		0.00220	J	0.00280	J
OU3-3	29.0	SP	NAS-SC-VOC-371	0.00939		0.00301			U	0.003544603		0.001476918			U	NAS-ENC-VOC-26	0.00410	J		U		U
OU3-5D	14.2		NAS-SC-VOC-380	1.757147		1.500472		8.150918		3.072348006		0.80257254		1.108700853		NAS-ENC-VOC-27						
OU3-5D	16.0		NAS-SC-VOC-382	3.844125		0.234735		0.413093		0.406255012		0.22454718		3.199437918		NAS-ENC-VOC-28						
OU3-5D	17.5		NAS-SC-VOC-385	0.668457		0.089757		0.227400		0.072486825		0.033707865		0.412697624		NAS-ENC-VOC-29						
OU3-5D	21.5		NAS-SC-VOC-391	0.037408		0.052103		0.002099		0.00154324	J	0.031019131		0.030556159		NAS-ENC-VOC-30						
OU3-5D	23.5		NAS-SC-VOC-395	0.061073		0.150873		0.091290		0.069411157		0.122816545		0.056574847		NAS-ENC-VOC-31						
OU3-5D	27.0		NAS-SC-VOC-401	0.079899		0.091191		0.085374		0.024641993		0.037198422		0.04473228		NAS-ENC-VOC-32						

Notes:

1. Data were obtained using one of three methods and then compared: (i) Sampled in field using UG coring device, immediately preserved in the field in methanol, and then analyzed at UG Laboratory; (ii) Sampled in field using EnCore sampler; perserved in methanol after delay of 24 to 72 hr, and then analyzed at UG Laboratory; and (iii) Sampled in field using EnCore sampler with no methanol preservation; and then analyzed at a commercial laboratory (TestAmerica, Houston, TX).

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TABLE 11
COMPARISON OF RESULTS OBTAINED WITH DIFFERENT SOIL COLLECTION AND ANALYSES METHODS:
EnCore Sampling and Field Preservation

Determining Source Attenuation History to Support Closure by Natural Attenuation
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Sorted data for purpose of calculating relative percent difference

				UG Results (mg / kg wet soil) -- Field Methanol Preservation		UG Results (mg / kg wet soil) -- EnCore w/ Delayed Methanol Preservation (24 - 72 hr)					Test America Results (mg / kg wet soil) - EnCore No Preservation			
				Concentration	Log Conc	Concentration	Log Conc	arison w/ UG Field Preservation RPD	›-Directional RPD		Concentration	Log Conc	parison w/ UG Field Preservation RPD	›-Directional RPD
			UG Field ID							Encore Field ID				
PCE														
OU3-6	12.0	SP	NAS-SC-VOC-290			0.000301486	-0.520732717			NAS-ENC-VOC-01				
OU3-6	13.5	SP	NAS-SC-VOC-295	0.26481	2.42292791	0.095646974	1.980671237	-94%	94%	NAS-ENC-VOC-02	0.06000	1.77815125	-126%	126%
OU3-6	16.0	CL	NAS-SC-VOC-297	0.02238	1.34986761	0.083066148	1.919424072	115%	115%	NAS-ENC-VOC-03	0.01600	1.204119983	-33%	33%
OU3-6	17.0	CL	NAS-SC-VOC-299	0.02599	1.41484248	0.005963596	0.775508202	-125%	125%	NAS-ENC-VOC-04	0.00450	0.653212514	-141%	141%
OU3-6	17.5	CL	NAS-SC-VOC-301	0.00271	0.43326118	0.001479117	0.170002666	-59%	59%	NAS-ENC-VOC-05				
OU3-6	18.0	CL	NAS-SC-VOC-302	0.00214	0.33088933	0.001492809	0.17404204	-36%	36%	NAS-ENC-VOC-06	0.00140	0.146128036	-42%	42%
OU3-6	18.5	CL	NAS-SC-VOC-303	0.00097	-0.0117204	0.000593514	-0.22656879	-48%	48%	NAS-ENC-VOC-07				
OU3-6	21.0	CL	NAS-SC-VOC-305	0.00111	0.04713224	0.000764689	-0.116515218	-37%	37%	NAS-ENC-VOC-08				
OU3-6	23.0	CL	NAS-SC-VOC-310	0.00746	0.87292082	0.007398407	0.869138229	-1%	1%	NAS-ENC-VOC-09	0.00570	0.755874856	-27%	27%
OU3-6	24.0	CL	NAS-SC-VOC-312	0.05730	1.75818583	0.059207922	1.772379818	3%	3%	NAS-ENC-VOC-10	0.00950	0.977723605	-143%	143%
OU3-6	24.5	CL	NAS-SC-VOC-315	0.02585	1.41244391	0.01148686	1.060201332	-77%	77%	NAS-ENC-VOC-11	0.00630	0.799340549	-122%	122%
OU3-6	26.0	SP	NAS-SC-VOC-318	0.00035	-0.4617591	0.000292577	-0.533759509	-17%	17%	NAS-ENC-VOC-12				
OU3-6	28.0	SP	NAS-SC-VOC-322			0.000147039	-0.832565986			NAS-ENC-VOC-13				
OU3-3	8.5	SP	NAS-SC-VOC-331	0.00041	-0.3858204	0.000572897	-0.241923389	33%	33%	NAS-ENC-VOC-14				
OU3-3	11.5	SP	NAS-SC-VOC-334	0.33558	2.52579376	0.490568758	2.690699887	38%	38%	NAS-ENC-VOC-15	0.28000	2.447158031	-18%	18%
OU3-3	13.0	CL	NAS-SC-VOC-337	2.52238	3.40180977	3.157478919	3.49934046	22%	22%	NAS-ENC-VOC-16	3.50000	3.544068044	32%	32%
OU3-3	16.5	CL	NAS-SC-VOC-342	20.15838	4.30445567	12.05676961	4.081230962	-50%	50%	NAS-ENC-VOC-17	3.10000	3.491361694	-147%	147%
OU3-3	18.0	CL	NAS-SC-VOC-346	7.73939	3.88870665	7.405520917	3.869555613	-4%	4%	NAS-ENC-VOC-18	3.70000	3.568201724	-71%	71%
OU3-3	19.0	CL	NAS-SC-VOC-350	2.31497	3.36454597	1.642927377	3.215618367	-34%	34%	NAS-ENC-VOC-19	0.70000	2.84509804	-107%	107%
OU3-3	21.0	CL	NAS-SC-VOC-353	0.24472	2.38866537	0.245215276	2.389547521	0%	0%	NAS-ENC-VOC-20	0.04200	1.62324929	-141%	141%
OU3-3	22.0	CL	NAS-SC-VOC-357	0.02816	1.44968185	0.020249493	1.306414153	-33%	33%	NAS-ENC-VOC-21	0.00470	0.672097858	-143%	143%
OU3-3	23.0	CL	NAS-SC-VOC-360	0.05166	1.71315085	0.046758137	1.669857202	-10%	10%	NAS-ENC-VOC-22	0.01000	1	-135%	135%
OU3-3	24.0	CL	NAS-SC-VOC-363	0.15465	2.1893507	0.045896501	1.661779577	-108%	108%	NAS-ENC-VOC-23	0.01800	1.255272505	-158%	158%
OU3-3	24.5	CL	NAS-SC-VOC-365	0.13790	2.13956427	0.048519087	1.68591262	-96%	96%	NAS-ENC-VOC-24	0.00930	0.968482949	-175%	175%
OU3-3	26.0	SP	NAS-SC-VOC-368	0.07331	1.86515562	0.019160984	1.282417799	-117%	117%	NAS-ENC-VOC-25	0.01300	1.113943352	-140%	140%
OU3-3	29.0	SP	NAS-SC-VOC-371	0.00939	0.97288844	0.003544603	0.549567561	-90%	90%	NAS-ENC-VOC-26	0.00410	0.612783857	-78%	78%
OU3-5D	14.2		NAS-SC-VOC-380	1.757147	3.24480801	3.072348006	3.487470407	54%	54%	NAS-ENC-VOC-27				
OU3-5D	16.0		NAS-SC-VOC-382	3.844125	3.58479748	0.406255012	2.608798732	-162%	162%	NAS-ENC-VOC-28				
OU3-5D	17.5		NAS-SC-VOC-385	0.668457	2.82507318	0.072486825	1.860259078	-161%	161%	NAS-ENC-VOC-29				
OU3-5D	21.5		NAS-SC-VOC-391	0.037408	1.57295926	0.00154324	0.188433573	-184%	184%	NAS-ENC-VOC-30				
OU3-5D	23.5		NAS-SC-VOC-395	0.061073	1.78584668	0.069411157	1.841429285	13%	13%	NAS-ENC-VOC-31				
OU3-5D	27.0		NAS-SC-VOC-401	0.079899	1.90254059	0.024641993	1.391675828	-106%	106%	NAS-ENC-VOC-32				
TCE														
OU3-6	12.0	SP	NAS-SC-VOC-290	0.00012	-0.9366752	0.000301486	-0.520732717	89%	89%	NAS-ENC-VOC-01				
OU3-6	13.5	SP	NAS-SC-VOC-295	0.11758	2.07033315	0.060385417	1.78093207	-64%	64%	NAS-ENC-VOC-02	0.03300	1.51851394	-112%	112%
OU3-6	16.0	CL	NAS-SC-VOC-297	0.01609	1.20660149	0.068160821	1.833534811	124%	124%	NAS-ENC-VOC-03	0.01100	1.041392685	-38%	38%
OU3-6	17.0	CL	NAS-SC-VOC-299	0.01823	1.26086554	0.005672689	0.753788953	-105%	105%	NAS-ENC-VOC-04	0.00380	0.579783597	-131%	131%
OU3-6	17.5	CL	NAS-SC-VOC-301	0.00832	0.91992775	0.006064382	0.782786523	-31%	31%	NAS-ENC-VOC-05	0.00210	0.322219295	-119%	119%
OU3-6	18.0	CL	NAS-SC-VOC-302	0.01035	1.01513608	0.00507555	0.705483121	-68%	68%	NAS-ENC-VOC-06	0.00410	0.612783857	-87%	87%
OU3-6	18.5	CL	NAS-SC-VOC-303	0.00779	0.89136962	0.004451357	0.648492473	-55%	55%	NAS-ENC-VOC-07	0.00240	0.380211242	-106%	106%
OU3-6	21.0	CL	NAS-SC-VOC-305	0.02132	1.32873368	0.0137644	1.138757287	-43%	43%	NAS-ENC-VOC-08	0.00640	0.806179974	-108%	108%
OU3-6	23.0	CL	NAS-SC-VOC-310	0.09848	1.99335168	0.082484369	1.916371658	-18%	18%	NAS-ENC-VOC-09	0.02600	1.414973348	-116%	116%
OU3-6	24.0	CL	NAS-SC-VOC-312	0.19280	2.28509752	0.18271692	2.261778766	-5%	5%	NAS-ENC-VOC-10	0.03300	1.51851394	-142%	142%
OU3-6	24.5	CL	NAS-SC-VOC-315	0.06967	1.84306137	0.038102755	1.580956384	-59%	59%	NAS-ENC-VOC-11	0.01800	1.255272505	-118%	118%
OU3-6	26.0	SP	NAS-SC-VOC-318	0.00518	0.71433215	0.002779483	0.443964096	-60%	60%	NAS-ENC-VOC-12	0.00170	0.230448921	-101%	101%
OU3-6	28.0	SP	NAS-SC-VOC-322			0.000147039	-0.832565986			NAS-ENC-VOC-13				
OU3-3	8.5	SP	NAS-SC-VOC-331	0.00041	-0.3858204	0.000381931	-0.418014648	-7%	7%	NAS-ENC-VOC-14				
OU3-3	11.5	SP	NAS-SC-VOC-334	0.35603	2.55148287	0.967574824	2.985684559	92%	92%	NAS-ENC-VOC-15	0.49000	2.69019608	32%	32%
OU3-3	13.0	CL	NAS-SC-VOC-337	0.51353	2.71056638	0.801859757	2.904098418	44%	44%	NAS-ENC-VOC-16	0.86000	2.934498451	50%	50%
OU3-3	16.5	CL	NAS-SC-VOC-342	1.28659	3.10944166	0.94214677	2.974118564	-31%	31%	NAS-ENC-VOC-17	0.26000	2.414973348	-133%	133%
OU3-3	18.0	CL	NAS-SC-VOC-346	0.22113	2.3446386	0.219780772	2.341989695	-1%	1%	NAS-ENC-VOC-18	0.10000	2	-75%	75%
OU3-3	19.0	CL	NAS-SC-VOC-350	0.04689	1.6710521	0.037158777	1.570061411	-23%	23%	NAS-ENC-VOC-19	0.01400	1.146128036	-108%	108%
OU3-3	21.0	CL	NAS-SC-VOC-353	0.03546	1.54978332	0.029723064	1.473093572	-18%	18%	NAS-ENC-VOC-20	0.00580	0.763427994	-144%	144%
OU3-3	22.0	CL	NAS-SC-VOC-357	0.05854	1.76741754	0.037628979	1.575522435	-43%	43%	NAS-ENC-VOC-21	0.01100	1.041392685	-137%	137%
OU3-3	23.0	CL	NAS-SC-VOC-360	0.09715	1.9874466	0.079827215	1.902150977	-20%	20%	NAS-ENC-VOC-22	0.02300	1.361727836	-123%	123%
OU3-3	24.0	CL	NAS-SC-VOC-363	0.05757	1.76020031	0.015404708	1.187653468	-116%	116%	NAS-ENC-VOC-23	0.00440	0.643452676	-172%	172%
OU3-3	24.5	CL	NAS-SC-VOC-365	0.02410	1.38201704	0.0076847	0.885626924	-103%	103%	NAS-ENC-VOC-24				
OU3-3	26.0	SP	NAS-SC-VOC-368	0.00692	0.84033204	0.0038644	0.587082079	-57%	57%	NAS-ENC-VOC-25	0.00220	0.342422681	-104%	104%
OU3-3	29.0	SP	NAS-SC-VOC-371	0.00301	0.47803842	0.001476918	0.16935632	-68%	68%	NAS-ENC-VOC-26				
OU3-5D	14.2		NAS-SC-VOC-380	1.500472	3.17622802	0.80257254	2.904484296	-61%	61%	NAS-ENC-VOC-27				
OU3-5D	16.0		NAS-SC-VOC-382	0.234735	2.37057853	0.22454718	2.351307604	-4%	4%	NAS-ENC-VOC-28				
OU3-5D	17.5		NAS-SC-VOC-385	0.089757	1.95307034	0.033707865	1.527731248	-91%	91%	NAS-ENC-VOC-29				
OU3-5D	21.5		NAS-SC-VOC-391	0.052103	1.71686584	0.031019131	1.49162963	-51%	51%	NAS-ENC-VOC-30				
OU3-5D	23.5		NAS-SC-VOC-395	0.150873	2.17861102	0.122816545	2.089256877	-21%	21%	NAS-ENC-VOC-31				
OU3-5D	27.0		NAS-SC-VOC-401	0.091191	1.95995092	0.037198422	1.570524521	-84%	84%	NAS-ENC-VOC-32				
cis-DCE														
OU3-6	12.0	SP	NAS-SC-VOC-290	0.59480	2.77437239	0.45328434	2.656370715	-27%	27%	NAS-ENC-VOC-01	0.26000	2.414973348	-78%	78%
OU3-6	13.5	SP	NAS-SC-VOC-295	2.94302	3.46879252	2.07690573	3.317416785	-35%	35%	NAS-ENC-VOC-02	0.85000	2.929418926	-110%	110%
OU3-6	16.0	CL	NAS-SC-VOC-297	1.57070	3.19609222	1.125507492	3.05134839	-33%	33%	NAS-ENC-VOC-03	0.28000	2.447158031	-139%	139%
OU3-6	17.0	CL	NAS-SC-VOC-299	0.34934	2.5432514	0.162035262	2.209609536	-73%	73%	NAS-ENC-VOC-04	0.07500	1.875061263	-129%	129%
OU3-6	17.5	CL	NAS-SC-VOC-301	0.15494	2.19015074	0.145840982	2.163879581	-6%	6%	NAS-ENC-VOC-05	0.04800	1.681241237	-105%	105%
OU3-6	18.0	CL	NAS-SC-VOC-302	0.09301	1.96854581	0.054039681	1.732712774	-53%	53%	NAS-ENC-VOC-06	0.04200	1.62324929	-76%	76%
OU3-6	18.5	CL	NAS-SC-VOC-303	0.05029	1.70149008	0.029082202	1.46362729	-53%	53%	NAS-ENC-VOC-07	0.01400	1.146128036	-113%	113%
OU3-6	21.0	CL	NAS-SC-VOC-305	0.03149	1.49815069	0.025081796	1.399358626	-23%	23%	NAS-ENC-VOC-08	0.01000	1	-104%	104%
OU3-6	23.0	CL	NAS-SC-VOC-310	0.02661	1.42500684	0.019991441	1.300844092	-28%	28%	NAS-ENC-VOC-09	0.00820	0.913813852	-106%	106%
OU3-6	24.0	CL	NAS-SC-VOC-312	0.03742	1.57313973	0.037721176	1.576585224	1%	1%	NAS-ENC-VOC-10	0.00730	0.86332286	-135%	135%
OU3-6	24.5	CL	NAS-SC-VOC-315	0.03389	1.53013215	0.016389788	1.214573341	-70%	70%	NAS-ENC-VOC-11	0.00760	0.880813592	-127%	127%
OU3-6	26.0	SP	NAS-SC-VOC-318	0.07822	1.8933091	0.050030703	1.699236601	-44%	44%	NAS-ENC-VOC-12	0.02300	1.361727836	-109%	109%
OU3-6	28.0	SP	NAS-SC-VOC-322	0.03738	1.57269582	0.02352632	1.371553997	-46%	46%	NAS-ENC-VOC-13	0.01400	1.146128036	-91%	91%
OU3-3	8.5	SP	NAS-SC-VOC-331	0.73585	2.86678991	0.722996119	2.859135966	-2%	2%	NAS-ENC-VOC-14	0.29000	2.462397998	-87%	87%
OU3-3	11.5	SP	NAS-SC-VOC-334	0.34069	2.53235989	1.922665805	3.283903802	140%	140%	NAS-ENC-VOC-15	0.59000	2.770852012	54%	54%
OU3-3	13.0	CL	NAS-SC-VOC-337	0.24170	2.38327707	0.478680299	2.680045554	66%	66%	NAS-ENC-VOC-16	0.44000	2.643452676	58%	58%
OU3-3	16.5	CL	NAS-SC-VOC-342	0.50787	2.70574932	0.368731563	2.566710315	-32%	32%	NAS-ENC-VOC-17	0.10000	2	-134%	134%
OU3-3	18.0	CL	NAS-SC-VOC-346	0.08332	1.92076286	0.082612631	1.917046452	-1%	1%	NAS-ENC-VOC-18	0.03700	1.568201724	-77%	77%
OU3-3	19.0	CL	NAS-SC-VOC-350	0.01582	1.19913204	0.014234209	1.153333336	-11%	11%	NAS-ENC-VOC-19	0.00440	0.643452676	-113%	113%
OU3-3	21.0	CL	NAS-SC-VOC-353							NAS-ENC-VOC-20	0.00120	0.079181246		
OU3-3	22.0	CL	NAS-SC-VOC-357							NAS-ENC-VOC-21	0.00160	0.204119983		
OU3-3	23.0	CL	NAS-SC-VOC-360							NAS-ENC-VOC-22	0.00220	0.342422681		
OU3-3	24.0	CL	NAS-SC-VOC-363							NAS-ENC-VOC-23				
OU3-3	24.5	CL	NAS-SC-VOC-365							NAS-ENC-VOC-24				
OU3-3	26.0	SP	NAS-SC-VOC-368							NAS-ENC-VOC-25	0.00280	0.44715803		
OU3-3	29.0	SP	NAS-SC-VOC-371							NAS-ENC-VOC-26				
OU3-5D	14.2		NAS-SC-VOC-380	8.150918	3.91120652	1.108700853	3.044814382	-152%	152%	NAS-ENC-VOC-27				
OU3-5D	16.0		NAS-SC-VOC-382	0.413093	2.61604809	3.199437918	3.505073688	154%	154%	NAS-ENC-VOC-28				
OU3-5D	17.5		NAS-SC-VOC-385	0.227400	2.35679002	0.412697624	2.615631968	58%	58%	NAS-ENC-VOC-29				
OU3-5D	21.5		NAS-SC-VOC-391	0.002099	0.32209588	0.030556159	1.485098763	174%	174%	NAS-ENC-VOC-30				
OU3-5D	23.5		NAS-SC-VOC-395	0.091290	1.96042207	0.056574847	1.752623391	-47%	47%	NAS-ENC-VOC-31				
OU3-5D	27.0		NAS-SC-VOC-401	0.085374	1.93132426	0.04473228	1.650621035	-62%	62%	NAS-ENC-VOC-32				
						Median RPD		**-33%**	**49%**				**-110%**	**110%**
			Number of ND		**9**	**Number of ND**		**7**					**15**	

Notes:
1. Data were obtained using one of three methods and then compared: (i) Sampled in field using UG coring device, immediately preserved in the field in methanol, and then analyzed at UG Laboratory; (ii) Sampled in field using EnCore sampler; perserved in methanol after delay of 24 to 72 hr, and then analyzed at UG Laboratory; and (iii) Sampled in field using EnCore sampler with no methanol preservation; and then analyzed at a commercial laboratory (TestAmerica, Houston, TX).

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TABLE J.2
COMPARISON OF RESULTS OBTAINED WITH DIFFERENT SOIL COLLECTION AND ANALYSES METHODS:
Field Extraction Methods and Field Duplicates at Different Laboratories
Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

				UG Results (µg / kg wet soil) -- Field duplicates extracted and analyzed separately							Stone Results (µg / kg wet soil) -- Rapid Field Extraction						RPD (%)			UG Results (µg / kg wet soil) -- Splits of methanol extract taken from Stone Rapid Field Extraction (Field Duplicates at Different Labs)						RPD (%)		
Borehole ID	Depth (ft bgs)	Lithology	UG Field ID	PCE	Flag	TCE	Flag	cis-DCE	Flag	Stone Field ID	PCE	Flag	TCE	Flag	cis-DCE	Flag	PCE	TCE	cis-DCE	PCE	Flag	TCE	Flag	cis-DCE	Flag	PCE	TCE	cis-DCE
OU3-6	12.0	SP	NAS-SC-VOC-290		U	0.1	J	594.8		NAS-STONE-VOC-001		U		U	560		-	-	-6.0	0.0858	J	0.1716	J	584.6917				4.3
OU3-6	13.5	SP	NAS-SC-VOC-295	264.8		117.6		2943.0		NAS-STONE-VOC-002	250		110		2400		-5.8	-6.7	-20.3	270.4473		113.9060		3043.0090		7.9	3.5	23.6
OU3-6	26.0	SP	NAS-SC-VOC-318	0.3	J	5.2		78.2		NAS-STONE-VOC-013		U		U	64	J	-	-	-20.0	0.3518	J	4.3977		73.7063				14.1
OU3-6	28.0	SP	NAS-SC-VOC-322		U		U	37.4		NAS-STONE-VOC-014		U		U		U	-	-	-	0.3374	J		U	32.0521				
OU3-3	8.5	SP	NAS-SC-VOC-331	0.4	J	0.4	J	735.9		NAS-STONE-VOC-015		U		U	680		-	-	-7.9	0.3253	J		U	803.4166				16.6
OU3-3	11.5	SP	NAS-SC-VOC-334	335.6		356.0		340.7		NAS-STONE-VOC-016	1200		1600		1700		112.6	127.2	133.2	984.5553		1240.0356		1291.3055		-19.7	-25.3	-27.3
OU3-3	26.0	SP	NAS-SC-VOC-368	73.3		6.9			U	NAS-STONE-VOC-026	50	J		U		U	-37.8	-	-	52.5095		7.4725		9.6941	J	4.9		
OU3-3	29.0	SP	NAS-SC-VOC-371	9.4		3.0			U	NAS-STONE-VOC-027		U		U		U	-	-	-	7.5138		2.7958			U			
OU3-6	16.0	CL	NAS-SC-VOC-297	22.4		16.1		1570.7		NAS-STONE-VOC-003		U		U	1400		-	-	-11.5	13.7010		12.1995		1543.1446				9.7
OU3-6	17.0	CL	NAS-SC-VOC-299	26.0		18.2		349.3		NAS-STONE-VOC-004		U		U	270		-	-	-25.6	10.4790		10.2755		248.7488				-8.2
OU3-6	17.5	CL	NAS-SC-VOC-301	2.7		8.3		154.9		NAS-STONE-VOC-005		U		U	170		-	-	9.3	1.8352		7.6743		148.6477				-13.4
OU3-6	18.0	CL	NAS-SC-VOC-302	2.1		10.4		93.0		NAS-STONE-VOC-006		U		U	94	J	-	-	1.1	1.6388	J	9.2868		95.0533				1.1
OU3-6	18.5	CL	NAS-SC-VOC-303	1.0	J	7.8		50.3		NAS-STONE-VOC-007		U		U	50	J	-	-	-0.6	0.9904	J	7.9231		56.2538				11.8
OU3-6	21.0	CL	NAS-SC-VOC-305	1.1	J	21.3		31.5		NAS-STONE-VOC-008		U		U		U	-	-	-	0.7733	J	14.8471		22.1160				
OU3-6	22.0	CL	NAS-SC-VOC-308	2.4		53.6		32.0		NAS-STONE-VOC-009		U	40	J	28	J	-	-29.1	-13.3	1.6019	J	40.7583		28.4774			1.9	1.7
OU3-6	23.0	CL	NAS-SC-VOC-310	7.5		98.5		26.6		NAS-STONE-VOC-010		U	68	J		U	-	-36.6	-	5.4902		78.1545		22.1222			13.9	
OU3-6	24.0	CL	NAS-SC-VOC-312	57.3		192.8		37.4		NAS-STONE-VOC-011	53	J	140		34	J	-7.8	-31.7	-9.6	41.2613		156.6838		33.9906		-24.9	11.2	0.0
OU3-6	24.5	CL	NAS-SC-VOC-315	25.8		69.7		33.9		NAS-STONE-VOC-012		U	47	J	27	J	-	-38.9	-22.6	17.0878		54.3987		27.9048			14.6	3.3
OU3-3	13.0	CL	NAS-SC-VOC-337	2522.4		513.5		241.7		NAS-STONE-VOC-017	8600		2400		1000		109.3	129.5	122.1	10077.7747		2194.6374		1130.6772		15.8	-8.9	12.3
OU3-3	16.5	CL	NAS-SC-VOC-342	20158.4		1286.6		507.9		NAS-STONE-VOC-018	12000		1100		440		-50.7	-15.6	-14.3	15189.1974		1104.6689		401.3630		23.5	0.4	-9.2
OU3-3	17.7	CL	NAS-SC-VOC-345	13368.3		410.0		139.2	J	NAS-STONE-VOC-019	7900		290		110	J	-51.4	-34.3	-23.4	10691.6299		305.2813			U	30.0	5.1	
OU3-3	18.0	CL	NAS-SC-VOC-346	7739.4		221.1		83.3		NAS-STONE-VOC-020	5600		180		68	J	-32.1	-20.5	-20.3	5310.1192		160.9127			U	-5.3	-11.2	
OU3-3	19.0	CL	NAS-SC-VOC-350	2315.0		46.9		15.8	J	NAS-STONE-VOC-021	1400			U		U	-49.3	-	-	2158.5249		42.3374			U	42.6		
OU3-3	21.0	CL	NAS-SC-VOC-353	244.7		35.5			U	NAS-STONE-VOC-022	190			U		U	-25.2	-	-	236.3022		32.5858			U	21.7		
OU3-3	22.0	CL	NAS-SC-VOC-357	28.2		58.5			U	NAS-STONE-VOC-023		U		U		U	-	-	-	20.9310		45.3872			U			
OU3-3	23.0	CL	NAS-SC-VOC-360	51.7		97.2			U	NAS-STONE-VOC-024	36	J	58	J		U	-35.7	-50.5	-	30.2627		67.5631		7.5657	J	-17.3	15.2	
OU3-3	24.0	CL	NAS-SC-VOC-363	154.7		57.6			U	NAS-STONE-VOC-025	100		35	J		U	-42.9	-48.8	-	75.6566		35.3860		4.3418	J	-27.7	1.1	

Notes:

1. Data were obtained using one of three methods and then compared: (i) Sampled in field using UG coring device, immediately preserved in the field in methanol, and then analyzed at UG Laboratory; (ii) Sampled in field using UG sampler; extracted immediately in field using Stone rapid extraction method, and then analyzed at Stone Laboratory; and (iii) Sampled in field using UG sampler; extracted immediately in field using Stone rapid extraction method, and then split of methanol extract was analyzed at UG Laboratory.

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TABLE J.3
COMPARISON OF RESULTS OBTAINED WITH DIFFERENT SOIL COLLECTION AND ANALYSES METHODS:
Field Extraction Methods and Field Duplicates at Different Laboratories
Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

					For separate samples (different labs)			For methanol extracts (different labs)			For seaparate samples (same labs)		
					RPD (%)			RPD (%)			RPD (%)		
UG Field ID	Stone Field ID	Borehole ID	Depth (ft bgs)	Lithology	PCE	TCE	cis-DCE	PCE	TCE	cis-DCE	PCE	TCE	cis-DCE
NAS-SC-VOC-290	NAS-STONE-VOC-001	OU3-6	12.0	SP	-	-	6.0	-	-	4.3		-38.9	1.7
NAS-SC-VOC-295	NAS-STONE-VOC-002	OU3-6	13.5	SP	5.8	6.7	20.3	7.9	3.5	23.6	-2.1	3.2	-3.3
NAS-SC-VOC-318	NAS-STONE-VOC-013	OU3-6	26.0	SP	-	-	20.0	-	-	14.1	-1.9	16.3	5.9
NAS-SC-VOC-322	NAS-STONE-VOC-014	OU3-6	28.0	SP	-	-	-	-	-	-			15.4
NAS-SC-VOC-331	NAS-STONE-VOC-015	OU3-3	8.5	SP	-	-	7.9	-	-	16.6	23.4		-8.8
NAS-SC-VOC-334	NAS-STONE-VOC-016	OU3-3	11.5	SP	-112.6	-127.2	-133.2	-19.7	-25.3	-27.3	-98.3	-110.8	-116.5
NAS-SC-VOC-368	NAS-STONE-VOC-026	OU3-3	26.0	SP	37.8	-	-	4.9	-	-	33.1	-7.6	
NAS-SC-VOC-371	NAS-STONE-VOC-027	OU3-3	29.0	SP	-	-	-	-	-	-	22.2	7.3	
NAS-SC-VOC-297	NAS-STONE-VOC-003	OU3-6	16.0	CL	-	-	11.5	-	-	9.7	48.1	27.5	1.8
NAS-SC-VOC-299	NAS-STONE-VOC-004	OU3-6	17.0	CL	-	-	25.6	-	-	-8.2	85.1	55.8	33.6
NAS-SC-VOC-301	NAS-STONE-VOC-005	OU3-6	17.5	CL	-	-	-9.3	-	-	-13.4	38.6	8.0	4.1
NAS-SC-VOC-302	NAS-STONE-VOC-006	OU3-6	18.0	CL	-	-	-1.1	-	-	1.1	26.6	10.9	-2.2
NAS-SC-VOC-303	NAS-STONE-VOC-007	OU3-6	18.5	CL	-	-	0.6	-	-	11.8	-1.7	-1.7	-11.2
NAS-SC-VOC-305	NAS-STONE-VOC-008	OU3-6	21.0	CL	-	-	-	-	-	-	36.2	35.8	35.0
NAS-SC-VOC-308	NAS-STONE-VOC-009	OU3-6	22.0	CL	-	29.1	13.3	-	1.9	1.7	39.2	27.3	11.7
NAS-SC-VOC-310	NAS-STONE-VOC-010	OU3-6	23.0	CL	-	36.6	-	-	13.9	-	30.5	23.0	18.4
NAS-SC-VOC-312	NAS-STONE-VOC-011	OU3-6	24.0	CL	7.8	31.7	9.6	-24.9	11.2	0.0	32.6	20.7	9.6
NAS-SC-VOC-315	NAS-STONE-VOC-012	OU3-6	24.5	CL	-	38.9	22.6	-	14.6	3.3	40.8	24.6	19.4
NAS-SC-VOC-337	NAS-STONE-VOC-017	OU3-3	13.0	CL	-109.3	-129.5	-122.1	15.8	-8.9	12.3	-119.9	-124.2	-129.6
NAS-SC-VOC-342	NAS-STONE-VOC-018	OU3-3	16.5	CL	50.7	15.6	14.3	23.5	0.4	-9.2	28.1	15.2	23.4
NAS-SC-VOC-345	NAS-STONE-VOC-019	OU3-3	17.7	CL	51.4	34.3	23.4	30.031	5.1	-	22.2	29.3	
NAS-SC-VOC-346	NAS-STONE-VOC-020	OU3-3	18.0	CL	32.1	20.5	20.3	-5.3	-11.2	-	37.2	31.5	
NAS-SC-VOC-350	NAS-STONE-VOC-021	OU3-3	19.0	CL	49.3	-	-	42.6	-	-	7.0	10.2	
NAS-SC-VOC-353	NAS-STONE-VOC-022	OU3-3	21.0	CL	25.2	-	-	21.7	-	-	3.5	8.5	
NAS-SC-VOC-357	NAS-STONE-VOC-023	OU3-3	22.0	CL	-	-	-	-	-	-	29.5	25.3	
NAS-SC-VOC-360	NAS-STONE-VOC-024	OU3-3	23.0	CL	35.7	50.5	-	-17.3	15.2	-	52.2	35.9	
NAS-SC-VOC-363	NAS-STONE-VOC-025	OU3-3	24.0	CL	42.9	48.8	-	-27.7	1.1	-	68.6	47.7	
					MEDIAN FOR ALL VOCS		20.3	MEDIAN FOR ALL VOCS		3.5	MEDIAN FOR ALL VOCS		18.9

Notes:

1. Data were obtained using one of three methods and then compared: (i) Sampled in field using UG coring device, immediately preserved in the field in methanol, and then analyzed at UG Laboratory; (ii) Sampled in field using UG sampler; extracted immedi using Stone rapid extraction method, and then analyzed at Stone Laboratory; and (iii) Sampled in field using UG sampler; extracted immediately in field using Stone rapid extraction method, and then split of methanol extract was analyzed at UG Laborato

GSI ENVIRONMENTAL

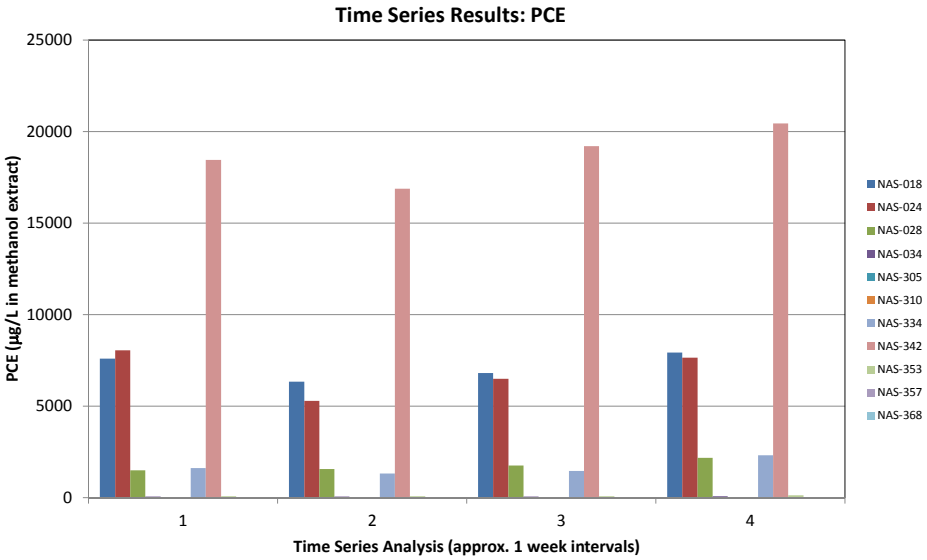
TABLE J.4
COMPARISON OF RESULTS OBTAINED WITH DIFFERENT SOIL COLLECTION AND ANALYSES METHODS:
Field Duplicates at Same Laboratory

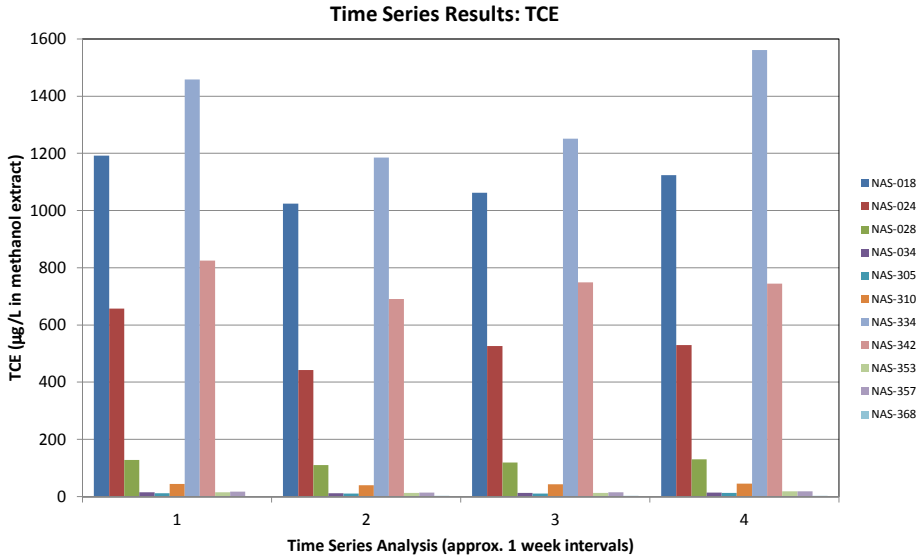
Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

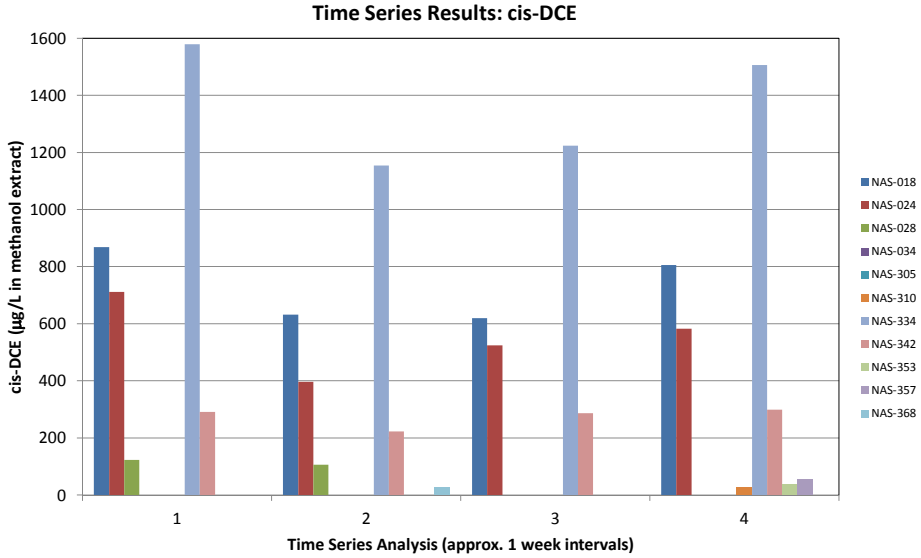
				Results for Original Sample						Results for Duplicate Sample						Relative Standard Deviation Between Duplicates			
Field ID	Duplicate ID	Borehole ID	Depth (ft bgs)	PCE	Flag	TCE	Flag	cis-DCE	Flag	PCE	Flag	TCE	Flag	cis-DCE	Flag	PCE RSD	TCE RSD	cis-DCE RSD	All Compounds
NAS-SC-VOC-113	NAS-SC-VOC-114	OU3-5	34	0.000254	J	0.000254	J	0.023539		0.0002204	J	0.0002204	J	0.0213791		10%	10%	7%	
NAS-SC-VOC-127	NAS-SC-VOC-128	OU3-9	13.5		U	0.010064		0.262144			U	0.0016955	J	0.2235923			101%	11%	
NAS-SC-VOC-144	NAS-SC-VOC-145	OU3-9	22	0.031566		2.490323		4.040767		0.0287038		2.4277047		4.1352627		7%	2%	2%	
NAS-SC-VOC-149	NAS-SC-VOC-150	OU3-9	24	0.025302		2.14801		3.213618		0.0270571		2.2200057		3.2816137		5%	2%	1%	
NAS-SC-VOC-169	NAS-SC-VOC-170	OU3-9	36.5		U		U		U		U		U		U				
NAS-SC-VOC-192	NAS-SC-VOC-193	OU3-10	19	0.002307	J	0.480261		0.608155		0.0025758	J	0.5747181		0.7128436		8%	13%	11%	
NAS-SC-VOC-20	NAS-SC-VOC-21	OU3-4	16	19.9879		2.756561		1.839598		17.432929		2.30186		1.5208048		10%	13%	13%	
NAS-SC-VOC-202	NAS-SC-VOC-203	OU3-10	25.5	0.00846		1.868988		0.067245		0.008913		1.9821009		0.0667527		4%	4%	1%	
NAS-SC-VOC-242	NAS-SC-VOC-243	OU3-11	22.5	0.000502	J	0.07347		0.029839		0.0016094	J	0.0638411		0.0270922		74%	10%	7%	
NAS-SC-VOC-252	NAS-SC-VOC-253	OU3-11	27	0.000873	J	0.119404		0.043991		0.0007567	J	0.121533		0.0446479		10%	1%	1%	
NAS-SC-VOC-266	NAS-SC-VOC-267	OU3-11	33.5		U	0.012338		0.012013	J		U	0.0112162		0.0114096	J		7%	4%	
NAS-SC-VOC-29	NAS-SC-VOC-30	OU3-4	18.7	3.498113		0.316169		0.21843		3.8618337		0.3362886		0.2284855		7%	4%	3%	
NAS-SC-VOC-299	NAS-SC-VOC-300	OU3-6	17	0.035514		0.024912		0.477312		0.0333346		0.0342479		0.4721641		4%	22%	1%	
NAS-SC-VOC-306	NAS-SC-VOC-307	OU3-6	21.5	0.002151	J	0.046847		0.043501		0.0021126		0.0420761		0.0424282		1%	8%	2%	
NAS-SC-VOC-348	NAS-SC-VOC-349	OU3-3	18.7	4.753798		0.099615			U	4.1653613		0.0854433			U	9%	11%		
NAS-SC-VOC-355	NAS-SC-VOC-356	OU3-3	21.67	0.092621		0.084614		0.009342	J	0.09173		0.0880706		0.0100025	J	1%	3%	5%	
NAS-SC-VOC-385	NAS-SC-VOC-386	OU3-5D	17.5	0.312857		0.123488		0.919663		0.37974		0.1375938		0.9636286		14%	8%	3%	
NAS-SC-VOC-395	NAS-SC-VOC-396	OU3-5D	23.5	0.132281		0.218618		0.088496		0.1611067		0.2550856		0.0961366		14%	11%	6%	
NAS-SC-VOC-402	NAS-SC-VOC-403	OU3-5D	28	0.06561		0.100391		0.19272		0.0714428		0.1104447		0.2196136		6%	7%	9%	
NAS-SC-VOC-60	NAS-SC-VOC-61	OU3-5	8	0.00161	J	0.001932	J	4.50524		0.0006196	J	0.0024786	J	5.3623754		63%	18%	12%	
NAS-SC-VOC-80	NAS-SC-VOC-81	OU3-5	18	1.942482		0.406296		0.551551		1.3811828		0.3015881		0.4697217		24%	21%	11%	
NAS-SC-VOC-94	NAS-SC-VOC-95	OU3-5	24	0.038515		0.167134		0.044934		0.0361003		0.1580789		0.0396879		5%	4%	9%	
														MEDIAN VALUES		7.8%	7.6%	5.3%	6.9%

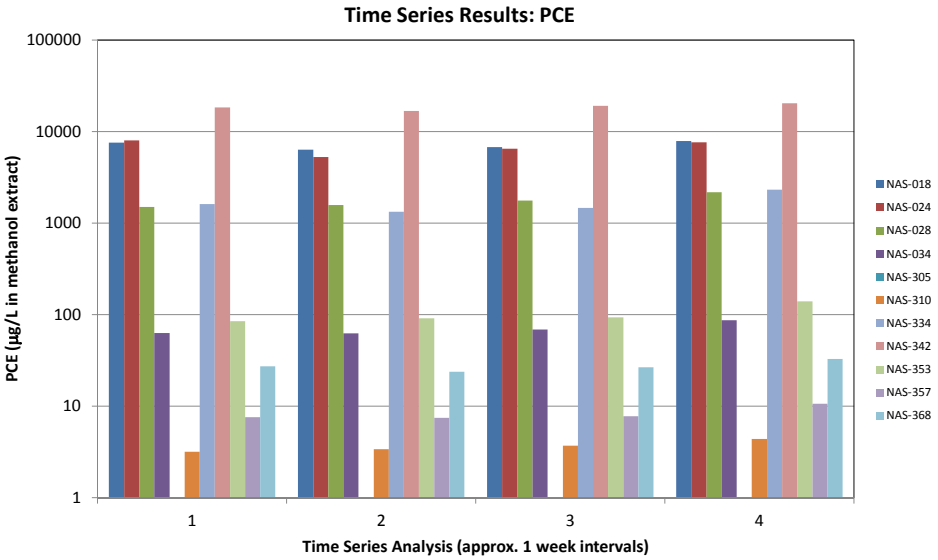
Notes:

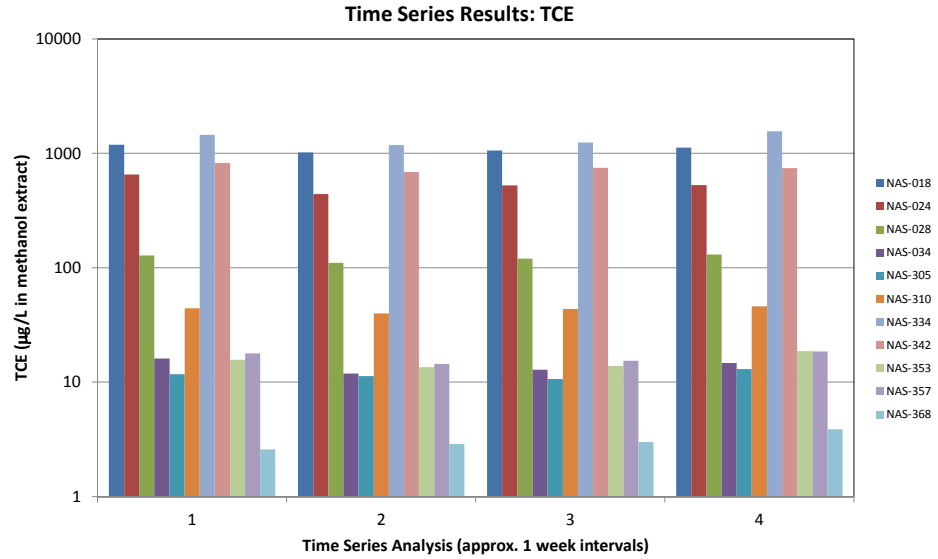
1. All data were obtained using the baseline method: (i) Sampled in field using UG coring device, immediately preserved in the field in methanol, and then analyzed at UG Laboratory (both the original and the duplicate samples).

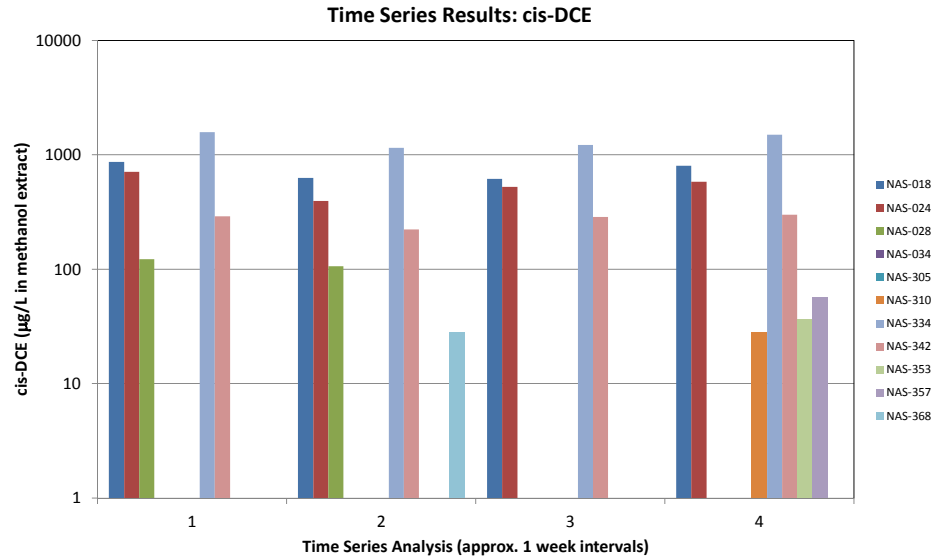

Time Series Results: PCE
PCE (µg/L in methanol extract)
25000
20000
15000
10000
5000
0
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368


Time Series Results: TCE
TCE (µg/L in methanol extract)
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368


Time Series Results: cis-DCE
cis-DCE (µg/L in methanol extract)
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368


Time Series Results: PCE
100000
10000
1000
100
10
1
PCE (µg/L in methanol extract)
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368


Time Series Results: TCE
10000
1000
100
10
1
TCE (µg/L in methanol extract)
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368


Time Series Results: cis-DCE
10000
1000
100
10
1
cis-DCE (µg/L in methanol extract)
1
2
3
4
Time Series Analysis (approx. 1 week intervals)
NAS-018
NAS-024
NAS-028
NAS-034
NAS-305
NAS-310
NAS-334
NAS-342
NAS-353
NAS-357
NAS-368

APPENDIX K

Other Groundwater Data from Demonstration Project

TABLE K.1
SUMMARY OF GROUNDWATER DATA COLLECTED USING GEOPROBE SP16 AND TEMPORARY PIEZOMETERS
Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

					VOCs in Groundwater (µg/L)					Dissolved Gases (µg/L)			Anions (mg/L)		Cations (mg/L)
Field ID	Location ID	Depth (ft bgs)	Average Depth (ft bgs)	Average Depth (m bgs)	PCE	TCE	cis-DCE	VC	Total CVOCs	Ethane	Ethene	Methane	Chloride	Sulfate	Iron
NAS-GW-CVOC-OU3-3 7.0-10.5 ft	OU3-3	7.0 - 10.5	8.75	2.67	620	637	13661	40	14958	0.501	2.73	135	24	13	13
NAS-GW-CVOC-OU3-3 11.5-15.0 ft	OU3-3	11.5 - 15.0	13.25	4.04	5598	5331	21481	220	32630	0.348	4.83	196	82	20	20
NAS-GW-CVOC-OU3-3 15.5-19.0 ft	OU3-3	15.5 - 19.0*	16.5	5.03	22945	6674	6237	471	36327	0.406	3.54	357	4400	78	78
NAS-GW-CVOC-OU3-3 17.0-19.0 ft	OU3-3	17.0 - 19.0	18	5.49	41505	6590	4813	464	53372	0.442	2.46	80.5	3800	110	110
NAS-GW-CVOC-OU3-3 19.5-21.5 ft	OU3-3	19.5 - 21.5	20.5	6.25	17670	4413	4517	100	26700	1.99	5.18	94.9	3400	180	180
NAS-GW-CVOC-OU3-3 22.0-24.0 ft	OU3-3	22.0 - 24.0	23	7.01	41630	5957	2984	398	50969	0.655	3.25	138	4000	120	120
NAS-GW-CVOC-OU3-3 24.5-28.0 ft	OU3-3	24.5 - 28.0	26.25	8.00	760	7	20	1	787	0.0615	0.0691	141	560	23	23
NAS-GW-CVOC-OU3-5 8.5-12.0 ft	OU3-5	8.5 - 12.0	10.25	3.12	817	158	29564	1395	31934	0.383	47.7	706	91	39	39
NAS-GW-CVOC-OU3-5 12.5-16.0 ft	OU3-5	12.5 - 16.0	14.25	4.34	19516	7415	27872	7287	62090	0.18	346	2665	2700	69	69
NAS-GW-CVOC-OU3-5 16.0-18.0 ft	OU3-5	16.0 - 18.0	17	5.18	18156	3350	11834	582	33922	0.933	58.8	782	2500	56	56
NAS-GW-CVOC-OU3-5 19.0-21.0 ft	OU3-5	19.0 - 21.0	20	6.10	1930	299	1316	50	3594	10.7	33.5	141	640	60	60
NAS-GW-CVOC-OU3-5 22.0-24.0 ft	OU3-5	22.0 - 24.0	23	7.01	297	173	311	5	786	0.529	2.69	1890	270	15	15
NAS-GW-CVOC-OU3-5 24.5-28.0 ft	OU3-5	24.5 - 28.0	26.25	8.00	348	364	893	5	1610	0.0615	0.321	6490	480	20	20
NAS-GW-CVOC-OU3-6 8.5-12.0 ft	OU3-6	8.5 - 12.0	10.25	3.12	7	2	2128	756	2892	0.0615	45.6	2750	68	61	61
NAS-GW-CVOC-OU3-6 12.5-16.0 ft	OU3-6	12.5 - 16.0	14.25	4.34	1134	175	11160	3821	16290	0.0615	144	6110	480	44	44
NAS-GW-CVOC-OU3-6 16.0-18.0 ft	OU3-6	16.0 - 18.0	17	5.18	4032	1288	18881	4764	28965	0.532	86.5	1820	1300	52	52
NAS-GW-CVOC-OU3-6 19.0-21.0 ft	OU3-6	19.0 - 21.0	20	6.10	192	69	2186	143	2590	0.0615	14.6	2370	240	17	17
NAS-GW-CVOC-OU3-6 22.0-24.0 ft	OU3-6	22.0 - 24.0	23	7.01	73	104	189	198	563	0.474	2.56	396	91	12	12
NAS-GW-CVOC-OU3-6 25.0-28.5 ft	OU3-6	25.0 - 28.5	26.75	8.15	17	18	1085	73	1194	0.0615	0.824	608	220	39	39

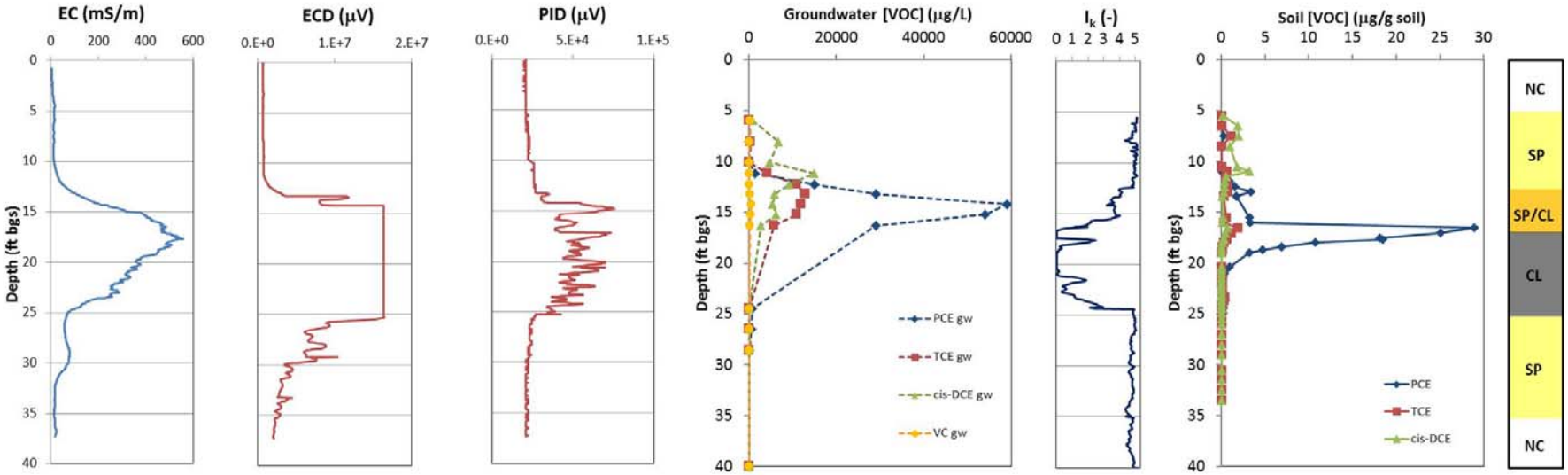
Notes:
1. Yellow highlighted values below MDL (MDL reported)
2. Average depth for OU3-3 15.5-19.0 ft sample adjusted to account for most groundwater coming from interval above clay
3. For depths where duplicate samples were collected, reported concentrations represent the average of two analyses

APPENDIX L

Composite Plots of Characterization Data from Demonstration Project

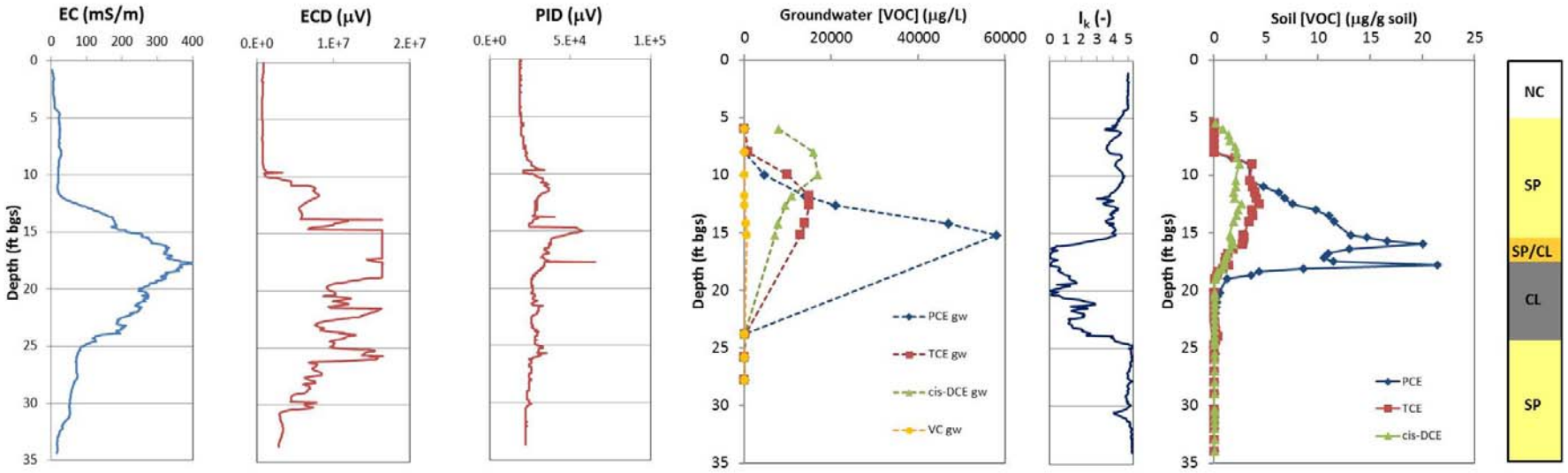
(a) **OU3-3**

MIP	Waterloo APS™	Cores



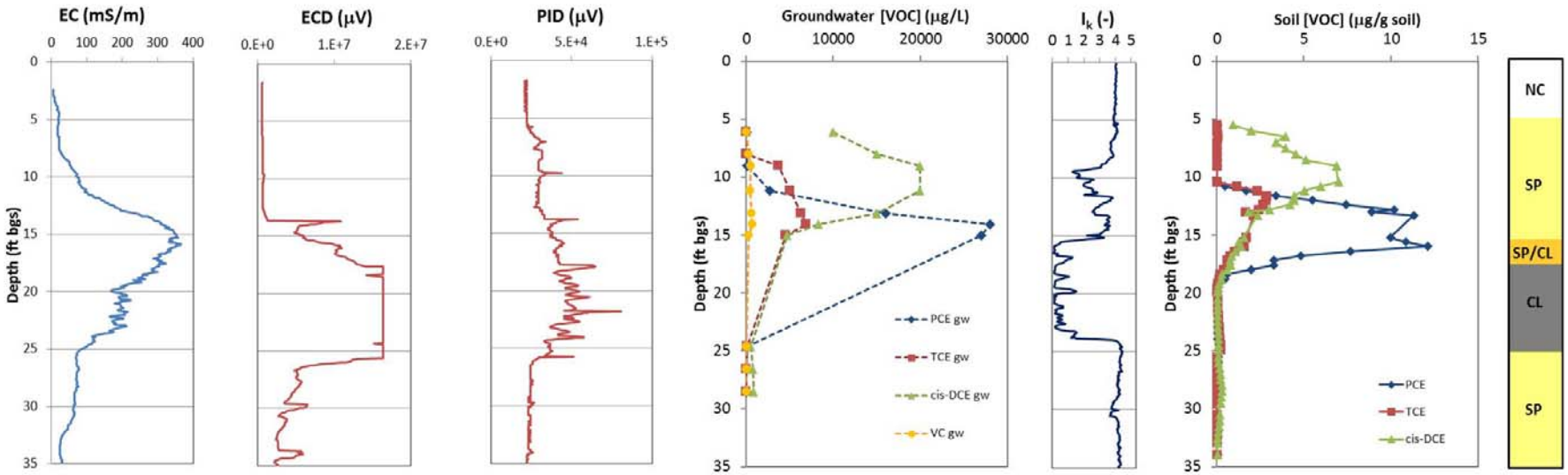
(b) **OU3-4**

MIP	Waterloo APS™	Cores



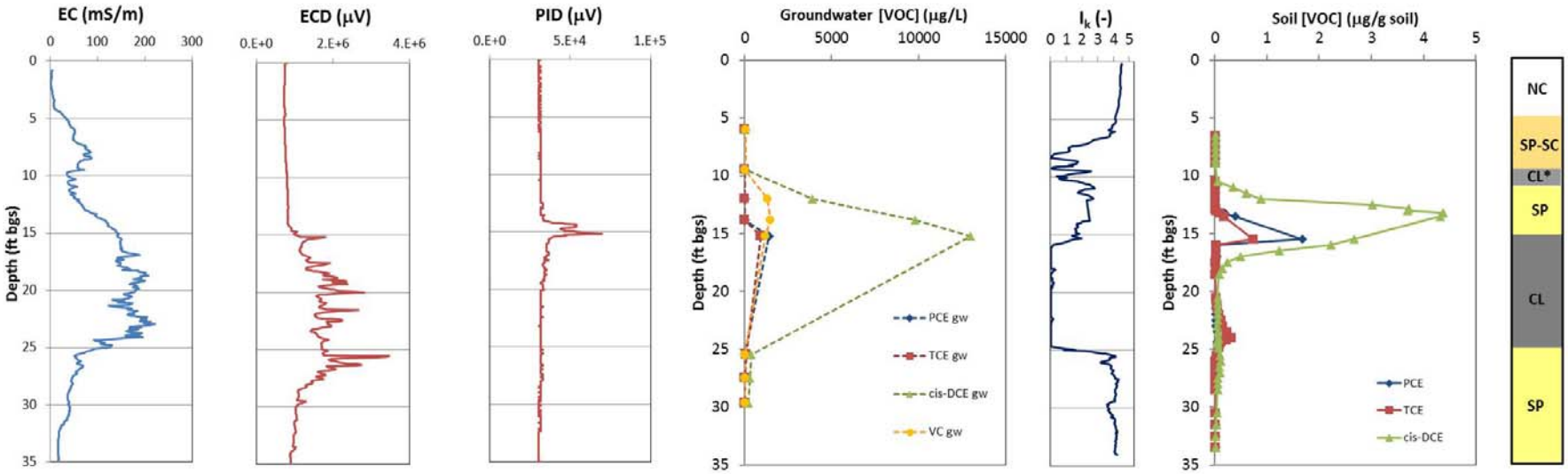
(c) **OU3-5**

MIP	Waterloo APS™	Cores



(d) **OU3-6**

MIP	Waterloo APS™	Cores



APPENDIX M

Biomarker Data from Demonstration Project

www.siremlab.com
130 Research Lane, Suite 2
Guelph, Ontario N1G 5G3
Phone (519) 822-2265
Fax (519) 822-3151

Certificate of Analysis: Gene-Trac® *Dehalococcoides* Assay

Customer: Dave Adamson, GSI Environmental Inc.

Project: ESTCP Source History

Customer Reference: G-3544

SiREM Reference: S-2305_revised

Report Issued: 8-Nov-11

Data Files: MyiQ-DHC-QPCR-0831
DHC-QPCR-Check-gel-0595
iQ5-DB-DHC-QPCR-0243
DHC-UP-0702

Table 1a: Test Results

Customer Sample ID	SiREM Sample ID	Sample Collection Date	Sample Matrix	Percent *Dhc* *	*Dehalococcoides* Enumeration/Gram**
OU3-6-12.0'	DHC-7684	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-13.5'	DHC-7685	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-16.0'	DHC-7686	18-Aug-11	Soil	0.001-0.003%	2×10^4
OU3-6-17.5'	DHC-7687	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-18.5'	DHC-7688	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-21.0'	DHC-7689	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-23.0'	DHC-7690	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-24.0'	DHC-7691	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-24.5'	DHC-7692	18-Aug-11	Soil	NA	1×10^4U, I
OU3-6-26.0'	DHC-7693	18-Aug-11	Soil	NA	1×10^4U, I
OU3-3-11.5'	DHC-7694	18-Aug-11	Soil	0.002-0.007%	4×10^4
OU3-3-13.0'	DHC-7695	18-Aug-11	Soil	0.003-0.0009%	2×10^4
OU3-3-16.5'	DHC-7696	18-Aug-11	Soil	NA	1×10^4U, I
OU3-3-18.0'	DHC-7697	18-Aug-11	Soil	NA	1×10^4U, I
OU3-3-19.0'	DHC-7698	18-Aug-11	Soil	NA	1×10^4U, I
OU3-3-21.0'	DHC-7699	18-Aug-11	Soil	NA	1×10^4U, I
OU3-3-23.0'	DHC-7700	18-Aug-11	Soil	0.001-0.003%	2×10^4
OU3-3-26.0'	DHC-7701	18-Aug-11	Soil	NA	1×10^4U

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130 Research Lane, Suite 2
Guelph, Ontario N1G 5G3
Phone (519) 822-2265
Fax (519) 822-3151

Notes:

* Percent *Dehalococcoides* (Dhc) in microbial population. This value is calculated by dividing the number of Dhc 16S ribosomal ribonucleic acid (rRNA) gene copies by the total number of bacteria as estimated by the mass of DNA extracted from the sample. Range represents normal variation in Dhc enumeration.

** Based on quantification of Dhc 16S rRNA gene copies. Dhc are generally reported to contain one 16S rRNA gene copy per cell; therefore, this number is often interpreted to represent the number of Dhc cells present in the sample.

I Sample inhibited the test reaction based on inability to PCR amplify extracted DNA with universal primers.
J The associated value is an estimated quantity between the method detection limit and quantitation limit.
U Not detected, associated value is the quantification limit.
B Analyte was also detected in the method blank.
NA Not applicable as *Dehalococcoides* not detected and/or quantifiable DNA not extracted from the sample.

Analyst: Jen Wilkinson
Jen Wilkinson
Biotechnology Technologist

Approved: Ximena Druar
Ximena Druar, B.Sc.
Molecular Biology Coordinator

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130 Research Lane, Suite 2
Guelph, Ontario N1G 5G3
Phone (519) 822-2265
Fax (519) 822-3151

Certificate of Analysis: Gene-Trac® VC, Vinyl Chloride Reductase (*vcrA*) Assay

Customer: Dave Adamson, GSI Environmental Inc.

Project: ESTCP Source History

Customer Reference: G-3544

SiREM Reference: S-2305_revised

Report Issued: 8-Sep-11

Data Files: iQ5-VC-QPCR-0428
VC-QPCR-Check-gel-0449
MyiQ-DB-VC-QPCR-0174

Table 1b: Test Results

Customer Sample ID	SiREM Sample ID	Sample Collection Date	Sample Matrix	Percent *vcrA* *	Vinyl Chloride Reductase (*vcrA*) Gene Copies/gram
OU3-6-16.0'	VCR-2925	18-Aug-11	Soil	0.0009-0.003%	1×10^4
OU3-3-11.5'	VCR-2926	18-Aug-11	Soil	0.07-0.2%	1×10^6
OU3-3-13.0'	VCR-2927	18-Aug-11	Soil	0.0006-0.002%	1×10^4
OU3-3-23.0'	VCR-2928	18-Aug-11	Soil	0.0003-0.001%	5×10^3J

Notes:

* Percent *vcrA* in microbial population. This value is calculated by dividing the number of vinyl chloride reductase A (*vcrA)* gene copies quantified by the total number of bacteria estimated to be in the sample based on the mass of DNA extracted from the sample. Range represents normal variation in enumeration of *vcrA* .

J The associated value is an estimated quantity between the method detection limit and quantitation limit.
U Not detected, associated value is the quantification limit.
B Analyte was also detected in the method blank.
NA Not applicable as *vcrA* not detected and/or quantifiable DNA not extracted from the sample.

Analyst: Jen Wilkinson
Jen Wilkinson
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Approved: Ximena Druar
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Table 2.1: Detailed Test Parameters, Test Reference S-2305

Customer Sample ID	OU3-6-12.0'	OU3-6-13.5'	OU3-6-16.0'	OU3-6-17.5'	OU3-6-18.5'	OU3-6-21.0'
SiREM Sample ID	DHC-7684	DHC-7685	DHC-7686/ VCR-2925	DHC-7687	DHC-7688	DHC-7689
Date Received	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11
Sample Temperature	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C
Filtration Date	NA	NA	NA	NA	NA	NA
Volume Used for DNA Extraction	0.20 g	0.20 g	0.20 g	0.19 g	0.19 g	0.18 g
DNA Extraction Date	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11
DNA Concentration in Sample (extractable)	2346 ng/g	2896 ng/g	2309 ng/g	3374ng/g	3322 ng/g	3493 ng/g
PCR Amplifiable DNA	ND	ND	Detected	ND	ND	ND
Dhc qPCR Date Analyzed	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11
***vcrA* qPCR Date Analyzed**	NA	NA	7-Nov-11	NA	NA	NA
qPCR Controls (see Tables 3 & 4)	Passed	Passed	Passed	Passed	Passed	Passed
Comments	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	- -	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.

Notes:

Refer to Tables 3 & 4 for detailed results of controls.
ND = not detected
°C = degrees Celsius
DNA = Deoxyribonucleic acid
Dhc = *Dehalococcoides*
vcrA = vinyl chloride reductase
PCR = polymerase chain reaction
qPCR = quantitative PCR
ng/g = nanograms per gram
g = grams

Table 2.2: Detailed Test Parameters, Test Reference S-2305

Customer Sample ID	OU3-6-23.0'	OU3-6-24.0'	OU3-6-24.5'	OU3-6-26.0'	OU3-3-11.5'	OU3-3-13.0'
SiREM Sample ID	DHC-7690	DHC-7691	DHC-7692	DHC-7693	DHC-7694/ VCR-2926	DHC-7695/ VCR-2927
Date Received	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11
Sample Temperature	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C
Filtration Date	NA	NA	NA	NA	NA	NA
Volume Used for DNA Extraction	0.17 g	0.18 g	0.20 g	0.20 g	0.19 g	0.20 g
DNA Extraction Date	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11
DNA Concentration in Sample (extractable)	3647 ng/g	3713 ng/g	2640 ng/g	2852 ng/g	3275 ng/g	3462 ng/g
PCR Amplifiable DNA	ND	ND	ND	ND	Detected	Detected
Dhc qPCR Date Analyzed	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11
***vcrA* qPCR Date Analyzed**	NA	NA	NA	NA	7-Nov-11	7-Nov-11
qPCR Controls (see Tables 3 & 4)	Passed	Passed	Passed	Passed	Passed	Passed
Comments	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	- -	- -

Notes:

Refer to Tables 3 & 4 for detailed results of controls.
ND = not detected
°C = degrees Celsius
DNA = Deoxyribonucleic acid
Dhc = *Dehalococcoides*
vcrA = vinyl chloride reductase
PCR = polymerase chain reaction
qPCR = quantitative PCR
ng/g = nanograms per gram
g = grams

Table 2.3: Detailed Test Parameters, Test Reference S-2305

Customer Sample ID	OU3-3-16.5'	OU3-3-18.0'	OU3-3-19.0'	OU3-3-21.0'	OU3-3-23.0'	OU3-3-26.0'
SiREM Sample ID	DHC-7696	DHC-7697	DHC-7698	DHC-7699	DHC-7700/ VCR-2928	DHC-7701
Date Received	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11	22-Aug-11
Sample Temperature	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C	8 ˚C
Filtration Date	NA	NA	NA	NA	NA	NA
Volume Used for DNA Extraction	0.20 g	0.18 g	0.19 g	0.19 g	0.17 g	0.20 g
DNA Extraction Date	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11	21-Oct-11
DNA Concentration in Sample (extractable)	2329 ng/g	5610 ng/g	3662 ng/g	3412 ng/g	2821 ng/g	3170 ng/g
PCR Amplifiable DNA	ND	ND	ND	ND	Detected	Detected
Dhc qPCR Date Analyzed	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11	24-Oct-11
***vcrA* qPCR Date Analyzed**	NA	NA	NA	NA	7-Nov-11	NA
qPCR Controls (see Tables 3 & 4)	Passed	Passed	Passed	Passed	Passed	Passed
Comments	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	Quantifiable DNA not extracted from sample.	- -	- -

Notes:

Refer to Tables 3 & 4 for detailed results of controls.
ND = not detected
°C = degrees Celsius
DNA = Deoxyribonucleic acid
Dhc = *Dehalococcoides*
vcrA = vinyl chloride reductase
PCR = polymerase chain reaction
qPCR = quantitative PCR
ng/g = nanograms per gram
g = grams

Table 3: Gene-Trac Dhc Control Results, Test Reference S-2305

Laboratory Control	Analysis Date	Control Description	Spiked Dhc 16S rRNA Gene Copies per Gram	Recovered Dhc 16S rRNA Gene Copies per Gram	Comments
Positive Control Low Concentration	24-Oct-11	qPCR with KB-1 genomic DNA (CSLD-0468)	5.0×10^5	4.4×10^5	- -
Positive Control High Concentration	24-Oct-11	qPCR with KB-1 genomic DNA (CSHD-0468)	5.6×10^7	5.2×10^7	- -
Negative Control	24-Oct-11	Tris Reagent Blank (TBD-0428)	0	7.8×10^3U	- -
DNA Extraction Blank	24-Oct-11	DNA extraction sterile water (EB-1545)	0	7.8×10^3U	- -

Notes:

Dhc = *Dehalococcoides*

DNA = Deoxyribonucleic acid

qPCR = quantitative PCR

16S rRNA = 16S ribosomal ribonucleic acid

U Not detected, associated value is the quantification limit.

Table 4: Gene-Trac VC Control Results, Test Reference S-2305

Laboratory Control	Analysis Date	Control Description	Spiked *vcrA* reductase Gene Copies per Gram	Recovered *vcrA* reductase Gene Copies per Gram	Comments
Positive Control Low Concentration	7-Nov-11	qPCR with KB-1 genomic DNA (CSLV-0296)	5.6×10^5	3.5×10^5	- -
Positive Control High Concentration	7-Nov-11	qPCR with KB-1 genomic DNA (CSHV-0296)	7.9×10^7	6.2×10^7	- -
Negative Control	26-Oct-11	Tris Reagent Blank (TBV-0267)	0	7.8×10^3U	- -
DNA Extraction Blank	7-Nov-11	DNA extraction sterile water (EB-1545)	0	7.8×10^3U	- -

Notes:

qPCR = quantitative PCR

DNA = Deoxyribonucleic acid

16S rRNA = 16S ribosomal ribonucleic acid

vcrA = vinyl chloride reductase

U Not detected, associated value is the quantification limit.

APPENDIX N

Carbon Isotope Results from Demonstration Project

APPENDIX N:
Results of Carbon Isotope Analyses
Determining Source Attenuation History to Support Closure by Natural Attenuation

Environmental Security and Technology Certification Program (ESTCP)
Project ER-201032

Compound-specific isotope analysis (CSIA) has increasingly been applied as a complementary tool to assess the degree of reductive dechlorination (Chartrand et al. 2005; Hunkeler et al., 1999; Sherwood Lollar et al., 2001; Song et al., 2002; Hunkeler et al., 2009, Marjorie et al., 2009). The method relies on differences in degradation rates between molecules with light and heavy carbon isotopes in the compounds, which lead to the preferential degradation of lighter isotopes and subsequent enrichment of heavy isotopes in the remaining compound. Previous studies have suggested that the method is particularly sensitive to assess reduction dechlorination of cis-1,2-DCE and VC because these steps are associated with strong fractionation, with reported fractionation factors for cis-1,2-DCE and VC of -16.5 and -25.6 ‰, respectively, compared to -3.9 and -6.8 ‰ for the steps PCE-TCE and TCE-cis-1,2-DCE (Hunkeler et al., 1999; Bloom et al., 2000, Hunkeler et al., 2002).

The degree of biodegradation over time and/or space can be reflected by an expected isotope pattern. As the concentration of the parent compound (PCE) decreases, the isotopic composition of the remaining parent get enriched in ^{13}C (i.e., tend toward more positive values) and the daughter (TCE) is depleted in ^{13}C compared to the parent compound. Furthermore, as the TCE is transformed to cis-1,2-DCE, the $\delta\ ^{13}C$ of the TCE also tend toward more enriched values. In cases where cis-1,2-DCE is accumulating, its isotopic composition will tend toward the isotopic composition of the parent compound. In cases where cis-1,2-DCE is further transformed to VC, the remaining cis-1,2-DCE can become more enriched in ^{13}C than the parent compound. In the case of VC, this compound is generally more depleted in ^{13}C (i.e., more negative $\delta\ ^{13}C$ values) than the parent compound; however, it can become more enriched than the parent compound if VC is further transformed to ethene (Abe et al., 2009).

For this project, CSIA was completed on groundwater samples collected from multiple depths at three locations within the former Building 106 source area. [Note that soil samples designed for CSIA analysis following water extraction were collected, but ultimately were not analyzed]. At each location, sampled depths included both the low permeability interval as well as the higher permeability zones above and below this interval. The isotope data are summarized in the accompanying graphs, and the complete results are presented in the accompanying table.

- ***OU3-3:*** This location contained the highest total CVOC concentrations at the site. The predominant compound in the clay layer is PCE with concentration ranging between approximately 18,000 and 42,000 µg/L. TCE (4400 to 6600 µg/L) and cis-1,2-DCE (3000 to 6200 µg/L) were present at lower concentrations within this layer. Within the overlying sandy aquifer, much lower concentrations for PCE were observed, ranging from 5600 µg/L

near the sand-clay interface to 620 µg/L at the shallowest depth. The predominant compound in the sand layers was cis-1,2-DCE at concentrations ranging from 21,000 and 14,000 µg/L, compared to 640 to 5300 µg/L for TCE. VC was a minor compound, ranging from 100 to 470 µg/L.

The isotopic composition for PCE in the high concentration clay zone ranges between -24 and -25 ‰. A similar $\delta^{13}C$ range is observed for TCE. More depleted $\delta^{13}C$ values compared to the parent compounds PCE and TCE are observed for cis-1,2-DCE with a value around -30 ‰. The most depleted $\delta^{13}C$ values with a value around -40 ‰ is observed for VC. The isotope pattern is in agreement with the CVOC concentration distribution, which showed that PCE has been affected by biodegradation but still is the predominant CVOC present. Based on the concentration and isotope data, as well as the typical enrichment factor for the PCE-TCE dechlorination steps, it is postulated that the original isotopic composition of PCE was approximately -27 to -28 ‰.

A different pattern is observed in the overlying sand aquifer, where cis-1,2-DCE was the predominant CVOC present. The change in CVOC composition was also reflected in the isotope data. The PCE showed a trend toward more enriched $\delta^{13}C$ values in the sand intervals relative to the values observed in the clay unit, reaching a maximum value of -18 ‰. A similar $\delta^{13}C$ trend was observed for TCE. This pattern is correlated with a decreasing trend in PCE and TCE concentration within this layer. cis-1,2-DCE showed a $\delta^{13}C$ trend toward -28 ‰, which could be closer to the isotopic composition of the parent compound PCE. It is important to highlight that TCE is also thought to have been released at the site, though possibly at much lower quantities than PCE. VC showed the most depleted $\delta^{13}C$ values, reaching -45 ‰ at the shallowest depth, which is consistent with the expected isotope pattern when VC is produced in minor quantities. The enriched $\delta^{13}C$ value of -25 ‰ could imply that VC has been transformed to ethene. Low levels of ethene (< 10 µg/L) were observed in samples from the sand unit, however ethene is not conservative and can also affected by biodegradation (Bloom et al., 2000; Abe et al., 2009).

In summary, the concentration and isotope data indicated that a higher degree of biodegradation is occurring in the sand units compared to the clay unit at location OU3-3.

- ***OU3-5:*** Based on the concentration and isotope data, a similar conclusion can be inferred at location OU3-5. At this downgradient location, the predominant compound in the clay layers was PCE (300 to 18,000 µg/L), though cis-1,2-DCE (310 to 12,000 µg/L) was present at larger concentrations than TCE (170 to 3400 µg/L). The highest PCE concentration is observed in the sands near the clay interface, and then a decreasing concentration pattern is observed with depth. TCE and cis-1,2-DCE follow a similar pattern. VC is the minor component ranging with depth between 5 and 580 µg/L.

  Despite the slightly different pattern in CVOC concentration with depth in the clay unit, the isotope pattern obtained at OU3-5 is relatively similar than the isotope data obtained at location OU3-3. PCE shows $\delta^{13}C$ values around -24 ‰. TCE showed slightly more depleted $\delta^{13}C$ values, around -25 and -27 ‰, than PCE. cis-1,2-DCE showed $\delta^{13}C$ values between -27

and -30 ‰, and VC ranged between -32 and -35 ‰. The isotope data were in agreement with the concentration data that showed that PCE has been affected by biodegradation; however, PCE still was the predominant compound. The relatively enriched $\delta^{13}C$ values observed for VC can be explained by transformation of VC to ethene (Abe et al., 2009), which was present in the clay unit at concentrations approaching 100 µg/L.

Similar to the patterns observed at OU3-3, greater changes in VOC and isotopic composition were observed in the sand unit at OU3-5. The predominant compound was cis-1,2-DCE with concentration ranging between 28,000 and 30,000 µg/L compared to TCE (160-7400 µg/L) and PCE (820-20,000 µg/L). VC was also present at relatively high concentrations in the sand (1400 to 7300 µg/L). TCE showed a significant $\delta^{13}C$ enrichment shift from -25 to -11 ‰, which was accompanied by a decreasing trend in TCE concentration. This pattern was in agreement with the transformation of most of the TCE to cis-1,2-DCE, which also showed a slight enrichment $\delta^{13}C$ trend from -30 to -26 ‰ toward the shallow part of the upper sand layer. The VC showed $\delta^{13}C$ values between -45 and -39 ‰, which reflected a minor conversion of cis-1,2-DCE to VC, which was consistent with the concentration data. Another interesting observation was that biodegradation also occurred in the lower sand unit and cis-1,2-DCE was also the predominant compound, with a concentration of 890 µg/L compared with 350 µg/L and 360 µg/L for PCE and TCE, respectively. The $\delta^{13}C$ value for PCE of -17 ‰ at this depth was one of the most enriched values observed at the site, and TCE was also more enriched in ^{13}C compared to what was measured in the clay unit. cis-1,2-DCE showed a $\delta^{13}C$ value of -29 ‰, indicating that cis-1,2-DCE was accumulating and was not further transformed to VC, which was consistent with the non-detectable VC observed at this depth.

The concentration and isotope data for location OU3-5 support the conclusion that a higher degree of biodegradation is occurring in the sand units compared to the clay unit.

- ***OU3-6:*** At this downgradient location, the concentration data showed cis-1,2-DCE was the predominant compound in both the sand and clay layers. For co-located samples collected moving deeper into the clay unit, the concentration profile consisted of approximately 19,000, 2200 and 190 µg/L for cis-1,2-DCE compared to 4000, 190 and 73 µg/L for PCE, 1300, 69 and 100 µg/L for TCE, and 4800, 140 and 200 µg/L for VC.

  Within the clay, the isotope data showed $\delta^{13}C$ values of approximately -22 ‰ for PCE and more depleted values ranging between -23 and -29 ‰ for TCE and -26 to -29 ‰ for cis-1,2-DCE. VC showed an enrichment trend with depth between -34 ‰ near the clay-sand interface to -20 ‰ at the deepest sampling point in the clay (Table x and Figure 5 of your power point presentation). The isotope data was in agreement with the concentration data that showed PCE has been affected by biodegradation and the main daughter product was cis-1,2-DCE with further transformation to VC. The isotope data also suggested that VC has been transformed to ethene, which was detected at a concentration around 100 µg/L.

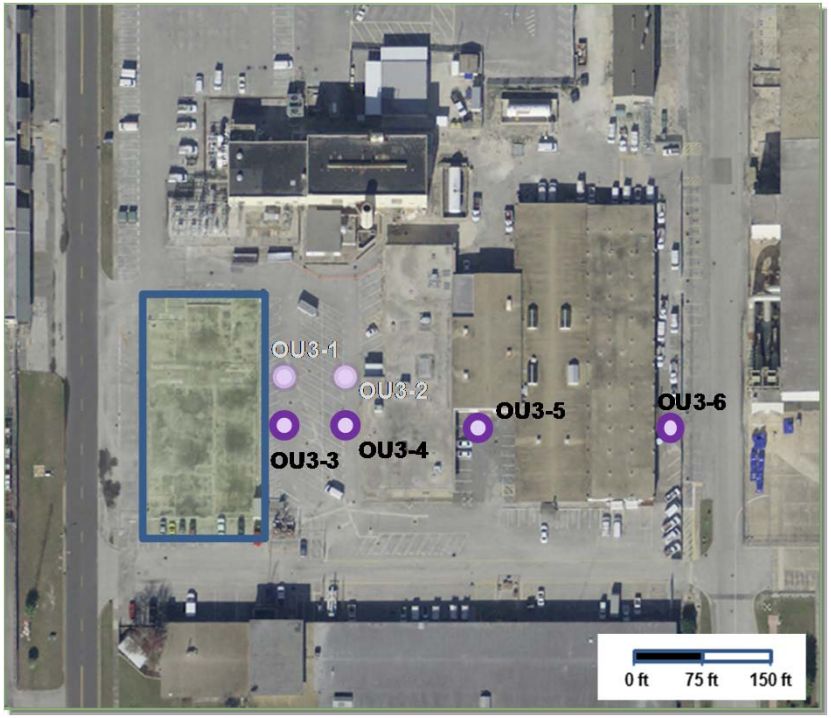
  In the sandy unit above the clay, the main daughter product was cis-1,2-DCE ranging between approximately 11,000 µg/L near the interface and 2100 µg/L in the shallow

sampling point. At these same depths, PCE was detected at concentrations of 1100 and 7 µg/L, TCE was detected at concentrations of 180 and 2 µg/L, and VC was detected at concentrations of 3800 and 760 µg/L. It is interesting to note than VC was present at higher concentrations than the parent compounds. A similar pattern showing cis-1,2-DCE as the main degradation product (but at much a lower concentration) was observed in the sand unit below the clay.

The isotope data show $\delta^{13}C$ values around -22, -29 and -35 ‰ for PCE, TCE and VC, respectively, near the interface. In the sand unit, an isotopic shift from -23 to -21 ‰ and from -35 to -20 ‰ is observed for cis-1,2-DCE and VC, respectively, toward the shallow part of the profile. The sand unit below the clay shows $\delta^{13}C$ values of -24 ‰ for TCE, -26 ‰ for cis-1,2-DCE and -32 ‰ for VC and a highly enriched value of -15 ‰ for PCE. The enriched $\delta^{13}C$ values for cis-1,2-DCE observed in the sand units above the clays, compared to an assumed value of -27 ‰ for the parent compound PCE, indicated that cis-1,2-DCE is not accumulating and it is further transformed to VC. Conversely, the isotope data for cis-1,2-DCE in the lower sand unit indicated that cis-1,2-DCE is accumulating within this layer. The isotope data were in agreement with the concentration data which showed that most of the PCE has been transformed to cis-1,2-DCE and this compound was further transformed to VC in the overlying sand unit but accumulating in the underlying sand unit. The enriched $\delta^{13}C$ values for VC were consistent with further transformation to ethene (Abe et al., 2009), which was detected at concentrations ranging between 10 and 100 µg/L. The higher concentrations tended to be observed in the overlying sand interval.

In summary, the isotope and concentration data showed that a higher degree of biodegradation of PCE was occurring in the sand units compared to the clay units. The data also showed that the degree of biodegradation increased along the groundwater flowpath. These patterns can be visually observed in the accompanying graph that shows the concentration and isotope data for VOCs along the groundwater flow system.

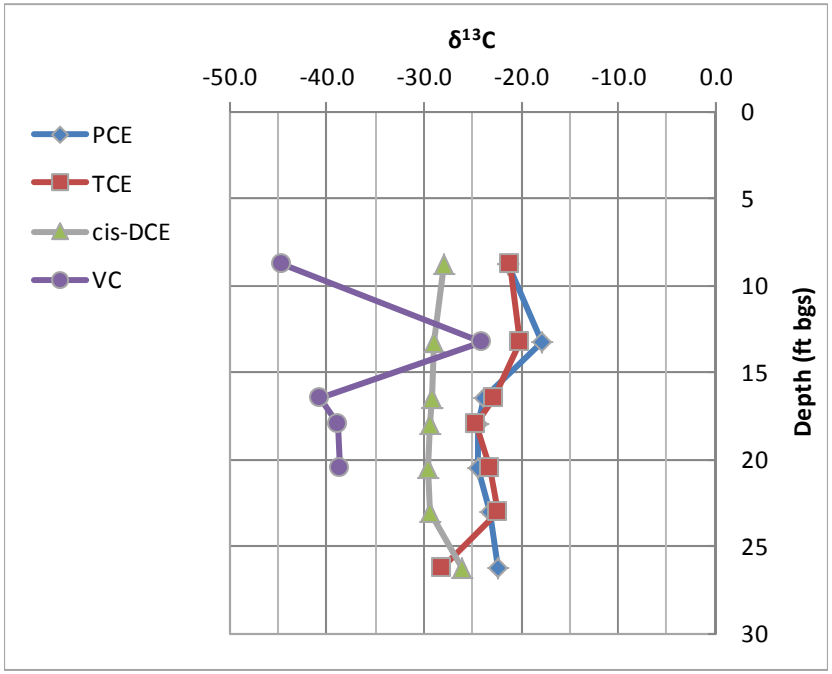
Methodology



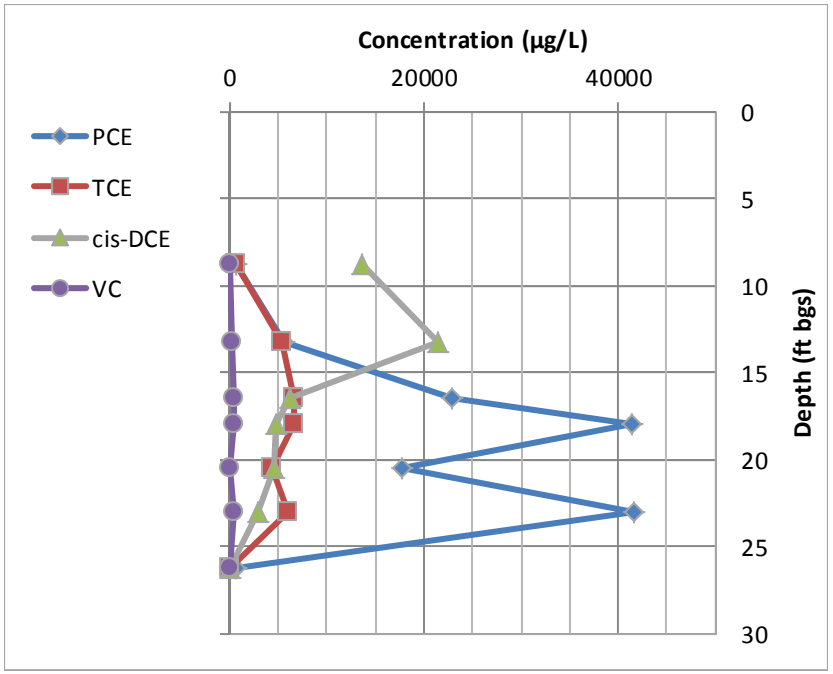
- Collected groundwater samples at 3 locations at Building 106 Source Area at OU3
  - OU3-3 → OU3-5 → OU3-6 (based on direction of groundwater flow)
- 6 to 7 depths per locations
  - 1 to 2 samples in shallow sands
  - 4 samples in lower K clays
  - 1 sample in deeper sands
- All samples collected using Geoprobe SP16 with 2-ft or 3.5-ft screened intervals
  - Results reported for mid-depth
- Sample analyses (isotope and CVOC) completed at University of Waterloo
  - ^{13}C was only isotope analyzed
  - Samples with $\delta^{13}C$ below analytical limit not plotted

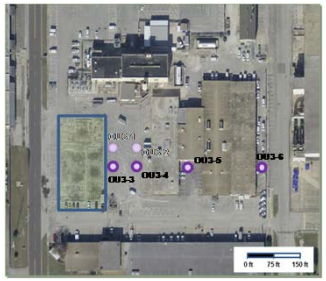
Location OU3-3

δ13C



Concentration



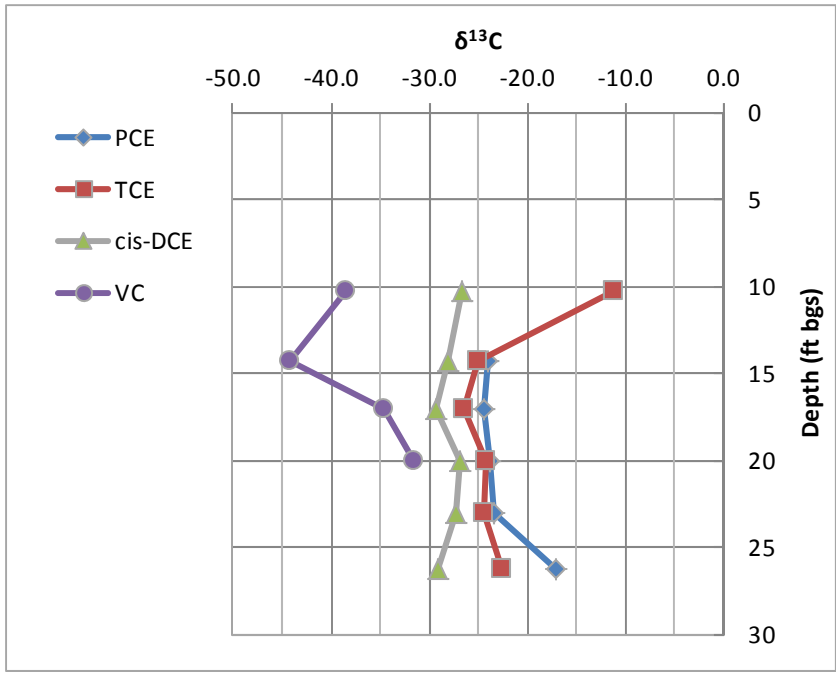


Notes:

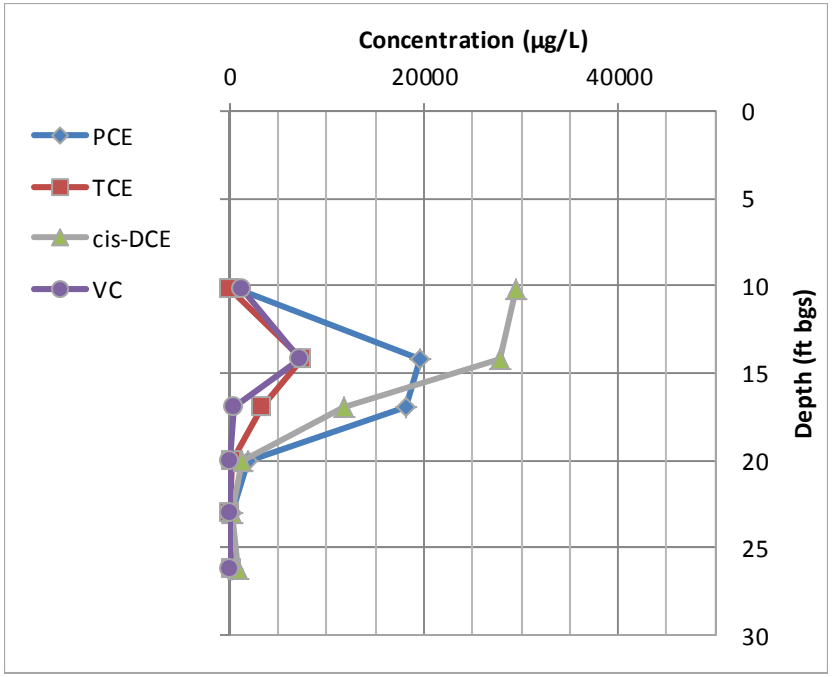
1. Sample at 23 ft bgs was below analytical limit for δ13C for VC.

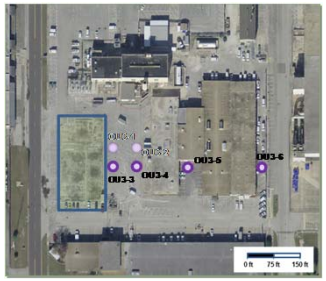
Location OU3-5

δ13C



Concentration



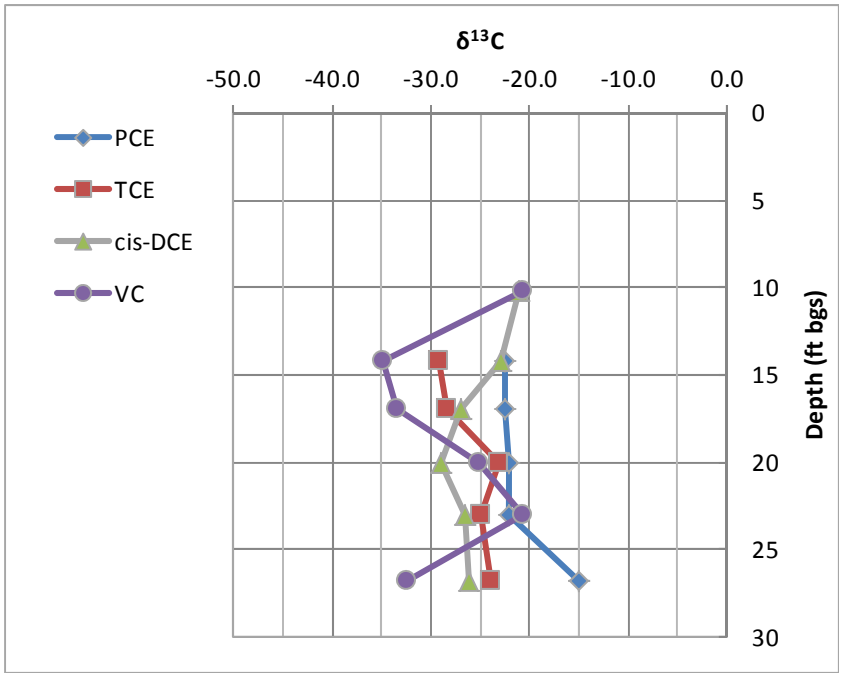


Notes:

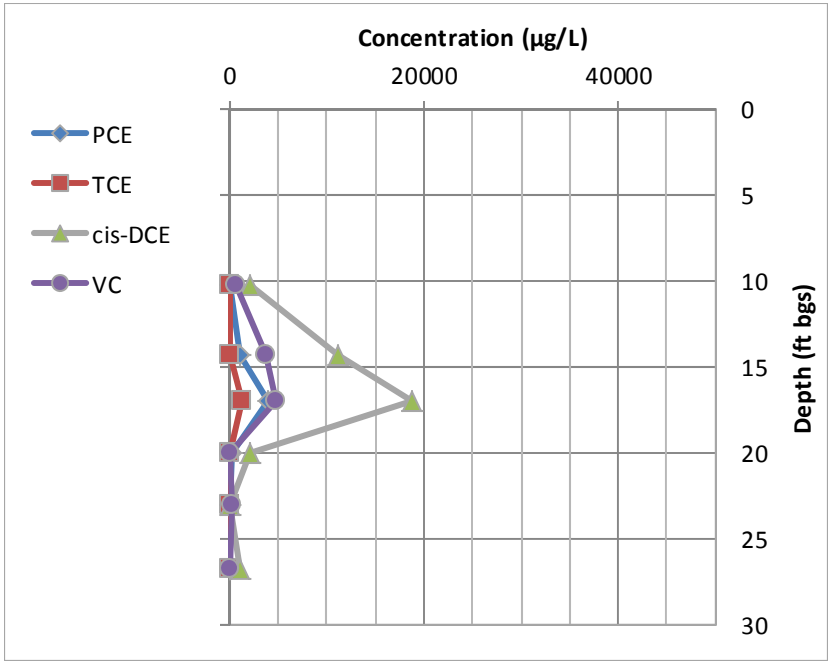
1. Sample at 10 ft bgs was below analytical limit for δ13C for PCE.

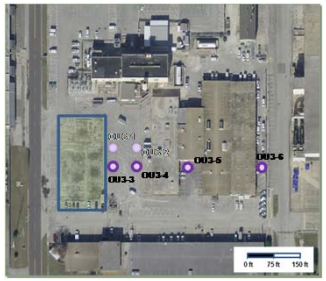
Location OU3-6

$\delta^{13}C$



Concentration

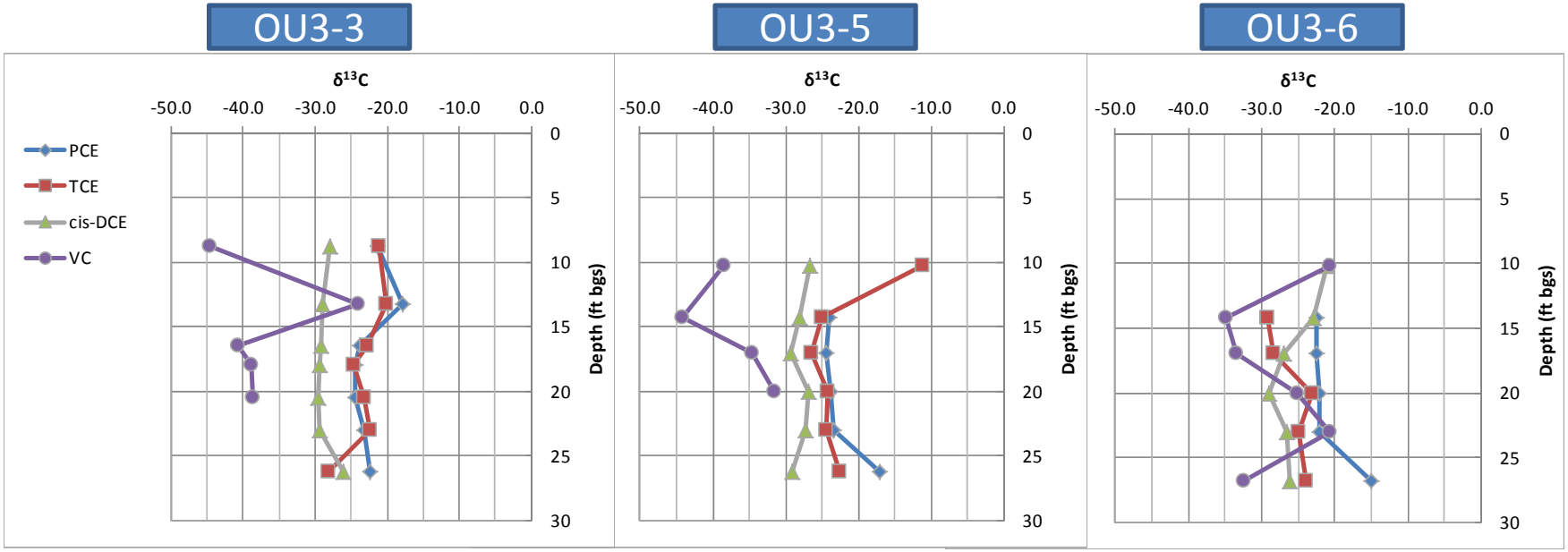




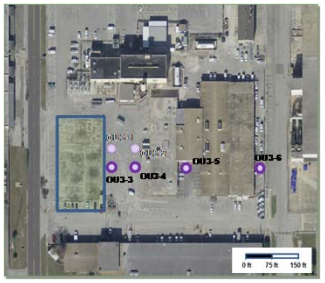
Notes:

1. Sample at 10 ft bgs was below analytical limit for $\delta^{13}C$ for PCE.

Profiles for All Locations

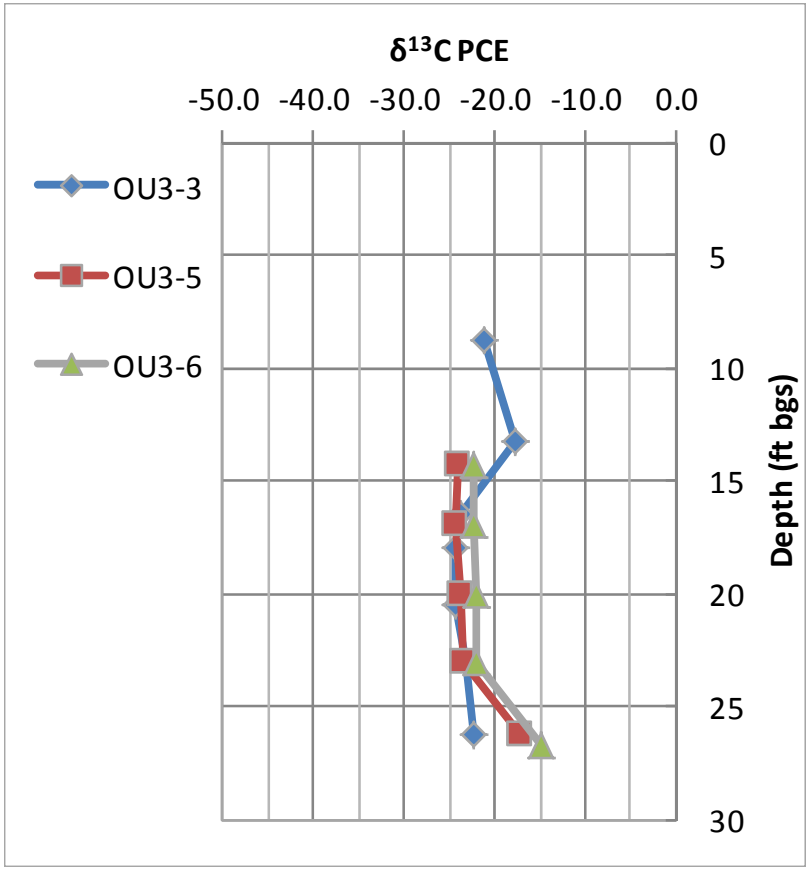


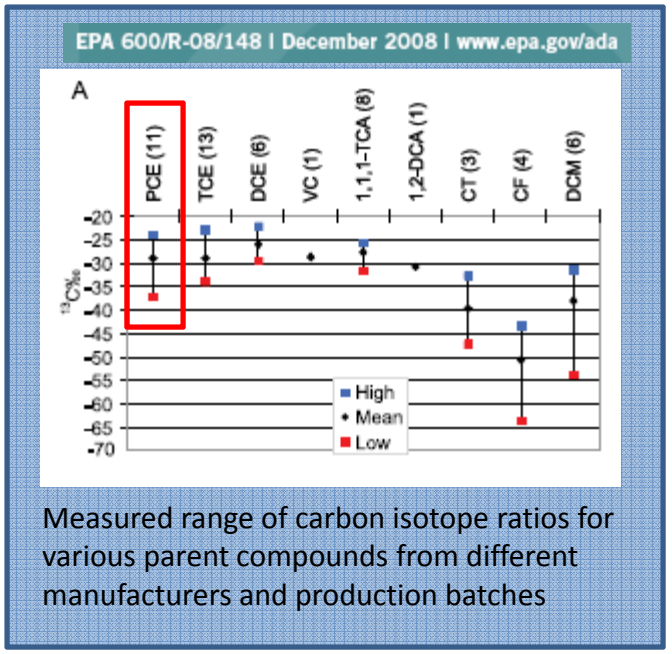
- General trend of more degradation moving downgradient (i.e., less negative $\delta^{13}C$ values for individual compounds)
- See compound-specific plots on subsequent slides



Groundwater Flow Direction

PCE Profiles for All Locations

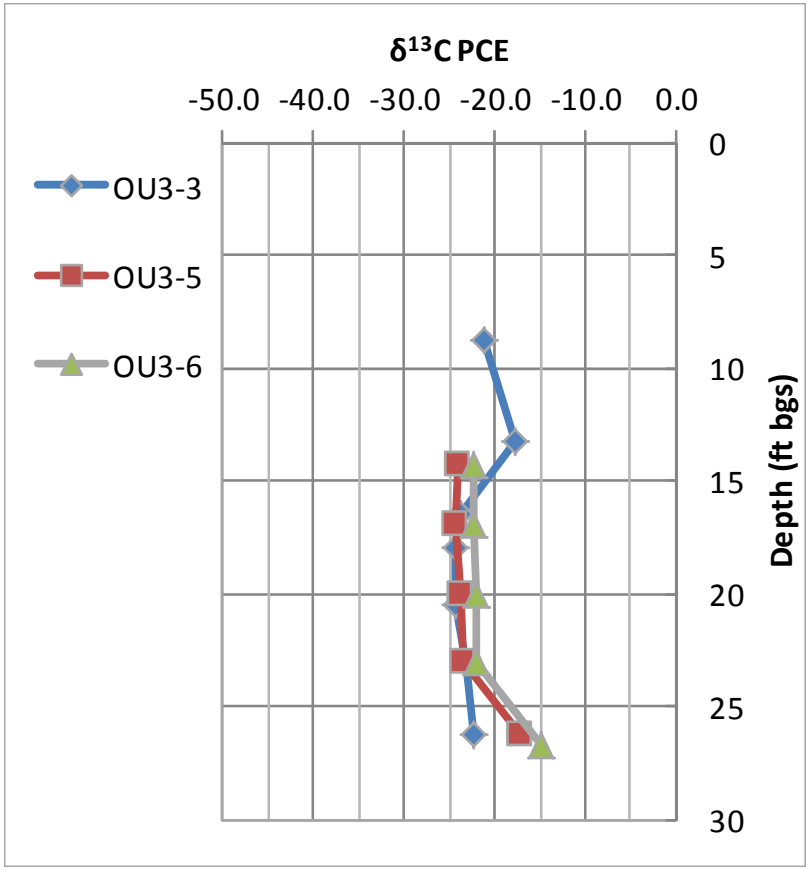




Measured range of carbon isotope ratios for various parent compounds from different manufacturers and production batches

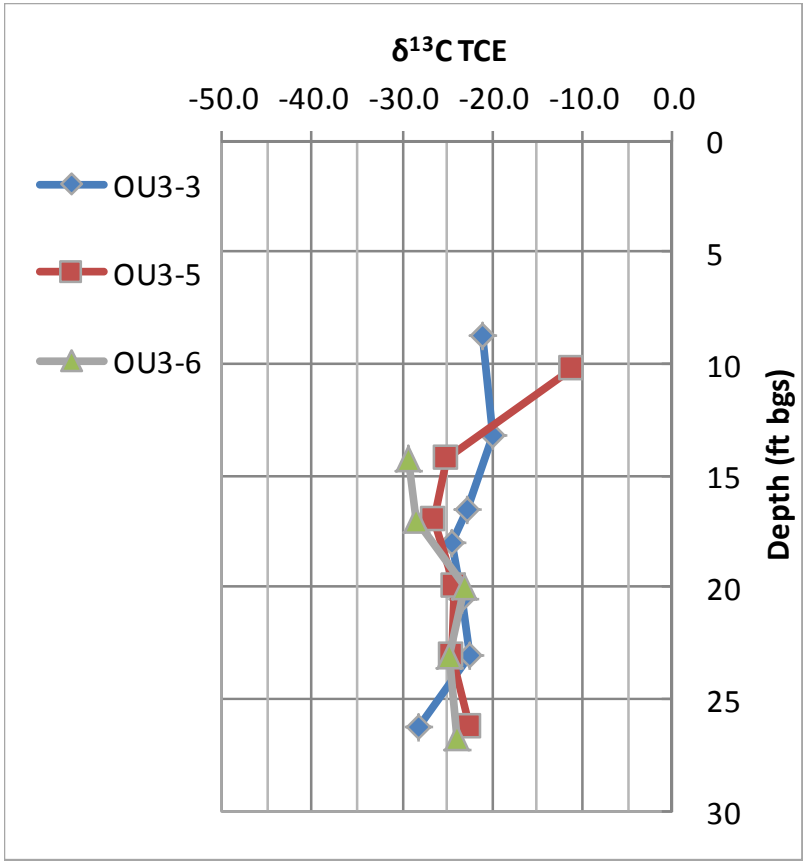
- Maximum values for PCE measured at OU3 (-25‰) are at lower end of PCE source range, indicating possible long-term degradation

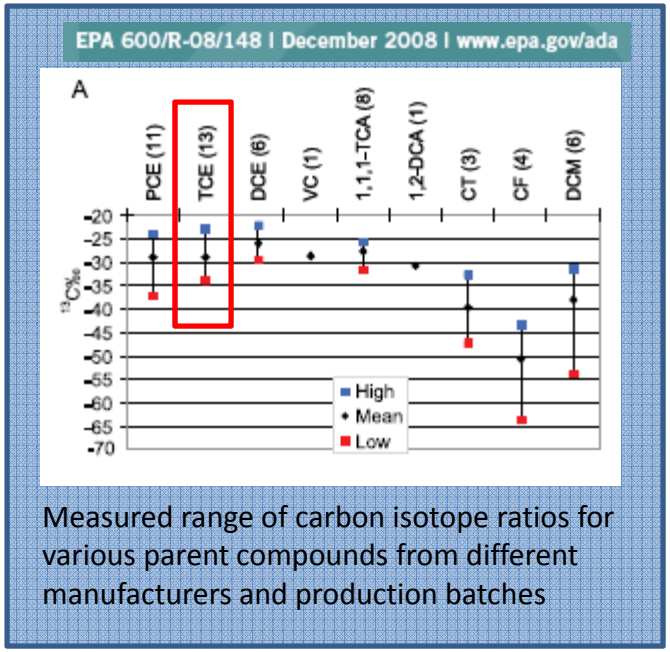
PCE Profiles for All Locations (continued)



- Slight indication of more degraded PCE above and below low K layers at all locations
  - Less negative $\delta^{13}C$ in samples above 15 ft and below 25 ft
- Slight shift to more degraded PCE moving downgradient
  - Consistently less negative $\delta^{13}C$ in samples from low k layer at OU3-6 relative to samples from low K layer at OU3-3 and OU3-5
- Fits conceptual model that most (or all) degradation of parent compound is occurring within high K intervals

TCE Profiles for All Locations

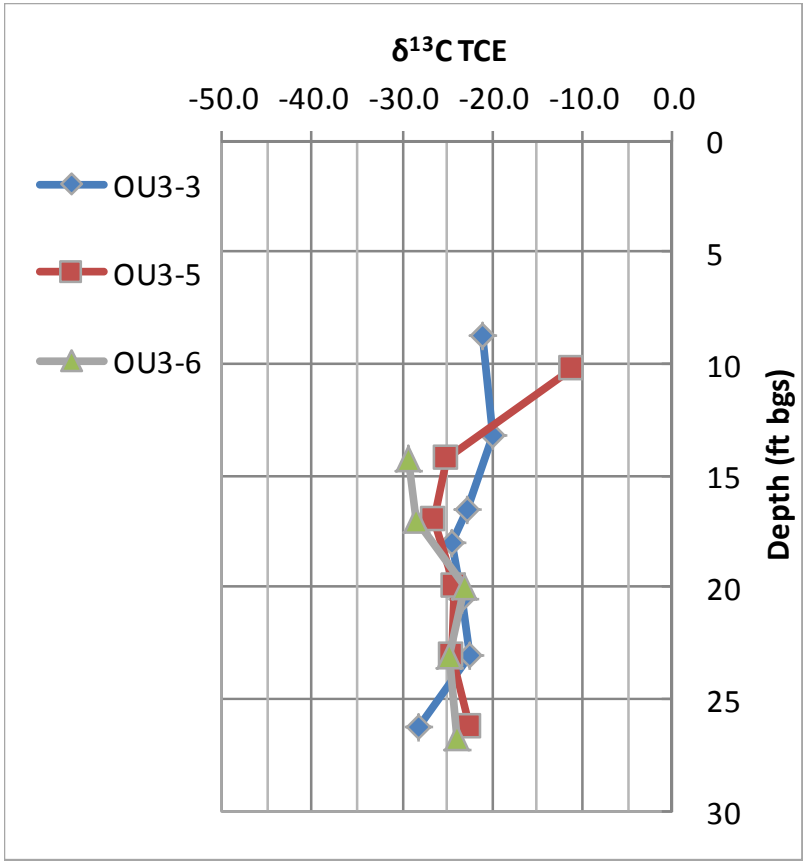




Measured range of carbon isotope ratios for various parent compounds from different manufacturers and production batches

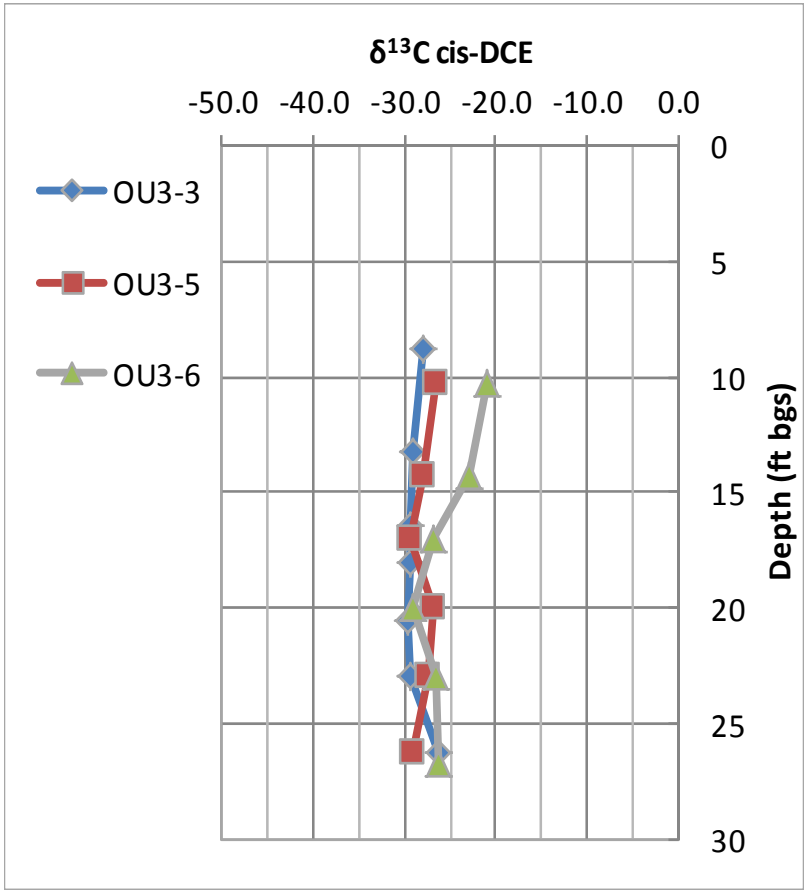
- Maximum values for TCE measured at OU3 (-29‰) are consistent with mean for TCE source

TCE Profiles for All Locations (continued)



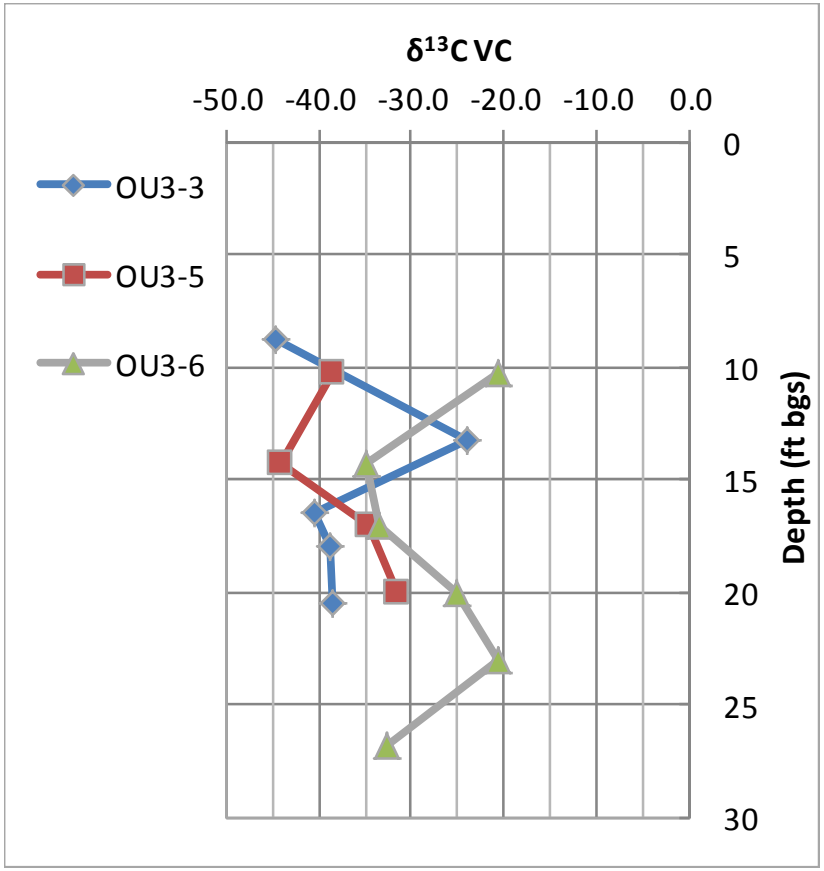
- Assessment complicated because TCE represents both source and product
  - Reductive dechlorination of PCE yields more negative $\delta^{13}C$ TCE values
  - Source TCE would be expected to have more positive $\delta^{13}C$ TCE values
- Upgradient locations (OU3-3 and OU3-5) characterized by less negative $\delta^{13}C$ values at shallow depths
  - Consistent with degradation of shallow TCE source?
- Downgradient location (OU3-6) characterized by more negative $\delta^{13}C$ values at shallow depths

cis-DCE Profiles for All Locations



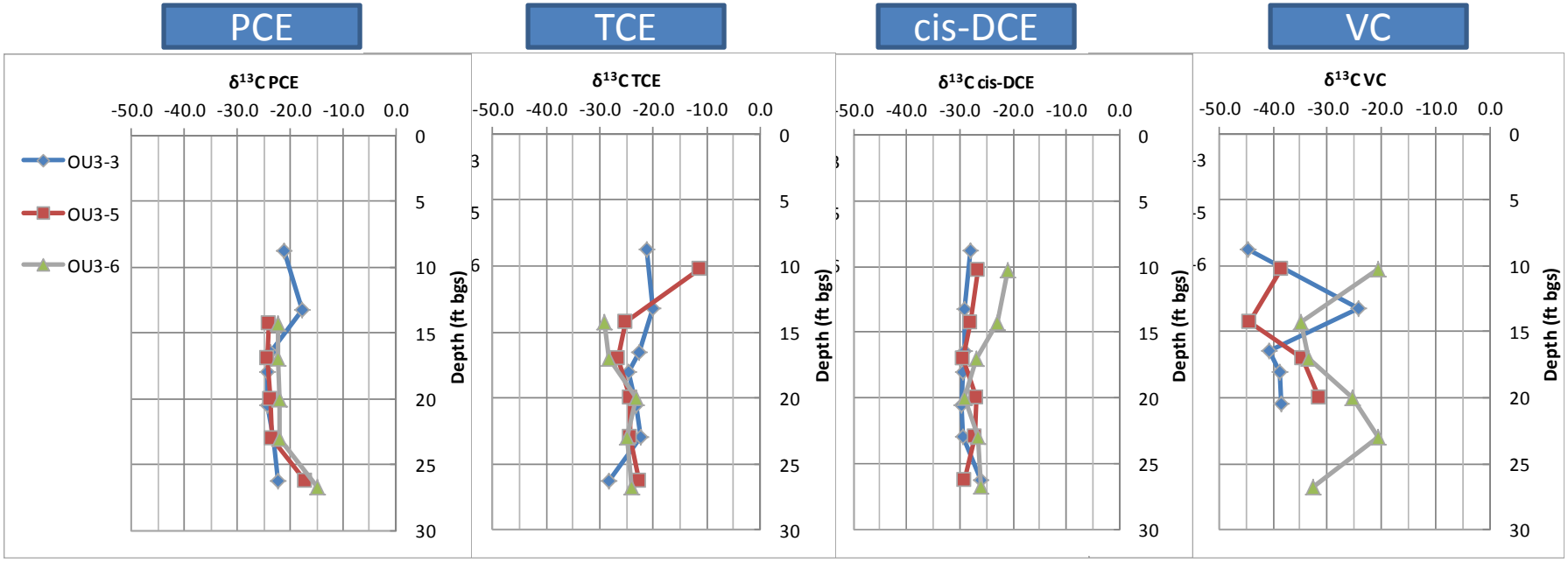
- General indication of more degraded cis-DCE above and below low K layers
  - Less negative $\delta^{13}C$ in samples above 15 ft and below 25 ft, particularly at OU3-3 and OU3-6
- Slight shift to more degraded cis-DCE moving downgradient
  - Consistently less negative $\delta^{13}C$ in samples from shallow sands at OU3-6 relative to OU3-3
- cis-DCE $\delta^{13}C$ values are consistently more negative than values for PCE and TCE at same depths/locations
- Fits conceptual model that most (or all) degradation of parent compound is occurring within higher K intervals

VC Profiles for All Locations

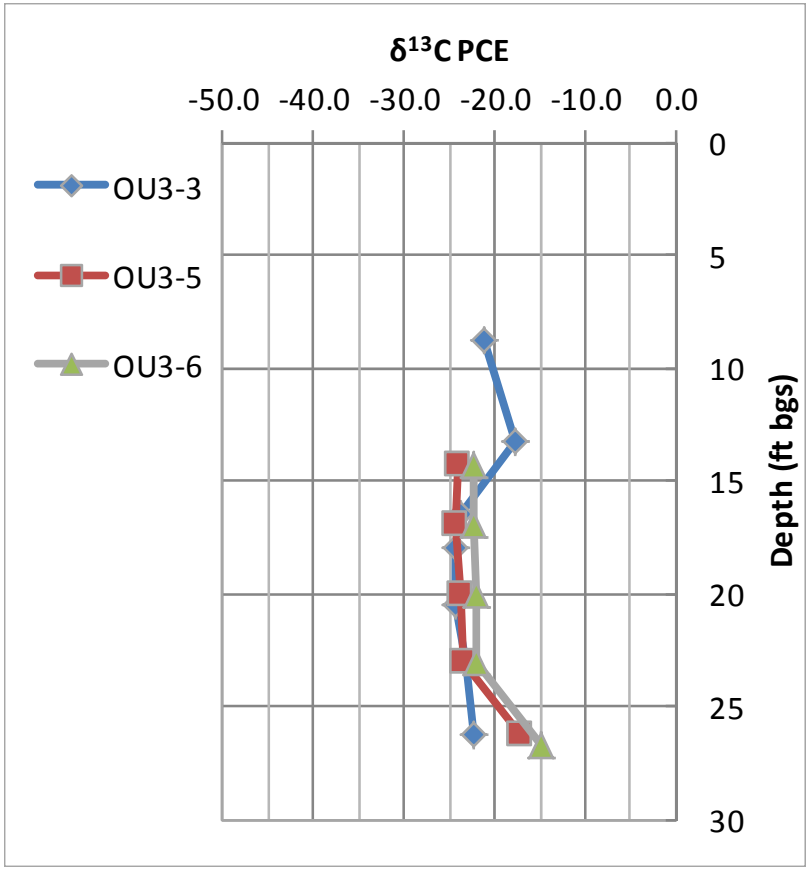


- Profiles exhibit significant variability
  - No distinct patterns in $\delta^{13}C$ values between locations
  - Hampered by generally low VC concentrations at most depths and locations
- VC $\delta^{13}C$ values are generally more negative than values for PCE, TCE, and cis-DCE at same depths/locations
  - Consistent with VC as a degradation product

Constituent-Specific Profiles for All Locations



Degradation Estimates Based on CSIA



EPA 600/R-08/148 I December 2008 I www.epa.gov/ada

$$f = e^{(\delta^{13}C_{groundwater} - \delta^{13}C_{source})/\varepsilon)}$$

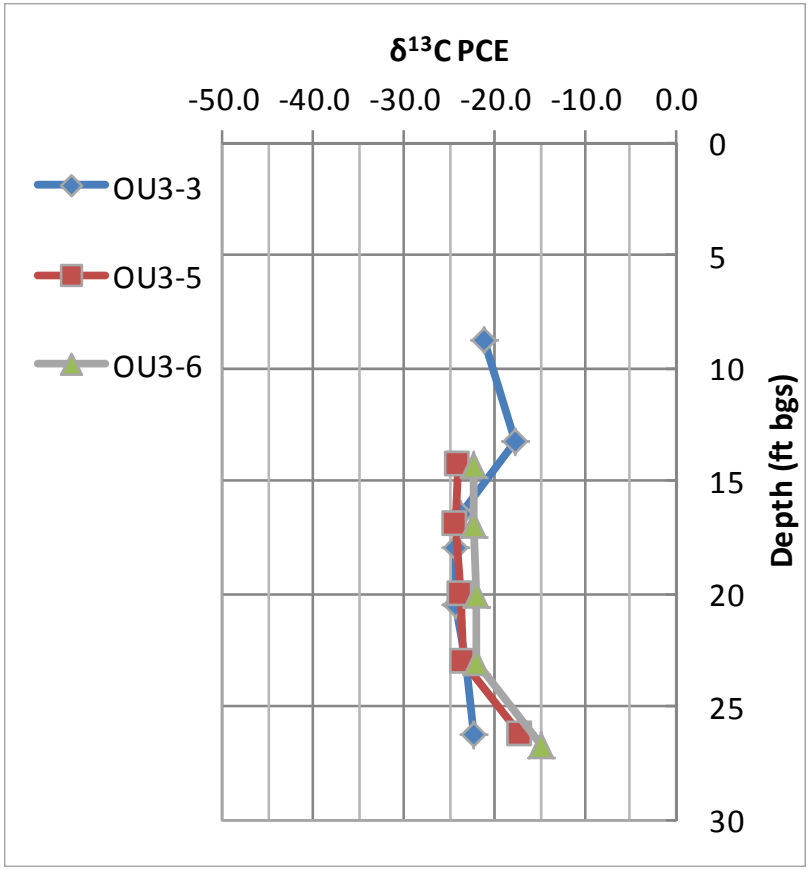
Modified Rayleigh Equation

f = ratio of concentration at time t and zero

ε = isotope enrichment factor

- Use Modified Rayleigh Equation to estimate fraction of source that has been biodegraded (f)
- Assume non-degraded PCE source is represented by maximum value at upgradient location
  - $\delta^{13}C$ = -24.5‰
- Assume extent of degradation at source represented by minimum value at upgradient location
  - $\delta^{13}C$ = -17.8 ‰

Degradation Estimates Based on CSIA (continued)



EPA 600/R-08/148 I December 2008 I www.epa.gov/ada

$$f = e^{(\delta^{13}C_{groundwater} - \delta^{13}C_{source})/\varepsilon)}$$

Modified Rayleigh Equation

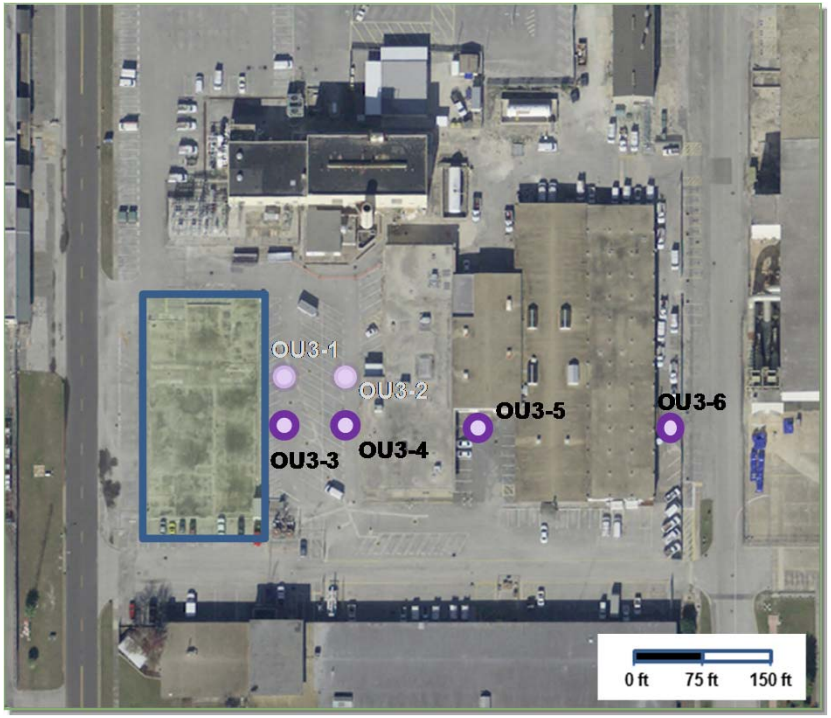
f = ratio of concentration at time t and zero

ε = isotope enrichment factor

- Apply Rayleigh relationship using literature values for PCE enrichment factor
  - Median = -3‰
  - Upper bound = -8.8‰
- **Calculate fraction of PCE biodegraded (f)**
  - **Median = 0.1**
  - **Upper bound = 0.47**

KEY POINT: This method is highly subjective. Using large PCE enrichment factors may be inappropriate based on similarity between $\delta^{13}C$ values for PCE and TCE.

Conclusions



Groundwater Flow Direction

- Data are variable but consistent with conceptual model that most degradation occurs in higher K intervals
  - Less negative $\delta^{13}C$ values for most compounds generally found in higher K intervals
- Extent of degradation increases moving downgradient
  - Consistent with GW (and soil) concentration data
- Diffusion of degraded parent compounds and metabolites into lower K intervals at downgradient locations

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TABLE N.1
RESULTS OF CARBON ISOTOPE ANALYSES

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

			Carbon Isotope Data												Groundwater Concentration Data (ug/L)			
			$\delta^{13}C$	Result	Repeat	$\delta^{13}C$	Result	Repeat	$\delta^{13}C$	Result	Repeat	$\delta^{13}C$	Result	Repeat				
#	Sample	Lab#	PCE	VPDB		TCE	VPDB		cis-DCE	VPDB		VC	VPDB		PCE	TCE	cis-DCE	VC
1	NAS-GW-CVOC-OU3-3 7.0-10.5 ft	270659	X	-21.31	-21.27	X	-21.10	-21.15	X	-27.99		X	-44.58	-43.93	620	637	13661	40
2	NAS-GW-CVOC-OU3-3 11.5-15.0 ft	270660	X	-17.81		X	-20.08		X	-29.04		X	-24.08		5598	5331	21481	220
3	NAS-GW-CVOC-OU3-3 15.5-19.0 ft	270661	X	-23.76		X	-22.69		X	-29.25		X	-40.58	-39.20	22945	6674	6237	471
4	NAS-GW-CVOC-OU3-3 17.0-19.0 ft	270662	X	-24.36		X	-24.62		X	-29.29		X	-38.87		41505	6590	4813	464
5	NAS-GW-CVOC-OU3-3 19.5-21.5 ft	270663	X	-24.45		X	-23.23		X	-29.61			-38.55		17670	4413	4517	100
6	NAS-GW-CVOC-OU3-3 22.0-24.0 ft	270664	X	-23.21		X	-22.47		X	-29.37		X	BAL		41630	5957	2984	398
7	NAS-GW-CVOC-OU3-3 24.5-28.0 ft	270665	X	-22.29	-22.59	X	-28.20	-28.38	X	-26.16	-26.67				760	7	20	1
8	NAS-GW-CVOC-OU3-5 8.5-12.0 ft	270666	X	BAL		X	-11.16		X	-26.67		X	-38.40		817	158	29564	1395
9	NAS-GW-CVOC-OU3-5 12.5-16.0 ft	270667	X	-24.04		X	-25.03	-24.16	X	-28.01	-28.66	X	-44.22		19516	7415	27872	7287
10	NAS-GW-CVOC-OU3-5 16.0-18.0 ft	270668	X	-24.40	-23.35	X	-26.44	-26.19	X	-29.36	-29.20	X	-34.58		18156	3350	11834	582
11	NAS-GW-CVOC-OU3-5 19.0-21.0 ft	270669	X	-23.77		X	-24.21		X	-26.89		X	-31.51		1930	299	1316	50
12	NAS-GW-CVOC-OU3-5 22.0-24.0 ft	270670	X	-23.35		X	-24.35		X	-27.29					297	173	311	5
13	NAS-GW-CVOC-OU3-5 24.5-28.0 ft	270671	X	-17.06		X	-22.58		X	-29.02					348	364	893	5
14	NAS-GW-CVOC-OU3-6 8.5-12.0 ft	270672	X	BAL					X	-21.09		X	-20.66		7	2	2128	756
15	NAS-GW-CVOC-OU3-6 12.5-16.0 ft	270673	X	-22.42		X	-29.26		X	-22.94		X	-34.86		1134	175	11160	3821
16	NAS-GW-CVOC-OU3-6 16.0-18.0 ft	270674	X	-22.41		X	-28.33		X	-26.93	-26.09	X	-33.36		4032	1288	18881	4764
17	NAS-GW-CVOC-OU3-6 19.0-21.0 ft	270675	X	-21.99	-22.75	X	-23.12	-24.04	X	-29.05		X	-25.19	-24.27	192	69	2186	143
18	NAS-GW-CVOC-OU3-6 22.0-24.0 ft	270676	X	-22.14		X	-24.83		X	-26.50		X	-20.64		73	104	189	198
19	NAS-GW-CVOC-OU3-6 25.0-28.5 ft	270677	X	-14.91		X	-23.89		X	-26.18		X	-32.52	-33.64	17	18	1085	73
20	Dup-1 = OU3-5 12.5-16.0	270678	X	-24.66		X	-24.66		X	-28.81		X	-35.73		19516	7415	27872	7287
21	Dup-2 = OU3-3 15.5-19.0	270679	X	-23.83	-23.17	X	-23.28		X	-28.80	-29.00	X	-39.06		22945	6674	6237	471

Notes:
1. All analyses completed at the University of Waterloo.
2. BAL=Below Analytical Limit

APPENDIX O

Overview of Rapid Extraction Methods for Analyses of Low Permeability Soils (from Stone Environmental Inc.)

Understanding Contaminant Mass in Low Permeability Layers

Challenges and Solutions with VOC Extractions

It is well known that low-permeability soils within aquifers represent long-term sources of contaminants contributing to plume persistence, even after the primary source has been isolated. An accurate understanding of the contaminant mass in such soils is critical for effective remedial design. It is essential that an investigation include a sampling and analysis program focused on these aquitard materials in addition to the groundwater sampling in the high-permeability zones. It is equally essential that the extraction and analytical method used have the ability to recover all, or nearly all of the mass present in these low-permeability materials. Failure to adequately assess the mass present in the "immobile porosity" of the aquitard materials can translate to failure of the remedial strategy.

Rapid and accurate analyses of volatile organic compounds (VOCs) in soil samples can be complicated by the diffusive flux rate-limited removal of VOCs from low-permeability samples.

Sampling for VOCs in soils requires adequate preservation techniques This requirement is underscored by the outstanding work of Alan Hewitt of Cold Regions Research and Engineering Laboratory and others, demonstrating that sampling without adequate preservation can lead to measurements that are orders of magnitude lower than what is really in the soil. Today, the two most common methods used for the preservation and analyses of VOCs in soil are 1) a low-level method: sodium bisulfate field preservation with analyses via purge and trap or heated headspace followed by GC/MS and 2) a medium to high-level method where the soils are immediately placed into methanol followed by mechanical agitationand analyses by GC/MS.

Even with sound field preservation techniques, erroneously low VOC concentrations result if the subsequent extraction does not adequately remove all of the contaminants from the soil. According to Hewitt (1998), the purge and trap and heated headspace methods often provide lower estimates than obtained by methanol extraction. Further, the differences between the two methods often increased with increasing organic carbon content in the soil matrix and analyte octanol/water portioning coefficient. Hewitt conludes that "when matrix interferences are expected or identified, methanol extraction should be the method of choice. If methanol is not used, then it should be recognized that in comparison, most alternative procedures will results in lower quantitative recoveries". Essentially, the methanol is superior to water as it can better prevent losses during storage due to volatilization and is much more efficient at desorbing the VOCs from the organic material present in the soil.

The primary major factor limiting the efficiency of VOC extraction from samples of silt and/or clay materials is that the transport of contaminants out of the sample is limited by the rate of diffusion. Decreasing the distance over which this transport has to occur, by completely disaggregating the clay material, accelerates the extraction. Dincutoiu et al (2003) conducted several experiments to determine a method for rapidly disaggregating these types of samples and achieving a nearly 100% extraction of TCE from clay samples. The results of the experiments are described below and compared to a "standard procedure" that involved shaking the clay/methanol samples for 30 minutes followed by a five-day equilibration period prior to analysis.

1. A 30-minute shake step resulted in an approximately 43% underestimation of TCE concentration as compared to the standard procedure. It was observed by the researchers that the clay material had not been significantly disaggregated during the agitation process.
2. A 1.5 hour sonication period resulted in significantly underestimated TCE concentration (between 8% and 54%) as compared to the standard procedure. The clay particles were found to settle rapidly forming very dense layers which likely inhibited the movement of contaminants out of these layers. Essentially, "reaggregation" occurred.
3. A stepwise shake/sonication/shake procedure (approximately 2 hours) resulted in nearly complete recovery of TCE. The sonication was required to break up the clay particles and the shaking step allowed for the particles to remain suspended in the methanol throughout the extraction.
4. To optimize the process, the authors devised an apparatus that allowed for the simultaneous shaking and sonication of the samples which lead to a nearly 100% extraction efficiency in a one-hour extraction period.

Industry standard extraction/analysis methods for soils (e.g., purge & trap) are not sufficient for adequate recovery of contaminants from low permeability materials. The efficiency of VOC extractions from soils is greatly dependent on the solvent used (methanol or water), the cohesiveness of the samples, and how well the particles are kept in suspension during the extraction; typically, the higher the clay content the tougher it is to disaggregate the soils during extraction process. Using fairly simple and available techniques, one can readily achieve very rapid and efficient extraction of VOCs from low-permeability soils. Given the likelihood of a large part (even the majority) of the total contaminant mass at a given site to be present in these low permeability layers, it is essential that adequate sampling, extraction and analytical procedures be employed.

References

Dincutoiu "A Novel technique for rapid Extraction of Volatile Organohalogen Compounds from Low Permeability Media" Juliana Dincutou, Tadeusz Gorecki, and Beth Parker. Envir. Sci. Technology 2003, 37, 3978-3984.

Hewitt, A. 1998. "Comparison of sample Preparation Methods for the Analyseis of Volatile Organic Compunds in Soil Samples: Solvent Extraction vs Vapor Partitioning" Alan D. Hewitt, Envir. Sci. Technology 1998, 32 143-149.

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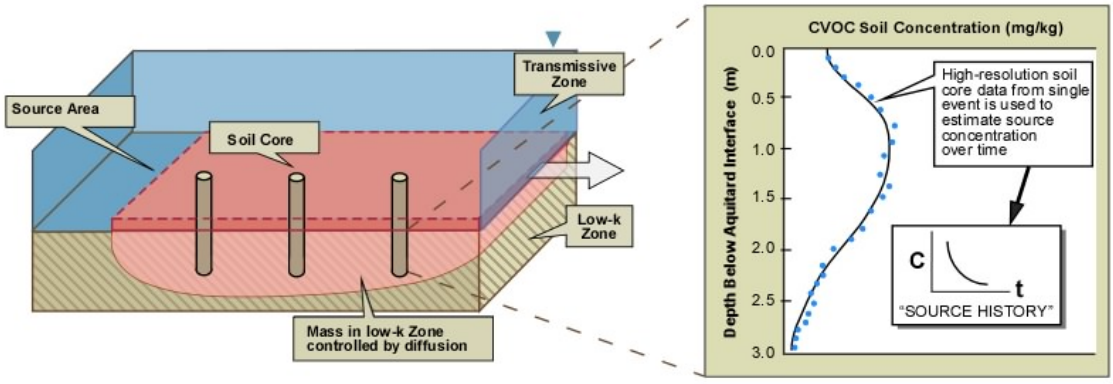
APPENDIX P

User's Manual for ESTCP Source History Tool

ESTCP Source History Tool

USER'S MANUAL

Version 1.0
September 2013



S.K. Farhat ♦ P.C. de Blanc ♦ C.J. Newell
D.T. Adamson

GSI ENVIRONMENTAL INC.
HOUSTON, TEXAS

ESTCP



DISCLAIMER

The *ESTCP Source History Tool* is available "as is." Considerable care has been exercised in preparing this manual and software product; however, no party, including without limitation the United States Government, GSI Environmental Inc., the authors and reviewers, make any representation or warranty regarding the accuracy, correctness, or completeness of the information contained herein, and no such party shall be liable for any direct, indirect, consequential, incidental or other damages resulting from the use of this product or the information contained herein. Information in this publication is subject to change without notice. Implementation of the ESTCP Source History Tool and interpretation of the predictions of the models are the sole responsibility of the user.

CITE USING

Farhat, S.K., P.C. de Blanc, C.J. Newell, and D.T. Adamson, 2013. Source History Tool, developed for the Environmental Security Technology Certification Program (ESTCP) by GSI Environmental Inc., Houston, Texas.

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SOURCE HISTORY TOOL

Environmental Security Technology Certification Program

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INTRODUCTION

One of the key constraints in the selection of remedies for closing sites contaminated by chlorinated solvents is that there is typically only a short time interval where monitoring data are available to assess trends. This problem is exacerbated in situations where source material is expected to be present because of uncertainty in plume stability versus source stability. In particular, this hinders an evaluation of monitored natural attenuation (MNA) as a remedy, despite the fact that recent historical surveys of MNA have determined that it was a feasible remedy in over 75% of the sites where it was included in the evaluation, either alone or in conjunction with an active treatment technology (McGuire et al., 2004; Newell, 2006). Often concentration trends are difficult to discern, even with the use of advanced statistical tools such as AFCEC's MAROS tool, such that insufficient evidence is available to demonstrate that natural attenuation is viable. This can delay the decision-making process until more data can be collected and evaluated, and any supplemental data is gathered to support a "lines of evidence" approach that is not necessarily definitive or reflective of long-term trends.

Furthermore, regulators frequently adhere to a conceptual model of an unchanging, non-attenuating source zone, and insist on source remediation projects to replace or augment natural attenuation. As a result, site managers often are faced with implementing a costly technology and demonstrating performance in terms of mass removal efficiency, even though estimates of the mass present or remaining in a source zone are typically difficult to make and are subject to significant uncertainty given the limitations in monitoring data and investigation resolution, especially as subsurface releases age over time.

To aid in the selection of MNA as a long-term remedy, the Environmental Security Technology Certification Program (ESTCP) of the U.S. Department of Defense (DoD) has funded the development of this ESTCP Source History Tool (Toolkit).

Based on the Microsoft Excel® platform, the Toolkit is an easy-to-use, comprehensive, free software tool that can assist site personnel reconstruct long-term source histories that extend back to the beginning of the original source release. Methods developed by Parker et al. (2004, 2005, 2008), specifically, the collection of closely spaced soil concentration measurements at discrete depths in low permeability zones within and downgradient of source zones to provide insight into historic concentration trends at interfaces with the low permeability zones, provide a focused way to reconstruct long-term source histories that extend back to the beginning of the original source release.

The Source History Tool was developed for the ESTCP by GSI Environmental Inc., Houston, Texas.

INTENDED USES AND LIMITATIONS

The **ESTCP Source History Tool** attempts to assist site managers and site consultants better understand and reconstruct long-term source histories. A long-term source history, from the beginning of releases at a site to present time, would help confirm a site conceptual model that shows attenuation is a significant process for both the source and the plume, and generate data that are well-suited for use in predicting future concentration and attenuation trends. Reducing the uncertainty associated with assessing long-term concentration trends before a remedy is selected and implemented, could assist site stakeholders select more appropriate remedies and improve effective risk communication with regulators and the public.

The Toolkit is intended to be used **as a screening level tool for reconstructing long-term source history effects.** The Toolkit brings key technical resources, an easy-to-use calculation worksheet, and case studies together into one easy-to-access platform.

In addition, the Toolkit provides a Monte Carlo-type approach to analyze uncertainty in the input parameters such as the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life. With this tool, groundwater practitioners can evaluate the accuracy of the hydrologic measurements that are being used for the reconstruction of source histories.

The Toolkit has the following assumptions and limitations:

- Assumes the User is familiar with basic groundwater transport and mass balance concepts.
- Assumes the presence of low permeability strata within or downgradient of the source zone.
- Assumes diffusion occurs only in the water phase.
- Requires presence and delineation of interface between two geologic strata with contrasting permeabilities.
- Collection of high-resolution data can be costly at sites with complex geology or deep contamination.
- Presence of multiple sources and/or commingled plumes can complicate analysis.
- Modeling may generate multiple “source histories” solutions, such that some User knowledge is required to narrow down solutions to most appropriate.
- Occurrence of reactions (abiotic or biotic), non-linear sorption, etc. within the low-k zones can complicate analysis.
- To run the Monte Carlo analysis, Users need to estimate what type of statistical distribution best fits the input data and what values best describe the distribution.

In many cases data will be unavailable to make these estimates, so the User may have to rely on scientific/engineering judgment to use the Monte Carlo analysis.

- The Monte Carlo analysis cannot account for plume data that are not part of the monitoring system. Actual concentration values can be outside the reported range of values from the Monte Carlo analysis (for example, if new data show high concentration zones that were not captured by the original monitoring network).

FREQUENTLY ASKED QUESTIONS

What is a low-k zone? Do I have these zones at my site?

Based on her research program at the University of Guelph, Dr. Beth Parker has a rule of thumb indicating that matrix diffusion can be an important process if there is a plume in a transmissive zone that is in contact with adjacent zones that have permeabilities lower than by a factor of 100 or more. In other words, if a contaminant plume moving in a 10^{-3} cm/sec sand is in contact with a 10^{-5} cm/sec silt, then the silt can be charged up with contaminants during a loading period (when concentrations in the sand are higher than the silt) and then slowly discharge contaminants into the sand via diffusion when the silt has higher concentrations than the sand.

What does the ESTCP Source History Tool do?

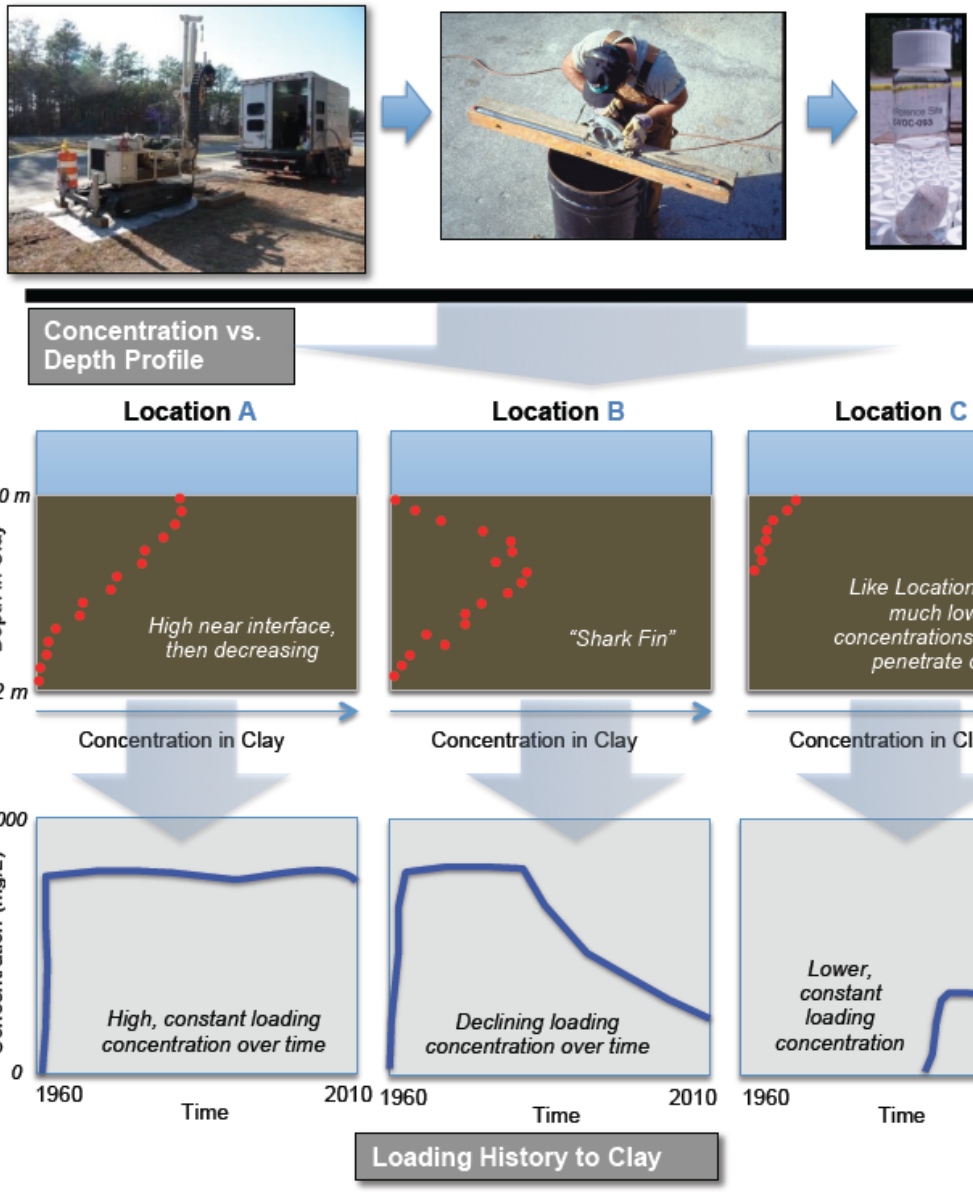
The Toolkit generates an estimate of the source concentration over time, i.e., a "source history", that can be used as a line of evidence for natural attenuation (see Exhibit 1 for Conceptual Example). At many sites, natural attenuation has been proposed, but not accepted by regulators due to concerns that the source is not being treated fast enough, or where routine monitoring data do not show definitive trends. A long-term source history, from the beginning of releases at a site to present time, would help confirm a site conceptual model that shows attenuation is a significant process for both the source and the plume, and generate data that are well-suited for use in predicting future concentration and attenuation trends. The Toolkit can assist site personnel reconstruct long-term source histories that extend back to the beginning of the original source release. Reducing the uncertainty associated with assessing long-term concentration trends before a remedy is selected and implemented, could assist site stakeholders select more appropriate remedies and improve effective risk communication with regulators and the public.

Do I need sampling data from the low-k zones to run the Toolkit?

Yes, you will need high-resolution, depth-discrete soil samples near geologic interfaces in contact with lower permeability zones, within or downgradient of the source, to generate a detailed contaminant profile with depth within these zones. These soil data are similar to a "tree ring" in that they provide historical information (even though they are collected at a single point in time).

EXHIBIT 1
Reconstructing Source Histories from High-Resolution Sampling of Low-k Zones: Conceptual Example

1. First collect high-resolution data to find the interfaces between contaminated transmissive zones and underlying/overlying low-k zones (typically clays or silts).
2. Then find the concentration vs. penetration depth profile in the low-k zone.
3. With this data, the general style of the long-term source history in the transmissive zone at the location the core was collected can be estimated.



What input data will I need?

The high-resolution soil contaminant profile with depth is the key input data, but there are a few other pieces of information that are important. Some of these input parameters are similar to what is used for existing solute transport models (e.g., Darcy groundwater velocity, size of the modeled area, information on when the source started, etc.) Other input data will look new to many Users, for example, you'll need to estimate the tortuosity of the low-k materials where matrix diffusion has occurred, diffusion coefficients, and fraction organic carbon of the clays and silts being modeled, etc. The Toolkit provides default values and advice on selecting representative values for your site conditions.

Does the Toolkit provide default values or guidance for input parameters?

Yes. The Toolkit asks you to provide these key input data:

1. What is your best estimate for the year the original release occurred? This is based on your understanding of site history.
2. What is your best guess for the concentration in the year of original release? It is rare to have monitoring data from the time of the release to now, so we've provided some guidance based on the maximum concentration ever observed (see Data Entry Step 3).
3. What is the **diffusion coefficient** for the contaminant of interest? The Toolkit provides a library of diffusion coefficients for the most common contaminants we deal with at sites.
4. What are the key transport properties of the clay: **tortuosity and retardation factor**? The Toolkit provides a calculator for you to estimate these parameters if you are not familiar with them.

What contaminants can be modeled with the Toolkit?

To date, most of the research involving matrix diffusion processes for low-k zones has focused on chlorinated solvents such as TCE (trichloroethene). However, in theory, the Toolkit should apply to almost any dissolved contaminant, including benzene and other aromatic compounds found in gasoline.

How does the Toolkit handle uncertainty?

The Toolkit utilizes a Monte Carlo-type approach to analyze uncertainty in the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life measurements. With this tool, groundwater practitioners can estimate 1) the accuracy of the hydrologic measurements being used for the source history reconstruction and 2) the sensitivity of the model to these parameters.

Of course, with more field data, the accuracy of the modeling results will increase.

How accurate are the Toolkit results?

Because of the simplifying assumptions in the model, and the early state of matrix diffusion modeling in general, we consider the Toolkit to be a screening level accuracy tool.

MODEL PROTOCOLS

Collection of High-Resolution Core Data

Application of the ESTCP Source History Tool requires high-resolution characterization data collected from soil cores in the low-k zone. This is because the output of the model—the source concentration history over time—is based on fitting predictions of soil concentrations (based on the one-dimensional diffusion equation) to actual (measured) soil data. Consequently, the more comprehensive the dataset, the greater the confidence that the model is capturing the general "style" of source attenuation history at the site.

Based on this objective, the following recommendations are made with respect to collecting high-resolution data from soil cores (additional detail is provided in Appendix 1):

ISSUE	RECOMMENDATION
Identifying suitable locations for coring	• Use one (or more) of several commercially-available rapid data acquisition tools (e.g., MIP, Waterloo Profiler, Geoprobe HPT) that provide high-resolution hydrostratigraphic information. • Focus on establishing the permeability distribution, particularly depth(s) where the interface between high and low permeability units occurs.

Core collection methods	• Many suitable options, including:
	  • Direct-push (Geoprobe) methods (dual-tube or MacroCore).
	  • Sonic methods (including AquaLok).
	  • Auger-based methods.

Sampling frequency with depth	• 1 sample per vertical ft of core or less at a minimum. • 1 sample per 0.2 to 0.5 vertical ft of core is preferred within low-k zones. • Also should collect samples within transmissive zone (though lower frequency than in low-k is acceptable)
Sampling frequency with time	• Collecting core data during a single event is acceptable for using the Toolkit.
Number of coring locations per source area	• Small and/or well-delineated source area: 1 -2 borings. • Larger, heterogeneous, and/or poorly-delineated site: 3-4 borings. • Focus on collecting cores along transects or flowpath to evaluate/confirm trends.
Analytical data to be collected	• Soil VOC concentration. • Soil f_{oc} (selected depths to get representative value or distribution of values). • Optional (to evaluate degradation or other processes; some may require collection of groundwater samples): isotopes (e.g., ^{13}C), molecular biomarkers (e.g., *Dehalococcoides)*, sulfate, methane, etc.
Sample handling and analysis considerations	• Immediate methanol preservation in field is strongly recommended. • Consider using extended and/or enhanced extraction methods to improve recovery and detection limits within low-k matrices.

ISSUE	RECOMMENDATION
Groundwater data	• Not required for Toolkit, but is useful for calibrating and confirming model simulations. • Collected at same time as soil data: useful in confirming concentrations near interface are being accurately simulated. • Collected over several events (years) following coring: useful in confirming predicted source history trends are reasonable. • May also provide valuable information regarding degradation.

How to Use the ESTCP Source History Tool

The Toolkit couples a detailed site characterization approach involving collection of high-resolution profiles of contaminant concentrations in lower permeability zones with transport modeling to reconstruct the source history at a site.

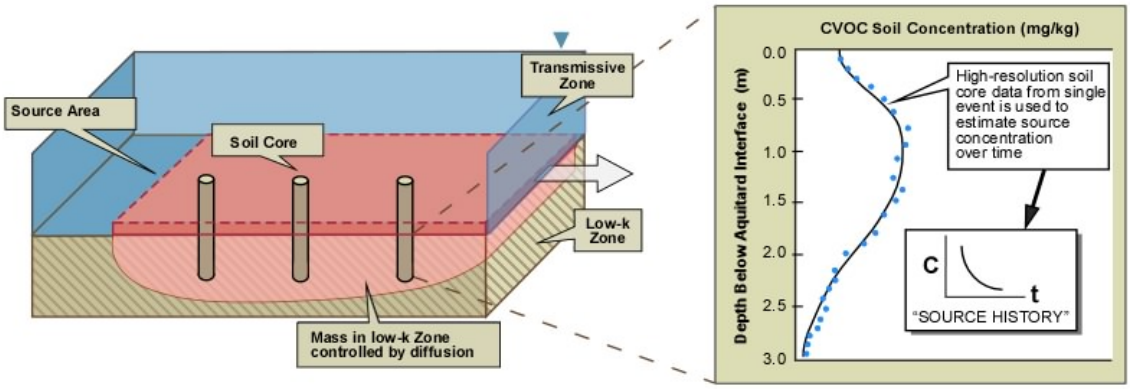


Figure 1: Conceptual model of the ESTCP Source History Tool.

Governing equations and assumptions are provided in Appendix 2. Guidelines for selecting key input parameters for the model are outlined in Data Entry. For help on results, see Model Results.

Uncertainty Analysis

Similar to other modeling approaches, the level of uncertainty in the estimated source history reconstruction is a key issue. The Toolkit provides a Monte Carlo-type approach to analyze uncertainty in the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life measurements. With this tool, groundwater practitioners can estimate the accuracy of the hydrologic measurements that are being used for the source history reconstruction.

Monte Carlo analysis is a method of analyzing and quantifying uncertainties in model outputs due to the uncertainties in the input parameters (Rong *et al.*, 1998). Monte Carlo analysis refers to a computer-based system that uses random numbers from a probability distribution to obtain an approximation for the parameter of interest (USEPA, 1997; Bergin and Milford, 2000).

In the standard Monte Carlo approach, simple random sampling and a large number of runs (typically 100 to 1000) are required to obtain a meaningful probability distribution for the parameter. For each run of the standard approach, a random number is generated for the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life entered by the User. This set of random inputs is then used to calculate concentration in the low-k unit. Repeating this procedure a large number times yields a probability distribution from which statistical characteristics such as mean, percentile, and variance can be obtained.

The Toolkit performs 253 iterations for the Monte Carlo approach (limited by the maximum number of lines that can be plotted in an Excel graph).

Guidelines for selecting key input parameters for the model are outlined in Uncertainty Analysis.

DATA ENTRY

Data Input Screen
Results
Uncertainty Analysis

Three important considerations regarding data input are:

1) To see the example dataset in the input screen of the software, click on the *Paste Example* button on the lower right portion of the input screen.
2) Because the Toolkit is based on an Excel® spreadsheet, you have to click outside of the cell where you just entered data or hit *Return* before any of the buttons will function. Additionally, **REMOVING OR ADDING** rows or columns in input screens may cause the program to crash.
3) Parameters used in the model are to be entered directly into the white/blue cells.

NOTE: Although literature values are provided, site-specific hydrogeologic, transport, and plume characteristic values will likely provide better results. If literature values are used and there is uncertainty in the value chosen, sensitivity analyses should be conducted to determine the effects of the uncertainty on model predictions.

Recommendations regarding calibrating (fitting) Toolkit to actual field data

The goal of this modeling approach is to match the ***style*** of the actual soil VOC concentration vs. depth data. The Toolkit generates a simulated soil VOC concentration profile (from the source concentration vs. time estimate) and the User attempts to match the shape of this profile to actual soil data.

After all input information has been entered, the initial model output is compared to high-resolution core data collected from the low-k unit. The initial run is based on a preliminary guess for the source concentration vs. time pattern (i.e., the source history). In most instances, this initial run will not produce modeled data that match field data. Considerations and recommended steps to improve the fit of simulated to field data are provided below.

In cases where a good comparison between field-measured vertical profiles of soil concentrations and model simulated concentrations can be made, the recommended sequence of model input values to change is:

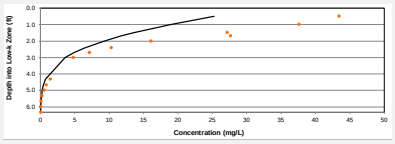
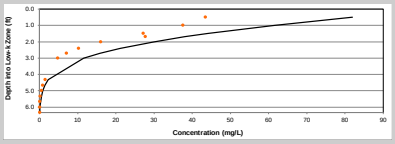
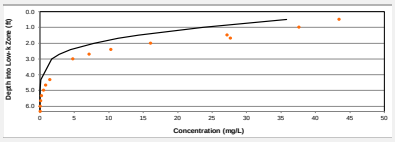
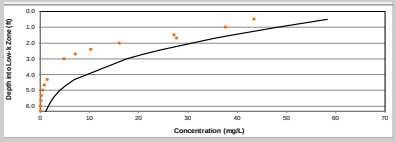
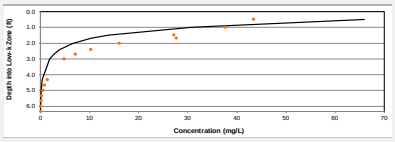
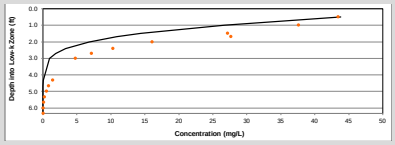
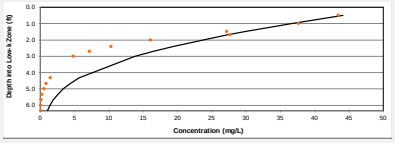
1. If the styles of the actual soil data and simulated soil data are significantly different, then the first step should be to simply select a different source concentration vs. time pattern (e.g., exponential decay instead of constant source). If there is no general improvement in the fit, then the User may wish to revert back to the initial guess for the pattern.

2. Next, change the "source concentration" (C_o). If the simulated concentrations (solid black line in the concentration vs. depth graph) are higher than observed concentrations, increase the concentration. Decrease the source concentration if simulated concentrations are lower than observed concentrations.
3. Fitting the data at the interface is easiest to achieve because it is highly dependent on the source concentration at the most recent timepoint. The latter should be adjusted until the condition is met.
4. The source concentration (C_o) can then be further adjusted as needed to match the peak concentration (either at the interface for constant source patterns, or at some depth below the interface for attenuating source patterns).
5. After choosing first-round guesses for the source concentration and the source concentration at the most recent timepoint, the source concentration at intermediate times can be adjusted as needed. Note that these values generally have limited impact on the extent that the target constituents penetrate to deeper intervals, but will influence the concentrations observed closer to the interface.
6. If it is still difficult to get a good fit, try changing the estimate for the original source release if there is some uncertainty on the exact year. To increase the simulated concentrations, move the start of the release period earlier in time. In other words, more time for diffusion into low-k zones during the source loading period will result in higher concentrations in the low-k zone.
7. To further improve the match, after working with the previous steps, consider changing some of the hydrogeologic and/or transport properties such as Darcy velocity (advection-diffusion dominated flow), tortuosity, and retardation factor. Other parameters in the model can also be changed to develop a better match.

Other helpful hints in achieving good results from the Toolkit are described below:

1. Clear evidence that the peak soil concentration occurs below the depth of the permeability interface (i.e., depth = 0) is indicative of a source concentration that has decreased over time. In such cases, exponential decay or linear decay patterns should be selected as a starting point and refinements made.
2. Conversely, a single depth-discrete sample with a high concentration from below the interface may be anomalous if this point is not consistent with the pattern of surrounding datapoints. In general, several points with high concentrations below the interface should be present before selecting an attenuation-based source concentration vs. time pattern.
3. The Root Mean Square (RMS) error and the Relative Error (RE) are suitable for evaluating the closeness of fit between actual and simulated data. However, neither should be considered an absolute optimization metric. Each can suffer from biases due to one or more datapoints that may (or may not) be representative of the entire dataset. In some cases, better (or more sensible) visual fits can be obtained even at higher RMS/RE error values.
4. The best fits occur when the following conditions are met and there is a close match between actual and simulated data: i) at the permeability interface; ii) at the depth where the peak concentration is encountered; and iii) at the deepest depth where the target constituent has been detected.

Additional guidance on obtaining good fits between actual and modeled data is provided in the following table:

PROBLEM IN MATCHING SOIL DATA	EXAMPLE (● = measured soil data) (— = simulated soil data)	POTENTIAL ADJUSTMENT(S) TO TRY TO IMPROVE MATCH
Measured concentration at interface is too low		• Increase source concentration at most recent timepoint • Increase initial source concentration (C_o) • Increase porosity
Measured concentration at interface is too high		• Decrease source concentration at most recent timepoint • Decrease initial source concentration (C_o) • Decrease porosity
Measured concentration is uniformly too low at most depths		• Increase source concentration at all timepoints • Increase initial source concentration (C_o) • Increase porosity
Measured concentration is uniformly too high at most depths		• Decrease source concentration at all timepoints • Decrease initial source concentration (C_o) • Decrease porosity
Measured concentration is overestimated at shallow intervals but underestimated at deeper intervals		• Decrease f_{oc}/K_d • Decrease initial source concentration (C_o) and/or source concentration at most recent timepoint, then increase source concentration at earlier timepoints
Measured concentration at interface shows good match but penetration to deeper intervals is insufficient		• Select earlier release date • Decrease foc/Kd • Increase source concentration at earlier timepoints • Increase tortuosity • Increase half-life in low k zone • Include vertical advection
Measured concentration at interface shows good match but excessive penetration to deeper intervals is observed		• Select later release date • Increase foc/Kd • Decrease source concentration at earlier timepoints • Decrease tortuosity • Decrease half-life in low k zone

It should be understood that the analysis can be complicated by the presence of multiple sources, commingled plumes, occurrence of reactions (abiotic or biotic), non-linear sorption, etc. within the low-k zones. The influence of degradation reactions can be accounted for in the Toolkit, but other factors that are not part of the model may be more difficult to incorporate. Because of the simplifying assumptions in the model, and the early state of matrix diffusion modeling in general, we consider the Toolkit to be a screening level accuracy tool.

Projected Modeled Parameter Sensitivity

To supplement the information provided in the previous sections, the following table summarizes how the individual input parameters influence the results. Specifically, it describes how an increase or a decrease in the value of these parameters can impact the simulated soil concentration vs. depth profile that is being fitted to the actual soil data.

PARAMETER	PRIMARY EFFECT OF INCREASING PARAMETER VALUE	PRIMARY EFFECT OF DECREASING PARAMETER VALUE
Diffusion Coefficient (D_o)	↑ penetration to deeper intervals	↓ penetration to deeper intervals
Porosity (n)	↓ penetration to deeper intervals	↑ penetration to deeper intervals
Soil bulk density (ρ_b)	↓ soil concentration ↓ penetration to deeper intervals	↑ soil concentration ↑ penetration to deeper intervals
f_{oc}/K_d	↑ soil concentration ↓ penetration to deeper intervals	↓ soil concentration ↑ penetration to deeper intervals
Half-life in low-k zone	↑ soil concentration ↑ penetration to deeper intervals	↓ soil concentration ↓ penetration to deeper intervals
Initial Source Concentration (C_o)	↑ soil concentration (particularly at interface) ↑ constituent penetration	↑ soil concentration (particularly at interface) ↑ penetration to deeper intervals
Release date (t_0)	↑ penetration to deeper intervals (from later dates)	↓ penetration to deeper intervals (from later dates)
Source Concentration at most recent timepoint	↑ soil concentration	↓ soil concentration
Source Concentrations at intermediate timepoints	↑ soil concentration	↓ soil concentration
OTHER INPUT INFORMATION		
Soil Type	Influences porosity and tortuosity	
Transport Type	Option to include vertical advection component	
Key Constituent	Influences diffusion coefficient and retardation factor	

Notes: (1) *Source concentration* refers to concentration of target constituent in the transmissive zone above low k zone; (2) *Soil concentration* refers to concentration of target constituent in the soil core collected from the low k zone; (3) *Penetration* refers to transport of detectable levels of the target constituent to deeper portions of the low k zone.

Data Input Screen:

Step 1: *Hydrogeology*

PARAMETER	TYPE OF MATERIAL IN LOW-k ZONE
Description	Description of the soil type in the low-k zone.
How to Enter Data	Choose from drop down list or enter directly. (Note that if using a Macintosh, the drop down options are accessed by pressing the mouse and clicking on the dropdown button.)

PARAMETER	TOTAL POROSITY (n)
Units	Unitless.
Description	Dimensionless ratio of the volume of voids to the bulk volume of the surface soil column matrix, but excluding secondary porosity (fractures, solution cavities, etc.). Total porosity is the ratio of all voids (including non-connected voids) to the bulk volume of the aquifer matrix. Effective porosity and any porosity data with secondary porosity information should not be used.
Typical Values	The model input screen has these default values: Clay 0.47 (mid-range of values below) Silt 0.48 (mid-range of values below) Sandstone/shale 0.10 (Pankow and Cherry (1996), Table 12.2) Fractured Sandstone 0.08 (Pankow and Cherry (1996), Table 12.2) Granite 0.006 (Pankow and Cherry (1996), Table 12.2) Values for total porosity from Domenico and Schwartz (1990), in part from Davis (1969), and Johnson and Morris (1962): **SEDIMENTARY** Porosity (-) Gravel, coarse 0.24 - 0.36 Gravel, fine 0.25 - 0.38 Sand, course 0.31 - 0.46 Sand, fine 0.26 - 0.53 Silt 0.34 - 0.61 Clay 0.34 - 0.60 **SEDIMENTARY ROCKS** Sandstone 0.05 - 0.30 Siltstone 0.21 - 0.41 Shale 0 - 0.10 **CRYSTALLINE ROCKS** Dense crystalline rocks 0 - 0.05 Koerner (1984) reports these values for unit weight for saturated soils (note no dry bulk density values are reported for these materials): Glacial till, very mixed grain: 0.20 Stiff glacial clay: 0.37 Soft very organic clay: 0.75 Soft glacial clay: 0.57 Soft slightly organic clay: 0.66 Soft bentonite: 0.84 One fractured microcrystalline limestone in Virginia had matrix porosities ranging from 0.0004 to 0.0065 (GSI Environmental).
Source of Data	Typically estimated. Occasionally obtained through physical property testing of site soil samples.

How to Enter Data	Enter directly. (Note that if the low-k zone description is selected from the drop down list, the Toolkit provides a default value for the parameter.)

PARAMETER	**TRANSPORT TYPE**
Description	The Toolkit can use diffusion as the sole transport process for contaminants in the low-k zone, or it can include both diffusion plus vertical (1-D) advection as relevant transport processes.
How to Enter Data	Choose from drop down list. (Note that if using a Macintosh, the drop down options are accessed by pressing the mouse and clicking on the dropdown button.)

PARAMETER	**HYDRAULIC CONDUCTIVITY (K)**
Units	cm/sec, ft(or m)/day, ft(or m)/yr.
Description	Measure of the permeability of the low-k layer. To characterize concentrations in the low-k layer utilizing advection, representative measurements are required for both the hydraulic conductivity and the hydraulic flow gradient of the flow system. Representative measurements of the hydraulic conductivity of the low-k layer should be obtained at one or more locations using appropriate slug test or pumping test methods (Newell et al., 2003). Apply a correction for anisotropy as needed (e.g., vertical conductivity value may be less than horizontal conductivity value). Note that this parameter is required only if the advection option is included in the Transport Type.
Typical Values	*Horizontal K* Clay: $<1x10^{-6}$ cm/s Fractured Sandstone: $1x10^{-6}$ - $1x10^{-2}$ cm/s Limestone: $1x10^{-7}$ - $1x10^{-4}$ cm/s Sandstone: $1x10^{-8}$ - $1x10^{-4}$ cm/s Shale: $1x10^{-11}$ - $1x10^{-7}$ cm/s Silt: $1x10^{-6}$ - $1x10^{-3}$ cm/s (Newell *et al*., 1996; Freeze and Cherry, 1979.) Note, for vertical hydraulic conductivities, dividing horizontal K by a factor of 3 or less is common for homogenous aquifers while dividing by a factor of 10 or more may be appropriate for heterogeneous aquifers (Freeze and Cherry, 1979; Parker et al., 2004).
Source of Data	Pump tests or slug tests at the site. It is strongly recommended that actual site data be used for all evaluations.
How to Enter Data	1) Select units, and 2) Enter directly.

PARAMETER	VERTICAL HYDRAULIC GRADIENT (i)
Units	ft/ft (or m/m).
Description	The head difference between two adjacent well relative to the distance between the screened intervals of the wells. It defines the direction of groundwater flow (upward or downward) and is proportional to the magnitude of the flow. Note that this parameter is required only if the advection option is included in the Transport Type.
Typical Values	0.0001 - 0.1 ft/ft (0.0001 - 0.1 m/m).
Source of Data	Calculated using static water level data from monitoring wells installed at the same location but screened at different depths within the same formation. The gradient is calculated as the difference between the measured water levels in these wells divided by the difference in screen depth between the wells.
How to Enter Data	Enter directly.

Step 2: *Transport*

PARAMETER	KEY CONSTITUENT DIFFUSED IN LOW-k ZONE
Description	Constituent of interest.
How to Enter Data	Enter directly or choose from drop down list.

PARAMETER	MOLECULAR DIFFUSION COEFFICIENT IN FREE WATER (D_o)
Units	cm^2/sec, m^2/sec.
Description	A factor of proportionality representing the amount of substance diffusing across a unit area through a unit concentration gradient in unit time.
Typical Values	Benzene 9.8E-06 cm^2/s; Ethylbenzene 7.8E-06 cm^2/s; Toluene 8.6-06 cm^2/s; Xylene 8.5E-06 cm^2/s; MTBE 9.4E-05 cm^2/s; Tetrachloroethene 8.2E-06 cm^2/s; Trichloroethene 9.1E-06 cm^2/s; cis-1,2-Dichloroethene 1.1E-05 cm^2/s; Vinyl Chloride 1.2E-05 cm^2/s; 1,1,1-Trichloroethane 8.8E-06 cm^2/s (TRRP, 2008) (Note that there is a wide range of reported values; for example, Wiedemeier et al. (1999) report a D_o for benzene of 1.1E-05 cm^2/s.) For more information see Pankow and Cherry, 1996 (for solvents) and Wiedemeier et al., 1999 (variety of constituents).
Source of Data	Chemical reference literature such as Pankow and Cherry, 1996 (for solvents); Wiedemeier et al., 1999 (variety of constituents); or other references with chemical properties.
How to Enter Data	1) Select units, and 2) Enter directly. (Note that if the constituent is selected from the drop down

	list, the Toolkit provides a value for the parameter.)

PARAMETER	LOW-k ZONE APPARENT TORTUOSITY FACTOR EXPONENT (p)
Units	Unitless.
Description	The Apparent Tortuosity Factor (τ) relates the molecular diffusion coefficient in free water (D_o) of a constituent in a porous medium to its effective diffusion coefficient (D_e). Values of τ can range between 0 and 1. Estimations of τ can be obtained using the relationship: $$\frac{D_e}{D_o} = \tau \cong n^p$$ Where *n* is the porosity and *p* the Apparent Tortuosity Factor Exponent. Depending on the geologic medium, values for p can vary between 0.3 and 5.4 (Charbeneau, 2000; Pankow and Cherry, 1996; Dullien, 1992; Lerman, 1979; and Millington and Quirk, 1961).
Typical Values	Clay: 1.33 Fractured Sandstone: 0.63 Granite: 0.57 Sandstone/Shale: 1 Silt: 0.33 (Payne et al., 2008.)
Source of Data	Literature.
How to Enter Data	Enter directly. (Note that if the low-k zone description is selected from the drop down list, the Toolkit provides a value for the parameter.)

PARAMETER	BULK DENSITY OF LOW-k ZONE (ρ_b)
Units	g/mL.
Description	Density of the saturated low-k zone (referred to as "soil"), excluding soil moisture.
Typical Values	Although this value can be measured in the lab, estimated values are used in most cases. A value of 1.7 g/mL is used frequently for unconsolidated media. Representative values in g/mL for specific geologic media are shown below (Lovanh et al., 2000; derived from Domenico and Schwartz, 1990). Clay: 1.0 - 2.4 — Loess: 0.75 - 1.6 Sands: 1.6 - 2.68 — Shale: 1.54 - 3.17 Limes: 1.74 - 2.79 — Granite: 2.24 - 2.46 Basalt: 2 - 2.7 — Medium Sand: 1.34 - 1.81 Koerner (1984) reports these values in g/mL for unit weight for saturated soils (note no dry bulk density values are reported for these materials): Glacial till, very mixed grain: 2.32 — Soft glacial clay: 1.77 Stiff glacial clay: 2.07 — Soft slightly organic clay: 1.58 Soft very organic clay: 1.43 — Soft bentonite: 1.27
Source of Data	Either from an analysis of soil samples at a geotechnical lab or more commonly, application of estimated values. Note the Toolkit assumes that concentration data is being entered on a dry

	weight basis. If concentration data is only available on a wet weight basis, then an easy correction is to enter the wet bulk density instead of the dry bulk density. The wet bulk density can be calculated by multiplying the dry density by the following factor: 1+moisture content/100.
How to Enter Data	Enter directly.

PARAMETER	**DISTRIBUTION COEFFICIENT (K_d)**
Units	L/kg.
Description	The partition (or distribution) coefficient between the pore water (ground water) and the soil solids. Calculated as: $$K_d = f_{oc} K_{oc}$$ where f_{oc} is the fraction organic carbon in the low-k zone and K_{oc} the partitioning coefficient.
How to Enter Data	Enter directly.

PARAMETER	**FRACTION ORGANIC CARBON IN LOW-k ZONE (f_{oc})**
Units	Unitless (gram per gram).
Description	Fraction of the aquifer material comprised of natural organic carbon in uncontaminated areas. More natural organic carbon is associated with higher adsorption of organic constituents within the aquifer matrix.
Typical Values	Although based on limited data, 0.0002 - 0.10 for low-k zones is a likely range. But values for some sites may be higher or lower. Examples: At the Moffatt Field site, the foc of the clay fraction is about 0.0066 (Roberts et al., 1990). Domenico and Schwartz (1990) report these values: silt (Wildwood Ontario): 0.00102; from Oconee River sediment: coarse silt: 0.029; medium silt: 0.02; fine silt: 0.0226. Chapman and Parker (2005) report a f_{oc} of glaciolacustrine aquitard composed of varved silts and clays: 0.0024 to 0.00104 with an average of 0.00054. Adamson (2012) reports f_{oc} = 0.001 for a clay layer in Jacksonville, Florida and f_{oc} values for silts at the MMR site in Massachusetts ranging from <0.0005 to 0.0022 (median value = 0.0014) for one core using Leco carbon analyzer; a second core had foc values < 0.005 for 10 samples and two samples with 0.00067 and 0.00084 (gram per gram). Values for f_{oc} using Walkley-Black wet oxidation method were generally higher by a factor of 2 to 3. Values ranging from 0 to 0.078 have been reported for silts at the F.W. Warren site in Wyoming, with a median value of 0.
Source of Data	The fraction organic carbon value should be measured, if possible, by collecting a sample of aquifer material from an uncontaminated saturated zone and performing a laboratory analysis (e.g., ASTM Method 2974-87 or

	equivalent). If unknown, a default value of 0.002 should be used (twice the typical default of 0.001 value used for transmissive systems).
How to Enter Data	Enter directly.

PARAMETER	ORGANIC CARBON PARTITIONING COEFFICIENT (K_{oc})
Units	mL/g.
Description	Chemical-specific partition coefficient between soil organic carbon and the aqueous phase. Larger values indicate greater affinity of organic constituents for the organic carbon fraction of soil. This value is chemical specific and can be found in chemical reference books.
Typical Values	Tetrachloroethene 155 mL/g; Benzene 66 mL/g Trichloroethene 93 mL/g; Ethylbenzene 204 mL/g cis-1,2-Dichloroethene 29 mL/g; Toluene 140 mL/g Vinyl Chloride 11 mL/g; Xylene 240 mL/g 1,1,1-Trichloroethane 110 mL/g; MTBE 14 mL/g (TRRP, 2008.) (Note that there is a wide range of reported values; for example, Mercer and Cohen (1990) report a K_{oc} for benzene of 83 mL/g.) For more information, see Pankow and Cherry, 1996 (for solvents) and Wiedemeier et al., 1999 (variety of constituents).
Source of Data	Chemical reference literature such as Pankow and Cherry, 1996 (for solvents); Wiedemeier et al., 1999 (variety of constituents); or other references with chemical properties. Alternatively, one can use relationships between K_{oc} and solubility or K_{oc} and the octanol-water partition coefficient (K_{ow}) to determine K_{oc}. A collection of values is presented in the Chemical Parameter Database included in this manual.
How to Enter Data	Enter directly. (Note that if the constituent is selected from the drop down list, the Toolkit provides a value for the parameter.)

PARAMETER	CONSTITUENT HALF-LIFE IN LOW-k ZONE ($t_{1/2}$)
Units	Days, years.
Description	Time for dissolved plume concentrations to decay by one half as contaminants migrate through the low-k zone. The amount of degradation that occurs is related to the number of degrading organisms that are present, the degradation rates of these organisms, and the residence time in the low k zone. If unknown, assume 1000 yrs.
Typical Values	Not well established; assume large value (1000 yrs) unless site-specific evidence suggests low values are appropriate Activity in low-k zones is generally thought to be minimal due to soil type constraints that limit microbial activity (e.g., pore size restrictions), but this is a subject of active research.
Source of Data	Typically obtained from microcosm studies.

	Note that many references report the first-order decay coefficients (k); these values can be converted to half-lives ($t_{1/2}$) using $t_{1/2}$ = 0.693 / k. **From site studies:** Biodegradation rate constants can be obtained from calibrated groundwater models.
How to Enter Data	Enter directly.

Step 3: *General*

PARAMETER	YEAR CORE SAMPLE COLLECTED FROM LOW-k ZONE (t_1)
Units	Year (yyyy).
Description	Year high-resolution core data was collected.
How to Enter Data	Enter directly.

PARAMETER	ENTER BEST GUESS FOR CONCENTRATION (C_0)
Units	mg/L.
Description	Representative historical loading concentration of the modeled area. If unknown, assume 10% of plume phase solubility. This value is a key parameter that can be changed during the calibration process to increase or decrease the simulated mass discharge, concentration, or mass to better match field data (see the beginning of this section).
Typical Values	0.0001 – 20,000 mg/L.
Source of Data	*Data Source 1. Site History or Process Information:* For example, the effective solubility of a constituent in a known DNAPL pool in the source could be used when modeling the source zone, or if the DNAPL in the pool was comprised of 50% Trichloroethene (TCE), a concentration of 550 mg/L (50% of TCE solubility of 1100 mg/L) could be used. Alternatively, one could use an estimate of the average historical concentration from the time the source started to the end of the loading period; sometimes a groundwater model with a source decay term (such as REMChlor (Falta et al., 2007)) can be used to estimate historical groundwater concentrations in the early period of a plume's life cycle. *Data Source 2. 10% of Solubility:* More commonly, good Data Source 1 information will not be available. In that case, we recommend using 10% of the plume phase solubility.
How to Enter Data	Enter directly.

Step 4: *High-Resolution Core Data*

PARAMETER	UNITS FOR DEPTH
Units	ft or m.

How to Enter Data	Select from drop down list.

PARAMETER	DEPTH INTO LOW-k ZONE
Units	ft or m.
Description	Vertical depth of the low-k zone from which high-resolution core data are collected.
How to Enter Data	Enter directly. Up to 500 discrete depth intervals can be entered into the Toolkit.

PARAMETER	SOIL CONCENTRATION
Units	mg/kg.
Description	Soil concentration in the low-k zone. These data are converted to equivalent groundwater (porewater) concentrations and displayed on the Concentration vs. Depth graph along with the simulated concentrations.
Source of Data	High-resolution vertical sampling in the area of interest.
How to Enter Data	Enter directly. Up to 500 discrete depth intervals can be entered into the Toolkit.

PARAMETER	IMPORT SOIL DATA
Description	High-resolution core data can be imported into the Toolkit. For this purpose, data must be a tab-delimited text file and follow the format: Depth Conc 0.05 28.96 1.00 25.07 Where the first row contains labels, the first column contains depth information, and the second column contains concentration information. Up to 500 discrete depth intervals can be entered into the Toolkit.

PARAMETER	VIEW ALL SOIL DATA
Description	All high-resolution core data can be viewed at once. On this screen data can be entered directly and/or edited.

Step 5: *Check Data (Optional)*

PARAMETER	CHECK INPUT DATA
Description	A check is performed to look for missing data. Users are prompted if input data are missing or appear unreasonable.

Step 6: *Match Data*

PARAMETER	STEP 1. BEST ESTIMATE FOR YEAR OF ORIGINAL RELEASE
Units	Year (yyyy).
Description	Year source loading started. Estimated from site historical records and is usually from the 1950s, 1960s, 1970s, or early 1980s. If the release was over a long period of time, it is usually better to enter the earliest year. For chlorinated solvents, it is almost always from the 1950s, 1960s, 1970s, or early 1980s based on common uses for these compounds. This can be used as a calibration parameter (see the beginning of this section).
How to Enter Data	Enter directly.

PARAMETER	STEP 2. SELECT GENERAL FIRST-ROUND CONCENTRATION VS. TIME PATTERN
Description	An initial guess for the pattern in source strength concentration over time. The Toolkit provides three options: constant source, linear decaying source, and exponentially-decaying source. The latter two options are based on evidence that source strength may decrease over time as natural processes deplete mass from the source zone (Newell et al., 2006, Zhu and Sykes, 2004; Parker and Park, 2004; Falta et al., 2005; Falta, 2008; Basu et al., 2008). The behavior of source material (i.e., DNAPL) following release is also strongly influenced by heterogeneities in subsurface environments.
How to Enter Data	Select radio button.

PARAMETER	STEP 3. ADJUST CONCENTRATIONS IN HISTOGRAM MANUALLY
Description	Vertical concentration profiles within the low-k zone are employed to establish the interface concentration vs. time pattern that would best represent this profile. This is done by systematically adjusting the interface concentration (C_o) at various time intervals (t) until a representative “best” fit is obtained Adjust the concentrations in the histogram manually, using the up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use Root Mean Square (RMS) error and Relative Error as guidelines for better/worse matches.
How to Enter Data	Enter directly or use up/down buttons.

PARAMETER	UNCERTAINTY ANALYSIS
Description	Uncertainty in parameter estimates is a key issue in evaluating source attenuation effects. The Toolkit also utilizes a Monte Carlo-type approach to analyze uncertainty in the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life measurements. With this tool, groundwater practitioners can estimate the accuracy of the hydrologic measurements that are being used for the source history reconstruction.

PARAMETER	PASTE EXAMPLE
Description	Clears **ALL** data related to the model in the Toolkit memory banks and pastes an example dataset.

PARAMETER	PRINT/EXPORT
Description	Prints the screen and graphs shown on the screen on the default printer. To print on a different printer, select the printer in the “Print” options in Excel® and then press the “Print” button. Exports the data shown on the Concentration vs. Depth graph as a text file for use in other programs.

Model Results

PARAMETER	TIME VS. CONCENTRATION AT TRANSMISSIVE ZONE-LOW-K ZONE INTERFACE GRAPH
Description	Graph of the concentration at the transmissive zone-low-k zone interface over time. The Toolkit assumes 10 time intervals for plotting the graph. The User may use the Log ←→ Linear button to see the results on a semi-log plot.

PARAMETER	CONCENTRATION VS. DEPTH INTO LOW-K ZONE GRAPH
Description	Graph of concentration vs. depth into low-k zone. Orange dots represent the actual high-resolution concentration data obtained from the soil core. The solid black line represents the Toolkit-simulated concentrations.

PARAMETER	RMS ERROR
Description	Root mean square (RMS) error is a commonly-used measurement employed by groundwater professionals. Second-order statistics, such as the RMS error, provide an indication of overall model calibration and an indication of the goodness-of-fit to the measured data because they are based on the absolute value of the residuals so that negative and positive values do not cancel each other out. RMS errors are calculated as follows: $$RMS = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}$$ Where x_i is the simulated value, y_i is the observed value, and n is the total number of values. An RMS error of 0 indicates a perfect match between predicted and measured values, and increasing values of RMS indicate an increasingly poor match of predicted to measured data.

PARAMETER	RELATIVE ERROR
Description	Relative error is the difference between simulated and observed values divided by the observed value. The Toolkit displays the *average* relative error. Relative error approaching 0 indicates a better match between simulated and measured values, and increasing values indicate an increasingly poor match of simulated to measured data.

Uncertainty Analysis: Data Entry

Uncertainty in parameter estimates is a key issue in reconstructing source history. The Toolkit utilizes a Monte Carlo-type approach to analyze uncertainty in the porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life measurements. With this tool, groundwater practitioners can estimate the accuracy of the hydrologic measurements that are being used for the source history reconstruction.

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PARAMETER	UNCERTAINTY ANALYSIS (EVALUATE HOW UNCERTAINTY IN INPUT DATA AFFECTS SOURCE HISTORY RECONSTRUCTION)
Description	This module uses the Monte Carlo approach to analyze uncertainty in the actual porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life measurements. In the Monte Carlo-type approach, a random number is generated for every value of actual porosity, apparent tortuosity factor exponent, fraction organic carbon/distribution coefficient, and constituent half-life entered by the User. This set of random inputs is then used to calculate concentration in the low-k unit. Repeating this procedure a large number times yields a probability distribution from which statistical characteristics such as mean, percentile, and variance can be obtained. The Toolkit performs 253 iterations for the Monte Carlo approach (limited by the maximum number of lines that can be plotted in an Excel graph).
How to Enter Data	1) Select the parameters to use in the uncertainty analysis. Individual or multiple parameters can be included. 2) Specify a probability distribution for each parameter (see Appendix A.3 of the User's Manual for details on probability distributions). The Toolkit assumes that the values entered in the Input screen are the mean values. 3) For the normal distribution, specify the standard deviation as a percent of the mean. For lognormal distributions, specify the error factor, EF; (the ratio of the 95th percentile to the median of the lognormal data or the ratio of the median to the 5th percentile). (NOTE: the error factor MUST be greater than one). For uniform distribution, specify the lower and upper limits as percentages of the mean (i.e., ± 10%). 4) Perform Input Uncertainty Analysis.

Uncertainty Analysis: Results

PARAMETER	CONCENTRATION VS. DEPTH INTO LOW-K ZONE GRAPH
Description	Graph of concentration vs. depth into low-k zone. Orange dots represent the actual high-resolution core data concentration. The solid black line represents the Toolkit simulated concentration based on the data provided on the main Input screen. Solid blue lines represent the Monte Carlo realizations.

PARAMETER	PRINT GRAPH
Description	Prints the screen and graphs shown on the screen on the default printer. To print on a different printer, select the printer in the "Print" options in Excel® and then press the "Print" button.

CHEMICAL PARAMETER DATABASE

Chemical Name	Organic Carbon Petitioning Coefficient[1] (log (K_{oc}) @20-25 °C)) (log (1/kg))*	Solubility (@20-25 °C) (mg/L)*
Acetone	-0.24	1.00×10^{6}
Acenaphthene	3.85	3.93×10^{0}
Acenaphthylene	4.00	3.93×10^{0}
Anthracene	4.15	4.50×10^{-2}
Benzene	1.58	1.75×10^{3}
Benzoic acid	1.83	6.22×10^{4}
Benzo (a) Anthracene	6.14	5.70×10^{-3}
Benzo (b) Fluoranthane	5.74	1.47×10^{-2}
Benzo (k) Fluoranthene	5.74	4.30×10^{-3}
Benzo (g,h,i) Perylene	6.20	7.00×10^{-4}
Benzo (a) Pyrene	5.59	1.20×10^{-3}
Bromodichloromethane	1.85	6.22×10^{1}
Butanol, n-	0.74	7.70×10^{4}
Carbon disulfide	2.47	2.30×10^{3}
Carbon tetrachloride	2.67	7.62×10^{2}
Chlorobenzene	2.46	4.45×10^{2}
Chloroethane	1.25	2.00×10^{4}
Chloroform	1.93	9.64×10^{3}
Chloromethane	1.40	4.00×10^{-3}
Chlorophenol, 2-	2.11	2.85×10^{4}
Chrysene	5.30	1.80×10^{-3}
Dibenzo (a,h) Anthracene	5.87	5.00×10^{-4}
Dibromochloromethane	2.05	5.25×10^{3}
Dichlorobenzene, (1,2) (-o)	3.32	1.50×10^{2}
Dichlorobenzene, (1,4) (-p)	3.33	1.45×10^{2}
Dichlorodifluoromethane	2.12	1.98×10^{3}
Dichloroethane, 1,1-	1.76	5.00×10^{3}
Dichloroethane, 1,2-	1.76	8.69×10^{3}
Dichloroethene, cis1,2-	1.38	8.00×10^{2}

Chemical Name	Organic Carbon Petitioning Coefficient[1] (log (Koc) @20-25 °C)) (log (1/kg))	Solubility (@20-25 °C) (mg/L)*
Dichloroethene, trans1,2-	1.46	1.75×10^{3}
Ethylbenzene	1.98	6.00×10^{2}
Ethylene glycol	-0.90	1.00×10^{6}
Fluoranthene	4.58	2.06×10^{-1}
Fluorene	3.86	1.69×10^{0}
Hexane, n-	2.68	1.30×10^{1}
Indeno (1,2,3,c,d) Pyrene	7.53	7.17×10^{2}
Methanol	-0.69	1.00×10^{6}
Methylene chloride	1.23	1.54×10^{4}
Methyl ethyl ketone	0.28	2.18×10^{5}
Methyl t-Butyl Ether	1.08	4.80×10^{4}
Naphthalene	3.11	3.29×10^{1}
Phenanthrene	4.15	1.60×10^{0}
Phenol	1.44	9.30×10^{4}
Pyrene	4.58	1.60×10^{-1}
Tetrachloroethane 1,1,2,2-	0.00	7.18×10^{2}
Tetrachloroethene	2.43	1.43×10^{2}
Toluene	2.13	5.15×10^{2}
Trichlorobenzene	3.91	3.03×10^{1}
Trichloroethane 1,1,1-	2.45	1.26×10^{3}
Trichloroethane 1,1,2-	1.75	5.93×10^{3}
Trichloroethene	1.26	1.00×10^{3}
Trichlorofluoromethane	2.49	2.47×10^{3}
Vinyl Chloride	0.39	2.54×10^{3}
Xylene (mixed isomers)	2.38	1.98×10^{2}
Xylene, m-	3.20	1.58×10^{2}
Xylene, o-	2.11	1.75×10^{2}

Notes:

1. Values obtained from “Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface” by Wiedemeier *et al*., 1999, Appendix B.

GEOLOGIC PARAMETER DATABASE

Parameter	Value	Units
Hydraulic Conductivity[1]		
Clean sands	0.001 - 1	cm/s
Clays	$<1 \times 10^{-6}$	cm/s
Gravels	>1	cm/s
Silts	1×10^{-6} - 1×10^{-3}	cm/s
Silty sands	1×10^{-5} - 1×10^{-1}	cm/s
Total Porosity[2]		
Basalt	0.03 - 0.35	(-)
Clay	0.34 - 0.60	(-)
Coarse Gravel	0.24 - 0.36	(-)
Fine Gravel	0.25 - 0.38	(-)
Fine Sand	0.26 - 0.53	(-)
Coarse Sand	0.31 - 0.46	(-)
Limestone	0.0 - 0.5	(-)
Sandstone	0.05 - 0.30	(-)
Shale	0.0 - 0.10	(-)
Silt	0.34 - 0.61	(-)
Siltstone	0.21 - 0.41	(-)
Effective Porosity[3]		
Clay	0.01 - 0.20	(-)
Fine Gravel	0.2 - 0.35	(-)
Medium Gravel	0.15 - 0.25	(-)
Coarse Gravel	0.1 - 0.25	(-)
Sandy Clay	0.03 - 0.2	(-)
Loess	0.15 - 0.35	(-)
Peat	0.3 - 0.5	(-)
Silt	0.01 - 0.3	(-)
Gravely Sand	0.2 - 0.35	(-)
Fine Sand	0.10 - 0.30	(-)
Medium Sand	0.15 - 0.30	(-)
Coarse Sand	0.20 - 0.35	(-)

Parameter	Value	Units
Effective Porosity[3]		
Glacial Sediments	0.05 - 0.2	(-)
Limestone	0.01 - 0.24	(-)
Unfractured Limestone	0.001 - 0.05	(-)
Sandstone	0.1 - 0.4	(-)
Siltstone	0.01 - 0.35	(-)
Fractured Granite	0.00005 - 0.01	(-)
Volcanic Tuff	0.02 - 0.35	(-)
Dry Bulk Density[2]		
Clay	1.00 - 2.40	(g/cm^3)
Silt	-	(g/cm^3)
Granite	2.24 - 2.46	(g/cm^3)
Fine Sand	1.37 - 1.81	(g/cm^3)
Medium Sand	1.37 - 1.81	(g/cm^3)
Coarse Sand	1.37 - 1.81	(g/cm^3)
Sandstone	1.60 - 2.68	(g/cm^3)
Gravel	1.36 - 2.19	(g/cm^3)
Limestone	1.74 - 2.79	(g/cm^3)

Notes:
1. From Newell *et al*., 1996.
2. From Wiedemeier *et al*., 1995.
3. From Wiedemeier *et al*., 1999 (originally from Domenico and Schwartz, 1990 and Walton, 1988).

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SOURCE HISTORY TOOL TROUBLESHOOTING TIPS

Minimum System Requirements

The Source History Tool requires a computer system capable of running Microsoft© Excel® (2007 or 2010) for Windows. Operation requires an IBM-compatible PC equipped with a Pentium or later processor running at a minimum of 450 MHz. A minimum of 256 MB of system memory (RAM) is strongly recommended. The Toolkit can also be run on a Macintosh capable of running Office 2011. Computers not meeting these recommendations will experience slow running times and/or problems with memory.

Installation and Start-Up

The software is installed by unzipping the Toolkit model file (SourceHistoryTool.zip) and keeping all the unzipped files in the same folder on your computer hard drive. To use the software, start Excel® and load the SourceHistoryTool.xlsm model file from the File / Open menu. If you are using Excel® 2010, you may see a message box that asks you whether you want to disable or enable the macros. For the Toolkit to operate effectively, you must *enable* the macros.

Spreadsheet-Related Problems

Backspace doesn't clear cell. Use the delete key on the keyboard or the mouse to clear data.

The buttons won't work. The Toolkit is built in the Excel® spreadsheet environment, and to enter data one must click anywhere outside the cell where data was just entered. If you can see the numbers you just entered in the data entry part of Excel® above the spreadsheet, the data have not yet been entered. Click on another cell to enter the data.

is displayed in a number box. The cell format is not compatible with the value (e.g., the number is too big to fit into the window). To fix this, select the cell, pull down the format menu, select *Format Cells* and click on the *Number* tab. Change the format of the cell until the value is visible. If the values still cannot be read, select the format menu, select *Cells,* and click on the *Font* tab. Reduce the font size until the value can be read.

***#DIV/0!* is displayed in a number box.** The most common cause of this problem is that some input data are missing. In some cases, entering a zero in a box will cause this problem. Double check to make certain that data required for your run have been entered in all of the input cells.

***#VALUE!* is displayed in a number box.** The most common cause of this problem is that some input data are missing. Double check to make certain that data required for your run have been entered in all of the input cells and all options have been selected.

Common Error Messages

Unable to Load Help File: The most common error message encountered with the Toolkit is the message 'Unable to Open Help File' after clicking on a *Help* button. Depending on the version of Windows® you are using, you may get an Excel® Dialog Box, a Windows® Dialog Box, or you may see Windows® Help load and display the error. This problem is related to the ease with which the Windows® Help Engine can find the data file, SourceHistoryTool.chm. Here are some suggestions (in decreasing order of preference) for helping WinHelp find it:

- If you are asked to find the requested file, do so. The file is called SourceHistoryTool.chm, and it was installed in the same directory/folder as the Source History Tool model file (SourceHistoryTool.xlsm).

- Use the File/Open menus from within Excel® instead of double-clicking on the filename or Program Manager icon to open the Source History Tool model file. This sets the *current directory* to the directory containing the Excel® file you just opened.

- If you are using a Macintosh, you will have to download a program able to read Microsoft® compiled HTML files, e.g., Chmox (free), xCHM (free), iCHM (free), etc.

ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1. RECOMMENDATIONS FOR COLLECTING HIGH-RESOLUTION FIELD DATA

Application of the ESTCP Source History Tool requires high-resolution characterization data collected from soil cores in the low-k zone. This is because the output of the model—the source concentration history over time—is based on fitting predictions of soil concentrations (based on the one-dimensional diffusion equation) to actual (measured) soil data. Consequently, the more comprehensive the dataset, the greater the confidence that the model is capturing the general "style" of source attenuation history at the site.

Based on this objective, the following recommendations are made with respect to collecting high-resolution data from soil cores:

Identify Suitable Coring Locations Using Rapid Data Acquisition Tools

An initial objective should be to obtain sufficient high-resolution characterization data to ensure a proper site conceptual is in place and locations for subsequent soil coring can be selected with confidence. To this end, methods should focus on seeking out and identifying permeability interfaces, as well as a better understanding of the relative contaminant distribution. There are several different commercially-available investigative tools that allow for rapid collection of quantitative information on stratigraphy and/or (to a more limited extent) relative contaminant levels. This includes systems such as the Membrane Interface Probe (MIP), Waterloo$^{APS\ TM}$, and Geoprobe HPT® that have been shown to provide direct or complimentary hydrostratigraphic data within low-k zones (Adamson et al., 2013). These subsurface tools can be advanced using direct-push equipment at drive rates favorable to recording large amounts of data in short periods of time; characterization of several hundred vertical feet per day is not uncommon. They provide a more comprehensive picture of site geologic heterogeneities, with data displayed real-time for on-site interpretation of results and adjustment of sampling intervals. These screening-level data can be used to focus coring efforts on locations and depths where low-k layers are indicated.

Core Collection Methods

Obtaining high-quality cores for high-resolution soil sub-sampling is a key goal for implementing this approach. There are a variety of readily-available and effective methods for collecting cores in unconsolidated sediments, and a few are highlighted below. Ultimately, the choice may depend on site conditions and User preferences.

- **Geoprobe Methods.** Direct-push techniques are very commonly used in relatively shallow unconsolidated units and tend to be viewed favorably due to flexibility and cost. Both the Macro-Core and dual-tube sampler methods are capable of obtaining quality cores from fine-grained units. The former is a piston-type system where a center rod holds the piston in place during advancement. The center rod is removed at the top of the sampling interval of interest and the tool string advanced and then retracted to collect the core. This system is effective in areas with heaving sands, however, a major limitation is that it is not

designed to prevent cross contamination between intervals. The dual-tube method prevents cross contamination because it consists of an outer casing around the inner casing that holds the sample liner. Further, its design allows for continuous coring. The primary disadvantage is that in sands, it may be difficult to avoid heaving and poor recovery may occur.

- **Sonic Methods.** Sonic rigs use physical vibration to advance to depths that are often not achievable using direct push methods. This approach makes it more successful in areas with very coarse unconsolidated soils, and also allows for faster drilling than other methods. A core barrel is advanced ahead of an outer casing, and cores collected either in a plastic sleeve or split barrel with a rigid plastic liner. This method allows for continuous coring. Primary disadvantages of the sonic methods are: 1) the costs are generally higher per vertical foot (which may not negatively impact overall costs due to the inherently faster drill rates); and 2) heating of cores may occur and contribute to loss of volatiles (this has been known to impact its regulatory acceptance in certain situations).

- **Auger Methods**. Hollow-stem augers (HAS) are commonly used for installing monitoring wells and can be suitable for environmental coring. They can utilize a split barrel that is advanced inside of the auger or a thin-wall Shelby tube. HSA does not require drilling fluids, and is an easy and reasonably fast approach that works well in shallow unconsolidated formations without significant coarse-grained sediments (i.e., boulders). Their primary disadvantages for coring relative to other options are the generation of cuttings and the inability to prevent cross contamination.

Other promising methods for collecting cores within low-k zones are currently in development, including the use of cryogenic freezing techniques during drilling to maintain core integrity and improve recovery.

Sampling Frequency with Depth

Increasing the number of samples per location essentially increases the level of confidence that an accurate soil VOC profile has been obtained. Consequently, the greater the confidence that the style of source history can be estimated using the Toolkit. Since the incremental costs of higher sampling frequencies are relatively modest, it is recommended that sampling programs use as high a frequency as project budgets reasonably permit. Because diffusion-dominated penetration into low-k units generally occurs within the first 5 to 10 ft, it is recommended that sampling frequencies of no more than 1 sample per ft be used to implement this approach. Further, sampling frequencies of 1 sample per 0.2 to 0.5 ft are highly preferable within the low-k zones.

It is highly recommended that sampling should be completed within the overlying and/or underlying higher permeability zones as well. Data from these zones can help establish vertical contaminant distribution and degradation patterns. Relative to the low-k zones, a lower sampling frequency with depth within these more transmissive zones is likely to be appropriate.

Sampling Frequency with Time

The objective of these methods is to collect core(s) at a single point in time. Therefore, repeated coring efforts over time are not required.

Number of Locations per Source Area

The number of locations per source area is a site-specific decision that should be based on the scale of the source area, level of heterogeneity, and uncertainty in the existing conceptual model. For a site where the source area is small and well-delineated (e.g., a single storage tank), one or two borings within the area of highest concentration may be sufficient to establish trends. However, larger sites or sites where there is greater heterogeneity and/or uncertainty may require several additional borings to adequately characterize the source area. Another option involves collecting cores from locations that are farther downgradient of the source area. These can be used to confirm the source history within the source area, but also to demonstrate attenuation along the plume flowpath.

Analytical Data to be Collected

At a minimum, volatile organic compound (VOC) analyses should be completed for all soil sub-samples from the low-k zone; soil VOC concentrations with depth are primary input data for the Toolkit. On a select number of samples (10 to 50%), analyses for the fraction of organic carbon should be performed. To the extent that the information is not already available, the porosity of the low-k zone soils should also be established through lab analyses. Both porosity and organic carbon are input parameters for the Toolkit. Grain size analyses should also be considered if there is a question about soil classification. Analyses that support an assessment of degradation (e.g., isotopes, biomarkers) may also be valuable in calibrating the model. Finally, core material can be collected for a site-specific assessment of diffusion coefficient, but this type of service is not commercially available and would require specific User expertise.

Sampling Handling and Analysis Considerations

To ensure high-quality data, it is critical to use methods that accurately characterize contaminants in low-k soils. Commercially-available protocols are aimed at complying with EPA Method 5035/5035A for preparing samples for VOC analysis by Method 8260 (or equivalent purge-and-trap gas chromatograph (GC) method). This method requires methanol preservation or freezing within 48 hours of sample collection. For samples that are expected to be high in concentration (> 250 μg/kg), options include: 1) soil sampled into a vial with methanol; or 2) soil collected in an EnCore sampler and shipped to a laboratory immediately (to ensure methanol preservation within 48 hours). For samples that are expected to be low in concentration (5 to 500 μg/kg), options include 1) soil sampled into vials with sodium bisulfate and methanol as a preservative; 2) soil collected in an EnCore sampler and shipped to a laboratory immediately (to ensure methanol preservation within 48 hours); and 3) soil sampled into vials containing water or methanol and shipped to a laboratory immediately (to ensure samples are frozen within 48 hours).

Regardless of the expected concentration, ***we strongly recommend methods that use methanol preservation in the field*** to eliminate the potential for contaminant losses during sampling handling and shipping. Data from ESTCP ER-201032 established that VOC concentrations in soils collected using EnCore samplers and sent to a commercial lab without field preservation were significantly biased relative to field-preserved samples (32% lower based on the slope of the regression line). Delaying the methanol preservation step until samples arrived at the laboratory was not sufficient for eliminating losses.

Key objectives in evaluating low-k soils are ensuring the extraction techniques are sufficient to overcome limitations in diffusion-dominated transport from these soils and analysis techniques are able to quantify trace contaminant levels. Options specifically aimed at meeting these data quality objectives include: 1) rapid field extraction (approximately 2 hr) using a combination of sonification and vigorous shaking; 2) extended extraction (several weeks) using continuous shaking with an option to enhance extraction using microwave-based techniques; and 3) direct (on-column) injection of methanol extracts (Dincutoiu et al., 2001; Dincutoiu et al., 2003; Górecka et al., 2001).

Collection of Groundwater Data

Groundwater concentration data are not used as input for the Toolkit. In other words, results can be obtained without collecting groundwater data from the site. However, groundwater data can be a valuable component to the source history approach in two ways, one short-term and one long-term:

1. ***Information at the interface can help calibrate the model.*** Groundwater data collected at a single timepoint provides supplemental information for understanding contaminant distribution. In particular, the groundwater concentration from a sample collected in the transmissive zone as close as possible to the interface with the low-k zone can be used to calibrate the modeled concentration at the interface. The latter value is converted from a soil concentration to an equivalent porewater concentration, such that direct comparison to an actual groundwater concentration is useful in confirming the assumptions involved in this conversion are reasonable. A close fit between actual and modeled data at the interface is key in ensuring that the fit across the entire interval is also close and that the style of the source history is being captured. Groundwater samples can also provide other valuable information that might otherwise be difficult to obtain with soil cores. This includes geochemical and dissolved gas concentration data that serve as lines of evidence for attenuation.

   There are several methods for collecting groundwater data quickly and efficiently within more transmissive zones. For high-resolution characterization purposes, it is very important that the samples are collected from relatively short intervals. This reduces the flow-weighting that occurs when collecting groundwater across conventional (10-ft) monitoring well screens, and ensures that representative, depth-discrete data are being generated. Methods that utilize this approach without relying on monitoring well installation include the Waterloo$^{APS\ TM}$ and the Geoprobe HPT-GWS. Both of these use very short screens (< 1 ft) to generate high-resolution groundwater data.

2. ***Temporal groundwater data can help confirm that the model-predicted trends in groundwater concentration are reasonable.*** Groundwater data collected over a longer time period can be compared to model predictions to determine if the trends are consistent. The focus should be on transmissive zones near the low-k zone interface since the Toolkit provides estimates of concentration within the transmissive zone. Groundwater samples can be collected in a variety of ways, but multi-level systems (e.g., Solinst Model 403 CMT®) may provide the most relevant information. Because collecting these data requires a more significant investment in terms of time and money, they would likely be a component of a long-term monitoring program after remedy selection (MNA) had been completed, although it is possible that it could be part of the remedial investigation/ feasibility study (RI/FS) stage.

It is important to note that collecting groundwater data from the low-k zone itself can be difficult, regardless of the method employed. This is largely the result of flow limitations within fine-grained media. In zones with even a modest level of heterogeneity, any groundwater that is collected may be largely from those sub-layers of highest permeability. This reduces confidence in how representative these data may be. Consequently, soil cores should always be the primary method for obtaining input data for the Toolkit.

APPENDIX 2. ESTIMATION OF AQUEOUS CONCENTRATION IN LOW-k ZONE

Purpose:
Determine the aqueous concentration in the low-k zone.

Given:
There is source material in a transmissive zone that loads up a source area or downgradient low-k zone before the source is removed.

Assumptions:
The Toolkit uses a simplified conceptual model of a two-layer aquifer system (a transmissive layer and a low-k layer) and assumes:

1. A loading period where there is a constant concentration of contaminants in the transmissive zone that drives contaminants into the low-k zone.
2. There is no DNAPL phase.
3. Diffusion occurs only in the water phase.

Summary:

Diffusion Dominated Transport

For diffusion dominated transport, aqueous concentrations in the low-k zone at a given time and depth can be estimated using (Carslaw and Jaeger, 1959):

$$C_{lk} = \sum \frac{1}{2}\left(I_j - I_{j+1}\right)\left\{\begin{array}{l}\exp\left(-x\sqrt{\frac{k}{D_{sT}}}\right) erfc\left[\left(\frac{x}{\sqrt{4D_{sT}t}}\right) - \sqrt{kt}\right] \\ + \exp\left(x\sqrt{\frac{k}{D_{sT}}}\right) erfc\left[\left(\frac{x}{\sqrt{4D_{sT}t}}\right) + \sqrt{kt}\right]\end{array}\right\} \qquad (1)$$

with I_j, k, and D_{sT} defined as:

$$I_j = \left(Source\ Concentration\ at\ t_j\right)\left(n + \rho_b K_d\right) \qquad (2)$$

$$k = \left(\frac{\ln(2)}{t_{1/2}}\right)\frac{n}{n + \rho_b K_d} \qquad (3)$$

$$D_{sT} = \frac{D_o n^{1+p}}{n + \rho_b K_d} \qquad (4)$$

Where:

- C_{l_k} = Concentration in the low-k zone (ML^{-1});
- x = Depth into low-k zone (L);
- t = Time increment (T);
- I_j = Interfacial concentration at time t_1 given by (ML^{-1});
- j = Time interval (T);
- $t_{1/2}$ = Constituent Half-Life in Low-k Zone (T^{-1});
- n = Porosity of low-k zone (unitless);
- ρ_b = Bulk density of low-k zone (M/L^3);
- K_d = Soil/water partitioning coefficient (L^3/M);
  = $f_{oc}.K_{oc}$;
- f_{oc} = Fraction organic carbon of the low-k layer (unitless);
- K_{oc} = Organic carbon partitioning coefficient (L^3/M).
- D_o = Molecular diffusion coefficient in free water (L^2/T); and
- p = Low-k Zone Apparent Tortuosity Factor Exponent (unitless).

Advection and Diffusion Dominated Transport

Aqueous concentrations in the low-k zone for advection and diffusion dominated transport can be estimated using:

$$C_{lk} = \sum \left(I_j - I_{j+1} \right) C(x,t,v,D_{sT},k) \qquad (5)$$

For slow degradation in the low-k zone (i.e., $k < 2\text{x}10^{-7}$ day^{-1}):

$$C(x,t,v,D_{sT},k) = \frac{1}{2} erfc\left(\frac{x-vt}{\sqrt{4D_{sT}t}} \right) + \sqrt{\frac{v^2 t}{\pi D_{sT}}} \exp\left(-\frac{(x-vt)^2}{4D_{sT}t} \right) - \frac{1}{2}\left(1 + \frac{vx}{D_{sT}} + \frac{v^2 t}{D_{sT}} \right) \exp\left(\frac{vx}{D_{sT}} \right) erfc\left(\frac{x+vt}{\sqrt{4D_{sT}t}} \right) \qquad (6)$$

With v defined as:

$$v = \frac{K.i}{n + \rho_b K_d} \qquad (7)$$

where

- K = Hydraulic conductivity (L/T); and
- i = Vertical hydraulic gradient (unitless)

For $k \geq 2\text{x}10^{-7}$ day^{-1}:

$$C(x,t,v,D_{sT},k) = \frac{v}{v+u}\exp\left[\frac{(v-u)x}{2D_{sT}}\right]erfc\left(\frac{x-ut}{4D_{sT}t}\right) + \frac{v}{v-u}\exp\left[\frac{(v+u)x}{2D_{sT}}\right] erfc\left(\frac{x+ut}{\sqrt{4D_{sT}t}}\right) + \frac{v^2}{2kD_{sT}}\exp\left(\frac{vx}{D_{sT}-kt}\right)erfc\left(\frac{x+vt}{\sqrt{4D_{sT}t}}\right) \quad (8)$$

With u defined as:

$$u = v + \sqrt{1 + \frac{4kD_{sT}}{v^2}} \quad (9)$$

Conversion of Soil Concentration to Aqueous Concentration

Assuming equilibrium chemical partitioning between the solid phase and pore water, and that no NAPL phase is present, total soil concentration can be converted to aqueous concentration using:

$$C_w = \frac{C_s \rho_b}{Rn} \quad (10)$$

With R defined as:

$$R = 1 + \frac{\rho_b K_d}{n} \quad (11)$$

Where:

- C_w = Pore water concentration in the low-k zone (ML^{-1});
- C_s = Soil concentration in the low-k zone (MM^{-1});
- ρ_b = Bulk density of low-k zone (M/L^3);
- R = Retardation factor (unitless);
- n = Porosity of low-k zone (unitless);
- K_d = Soil/water partitioning coefficient (L^3/M);
  = $f_{oc}.K_{oc}$;
- f_{oc} = Fraction organic carbon of the low-k layer (unitless); and
- K_{oc} = Organic carbon partitioning coefficient (L^3/M).

Note the Toolkit assumes that concentration data is being entered on a dry weight basis. If concentration data is only available on a wet weight basis, then an easy correction is to enter the wet bulk density instead of the dry bulk density. The wet bulk density can be calculated by multiplying the dry density by the following factor: 1+moisture content/100.

APPENDIX 3. PROBABILITY DISTRIBUTIONS

This section describes in greater detail the probability distributions employed in the Monte Carlo analysis. The Source History Tool offers the User three distribution options: normal, lognormal, and uniform.

Normal Distributions

Normal distributions are defined by the density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)} \qquad -\infty < x < \infty$$

where, σ is the standard deviation and μ the mean of the distribution. The Toolkit assumes that the values entered in the main input screen are the means. The uncertainty analysis requires the User to specify a σ as a percentage of the mean.

Lognormal Distributions

A lognormal distribution is a distribution whose logarithms are normally distributed. The lognormal density function is:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)} \qquad x, \sigma > 0$$

where, σ is the standard deviation and μ the mean of the underlying normal distribution.

Lognormal distributions are typically specified in two ways throughout literature (Swiler and Wyss, 2004). One way, as described above, is to use the mean and standard deviation of the underlying normal distribution. The other way is to use the mean of the lognormal distribution (α) and a term called the "Error Factor." For a lognormal distribution, the error factor is the ratio of the 95th percentile to the median, or equivalently, the ratio of the median to the 5th percentile. Therefore, the error factor represents the width of a 90% confidence interval around the median.

In terms of the error factor, the relationship between the underlying normal distribution and the lognormal distribution can be described by:

$$\sigma = \ln(\text{error factor})/1.645$$

and

$$\mu = \ln(\alpha) - \frac{\sigma^2}{2}$$

where, α is the mean of the lognormal distribution, and σ and μ the standard deviation and mean of the underlying normal distribution, respectively.

The Toolkit describes the lognormal distribution using the error factor.

Uniform Distributions

A uniform distribution is specified over a particular interval and implies that all the points within that interval have equal probability of occurring. The uniform probability distribution function is:

$$f(x) = \frac{1}{B - A} \qquad A \leq x \leq B$$

where, A and B are the lower and upper bounds, respectively.

CASE STUDIES

CASE STUDY 1. NAS JACKSONVILLE, FLORIDA FORMER BUILDING 106

Overview:

The ESTCP Source History Tool was used to estimate source loading history based on high-resolution sampling of low-k zones at the former Building 106 area in Operable Unit 3 (OU3), a former dry cleaner site, at Naval Air Station (NAS) Jacksonville, Florida. The high-resolution data was obtained by GSI Environmental and the University of Guelph as part of an ESTCP-sponsored project (ESTCP ER-201032). The site was studied using University of Guelph high-resolution core sampling techniques. Mr. Mike Singletary of the Naval Facilities Engineering Command was the Navy point of contact for this project.

This building was the former dry cleaner for the air station and is located in the north/northwest portion of OU3. It was operated as a dry cleaner beginning in 1962 and was believed to have used approximately 150 gallons of PCE per month until 1990 or so when dry cleaning operations were discontinued and the building was demolished shortly afterwards. Chlorinated ethenes have been detected in the soil and groundwater beneath the site, including in a lower permeability clay layer that is present within the sandy shallow aquifer.

The Toolkit was applied as follows:

- Step 1: Initial values of all parameters, site-specific or Toolkit default parameters, were entered into the model. Tetrachloroethene (PCE) is the dominant compound and was chosen as the constituent type.
- Step 2. Toolkit simulated concentrations in the low-k unit were compared to observed PCE soil concentrations at a location near the source area (location OU3-3 in Figure 1.1).
- Step 3. Input parameters were adjusted, as needed, to improve the comparison of simulated and observed PCE concentrations.

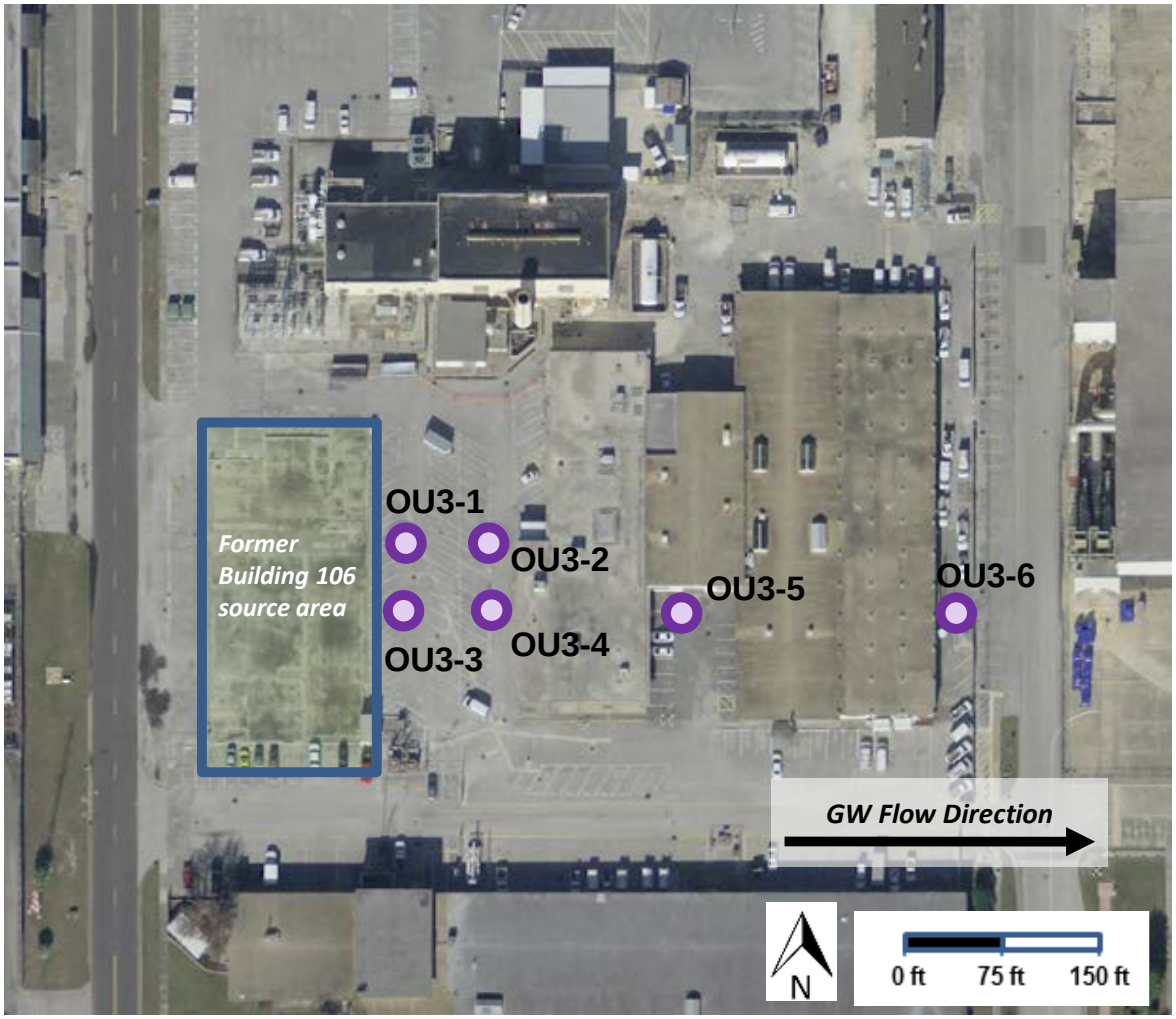


Figure 1.1. Site Layout. Building 106 in Operable Unit 3, Naval Air Station, Jacksonville, Florida. Data from Location OU3-3 were used in Case Study 1.

Input Data:

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material: • Low-k zone porosity: • Transport type:	Clay 0.38 (-) Diffusion only	• Site information • Site information • Site information
Transport	• Key constituent: • Molecular diffusion coefficient in free water: • Low-k. zone apparent tortuosity factor exponent: • Low-k zone bulk density: • Low-k. zone fraction organic carbon: • Organic carbon partitioning coefficient: • Constituent half-life in low-k zone:	PCE 8.2E-10 (m^2/sec) 1.33 (-) 1.5 (g/mL) 0.0018 (-) 155 (L/kg) 1000 (yr)	• Site information • Literature (Toolkit default) • Literature (Toolkit default) • Site information • Site information • Literature (Toolkit default) • Estimated site information
General	• Year core sample collected: • Source concentration:	2011 Initial – 14.3 (mg/L) Calibrated - 71 (mg/L)	• Site information • Initial: Toolkit suggestion of 10% PCE solubility .
Match Data	• Source loading starts in year: • Source decay method:	Initial - 1979 Calibrated – 1962 Constant	• Initial - median date of dry cleaner operation Calibrated - within range of estimated site values • Site information

High-Resolution Core Data Collected at OU3-3

Depth (ft)	0.5	1.0	1.5	1.7	2.0	2.4	2.7	3.0	4.33	4.67	5.0	5.33	5.67	6.0	6.33
PCE Conc (mg/L)	29.0	25.1	18.1	18.5	10.7	6.9	4.7	3.2	0.99	0.58	0.35	0.17	0.09	0.04	0.03

Model Summary:

- The Toolkit was used to reconstruct the source history based on PCE soil concentrations in the low-k zone at a former dry cleaner site (OU-3 Building 106) at Naval Air Station Jacksonville, Florida studied using University of Guelph high-resolution core sampling techniques. Mr. Mike Singletary of the Naval Facilities Engineering Command was the point of contact for this project.
- Toolkit default values were used as input parameters where necessary. Source concentration and year source release occurred were varied until a reasonable comparison between simulated and observed low-k zone concentrations was obtained.
- Toolkit inputs and outputs are shown on Figures 1.2 and 1.3 for the initial and calibrated models, respectively.
- To run the model, hydrogeological data were entered in Section 1, transport parameters in Section 2, general information in Section 3, high-resolution core data in Section 4, and data for matching in Section 6.

KEY POINT:

The Toolkit was able to reproduce observed low-k zone concentrations reasonably well at this location. Root mean square (RMS) and average relative errors of 2.9 mg/L and 0.16, respectively, were observed.

The initial site estimated source concentration and release date were unable to reproduce the observed concentrations in the low-k zone. A better comparison between simulated and observed concentrations was obtained by increasing the concentration and employing an earlier release date. Based on the calibrated model, the Toolkit yielded a good comparison to soil core concentrations.

Note that although for this evaluation, only the source concentration and release date were used as calibration parameters, there could be other combinations of input parameters that could be adjusted to yield similar or better results.

The modeling demonstrated that the locations at this source area were characterized by relatively constant source histories, i.e., source loading that changed gradually over time. The soil profiles generally exhibited decreasing concentration with depth, which is a distinguishing characteristic of continued loading over these low-k zones by a source strength that remains high relative to historical values. This is consistent with the assumption that the majority of degradation activity is occurring in the transmissive zones as opposed to in the low-k zones. Had degradation in the low permeability zones been occurring to a significant degree, then it would have been difficult to obtain similar source histories with the parent compound alone vs. the parent compound plus its degradation products.

The modeling suggests that an appreciable decline in the source strength cannot be verified. Consequently, monitored natural attenuation may not an appropriate site remedy if source control is a requirement. However, modeling results from downgradient locations (not shown) indicate that attenuation processes are clearly helping to maintain plume stability and reduce risk.

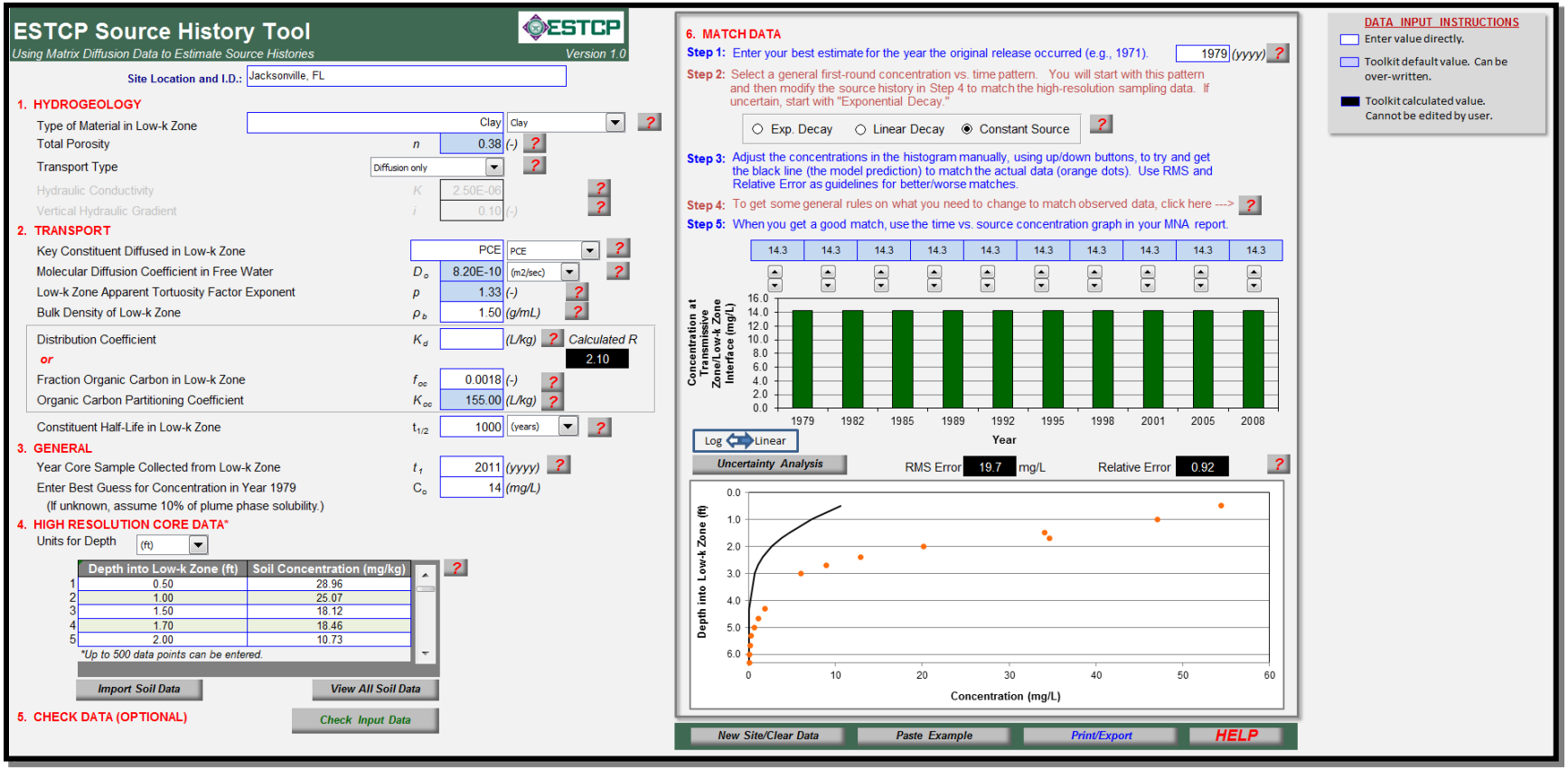


Figure 1.2. Initial Model for Case Study 1.

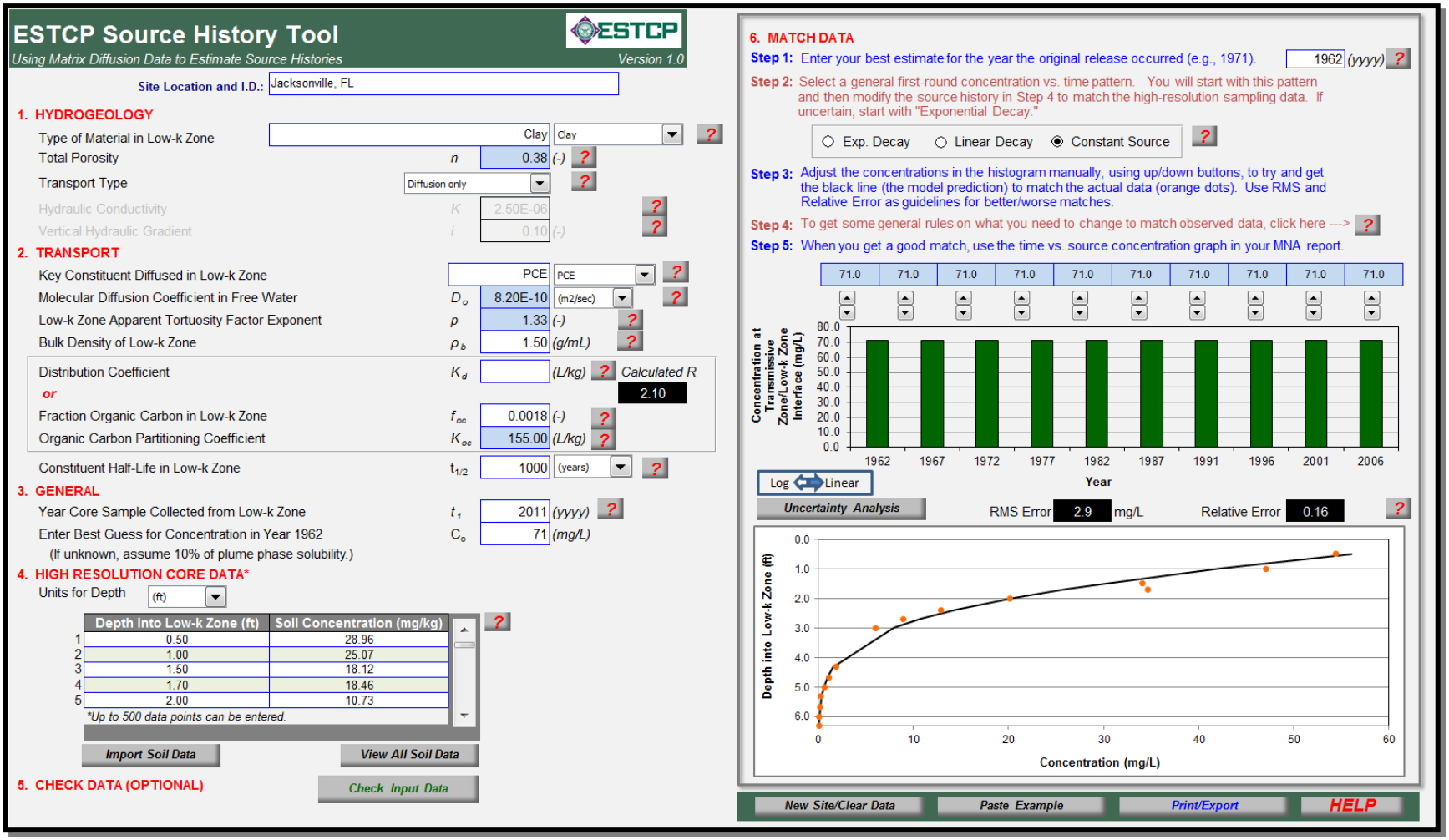


Figure 1.3. Calibrated Model for Case Study 1.

CASE STUDY 2. NAS JACKSONVILLE, FLORIDA BUILDING 780

Overview:

The ESTCP Source History Tool was used to estimate source loading history based on high-resolution sampling of low-k zones at the Building 780 area in Operable Unit 3 (OU3) at Naval Air Station (NAS) Jacksonville, Florida. The high-resolution data was obtained by GSI Environmental and the University of Guelph as part of an ESTCP-sponsored project (ESTCP ER-201032). The site was studied using University of Guelph high-resolution core sampling techniques. Mr. Mike Singletary of the Naval Facilities Engineering Command was the Navy point of contact for this project.

This building housed a paint stripping and solvent recycling operation and currently is used as a general (non-hazardous) recycling facility and is located in the northern portion of OU3. The exact start date for solvent use is unknown, but it reportedly occurred throughout the 1970s and 1980s to strip paints from aircraft and parts (as well as disposal of spent jet fuels). Chlorinated solvents such as TCE and 1,1,1-TCA have been detected in the soil and groundwater beneath the site, including in a lower permeability clay layer that is present within the sandy shallow aquifer. In 1998, a soil-vapor extraction system and a groundwater pump-and-treat system were implemented at Building 780 to address contamination associated with this source as part of the Record of Decision. These systems were shut down following the 2004-2005 optimization review.

The Toolkit was applied as follows:

- Step 1: Initial values of all parameters, site-specific or Toolkit default parameters, were entered into the model. In this case, the parameters for cis-1,2-dichloroethene (cis-DCE) were used since it is the most prevalent compound detected in soil samples.
- Step 2. Toolkit simulated concentrations in the low-k unit were compared to observed soil concentrations (entered as total chlorinated ethenes) at a location near the presumed source (location OU3-9 in Figure 2.1).
- Step 3. Input parameters were adjusted, as needed, to improve the comparison of simulated and observed concentrations.

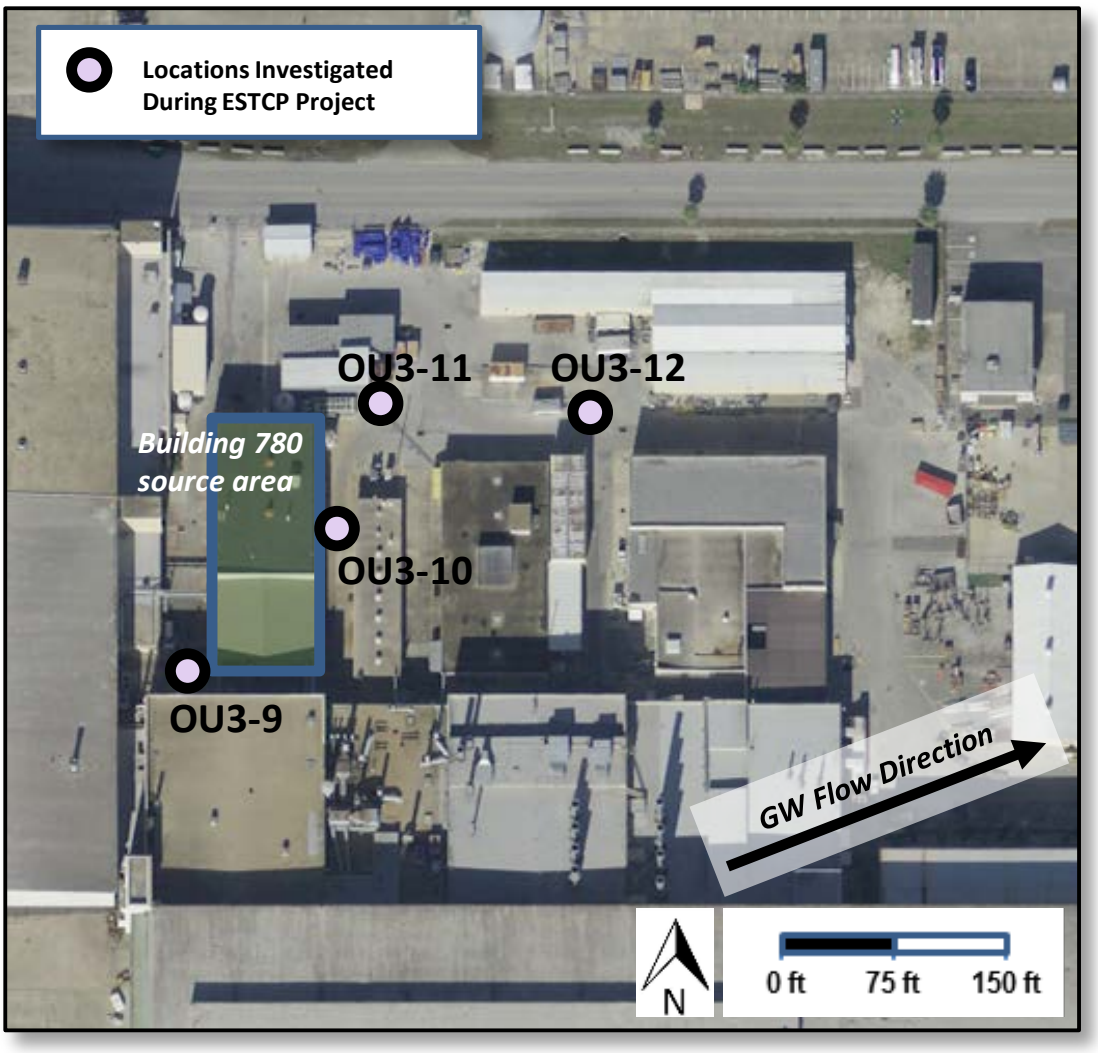


Figure 2.1. Site Layout. Building 780 in Operable Unit 3,
Naval Air Station, Jacksonville, Florida. Data from location OU3-9 were used in Case Study 2.

Input Data:

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material:	Clay	• Site information
	• Low-k zone porosity:	0.38 (-)	• Site information
	• Transport type:	Diffusion only	• Site information
Transport	• Key constituent:	Cis-DCE	• Site information
	• Molecular diffusion coefficient in free water:	1.13E-9 (m^2/sec)	• Literature (Toolkit default)
	• Low-k. zone apparent tortuosity factor exponent:	Initial - 1.33 (-) Calibrated – 1.00 (-)	• Literature (Toolkit default)
	• Low-k zone bulk density:	1.5 (g/mL)	• Site information
	• Low-k. zone fraction organic carbon:	0.0018 (-)	• Site information
	• Organic carbon partitioning coefficient:	29 (L/kg)	• Literature (Toolkit default)
	• Constituent half-life in low-k zone:	1000 (yr)	• Estimated site information
General	• Year core sample collected:	2011	• Site information
	• Source concentration:	Initial – 80 (mg/L) Calibrated - 150 (mg/L)	• Initial: Toolkit suggestion of 10% cis-DCE solubility .
Match Data	• Source loading starts in year:	Initial - 1975 Calibrated – 1971	• Initial - median date of solvent use Calibrated - within range of estimated site values
	• Source decay method:	Linear decay Calibrated - histogram concentrations adjusted manually.	• Site information

High-Resolution Core Data Collected at OU3-9

Depth (ft)	0.1	0.9	1.3	1.8	2.3	2.8	3.3	3.8	4.3	4.8	5.3	5.9
Cis-DCE Conc (mg/L)	4.84	5.55	6.03	8.38	8.07	7.99	7.43	8.26	6.35	6.52	7.58	2.27

Model Summary:

- The Toolkit was used to reconstruct the source history based on cis-DCE soil concentrations in the low-k zone at a former solvent use site (OU-3 Building 780) at Naval Air Station Jacksonville, Florida studied using University of Guelph high-resolution core sampling techniques. Mr. Mike Singletary of the Naval Facilities Engineering Command was the point of contact for this project.
- Toolkit default values were used as input parameters where necessary. Source concentrations (both initial source concentration and histogram source concentrations), year source release occurred, and apparent tortuosity factor exponent were varied until a reasonable comparison between simulated and observed low-k zone concentrations was obtained.
- Toolkit inputs and outputs are shown on Figures 2.2 and 2.3 for the initial and calibrated models, respectively.
- To run the model, hydrogeological data were entered in Section 1, transport parameters in Section 2, general information in Section 3, high-resolution core data in Section 4, and data for matching in Section 6.0.

KEY POINT:

The Toolkit was able to reproduce observed low-k zone concentrations reasonably well at this location. Root mean square (RMS) and average relative errors of 5.9 mg/L and 0.2, respectively, were observed.

The initial site estimated source concentration, release date, and apparent tortuosity exponent factor were unable to reproduce the observed concentrations in the low-k zone. A better comparison between simulated and observed concentrations was obtained by increasing the release year concentration, varying the concentrations in the histogram, employing an earlier release date, and decreasing the apparent tortuosity exponent factor. Based on the calibrated model, the Toolkit yielded a reasonable comparison to soil core concentrations.

Note that although for this evaluation, only the source concentrations, release date, and apparent tortuosity exponent factor were used as calibration parameters, there could be other combinations of input parameters that could be adjusted to yield similar or better results.

The modeling demonstrated that the locations at this source area were characterized by declining source histories for total chlorinated ethenes, i.e., source loading that changed gradually over time. Soil profiles generally exhibited a maximum concentration at some distance (1 to 4 ft) into the low-k clay, with lower concentrations measured near the interface. This pattern is a distinguishing characteristic of a declining source strength over time, such that the diffusion out of the low-k zone (due to a change in the concentration gradient) has decreased concentrations near the low-k interface.

The modeling suggests that an appreciable decline in the source strength has occurred over time as a result of significant attenuation at this location. Consequently, monitored natural attenuation may be an appropriate site remedy.

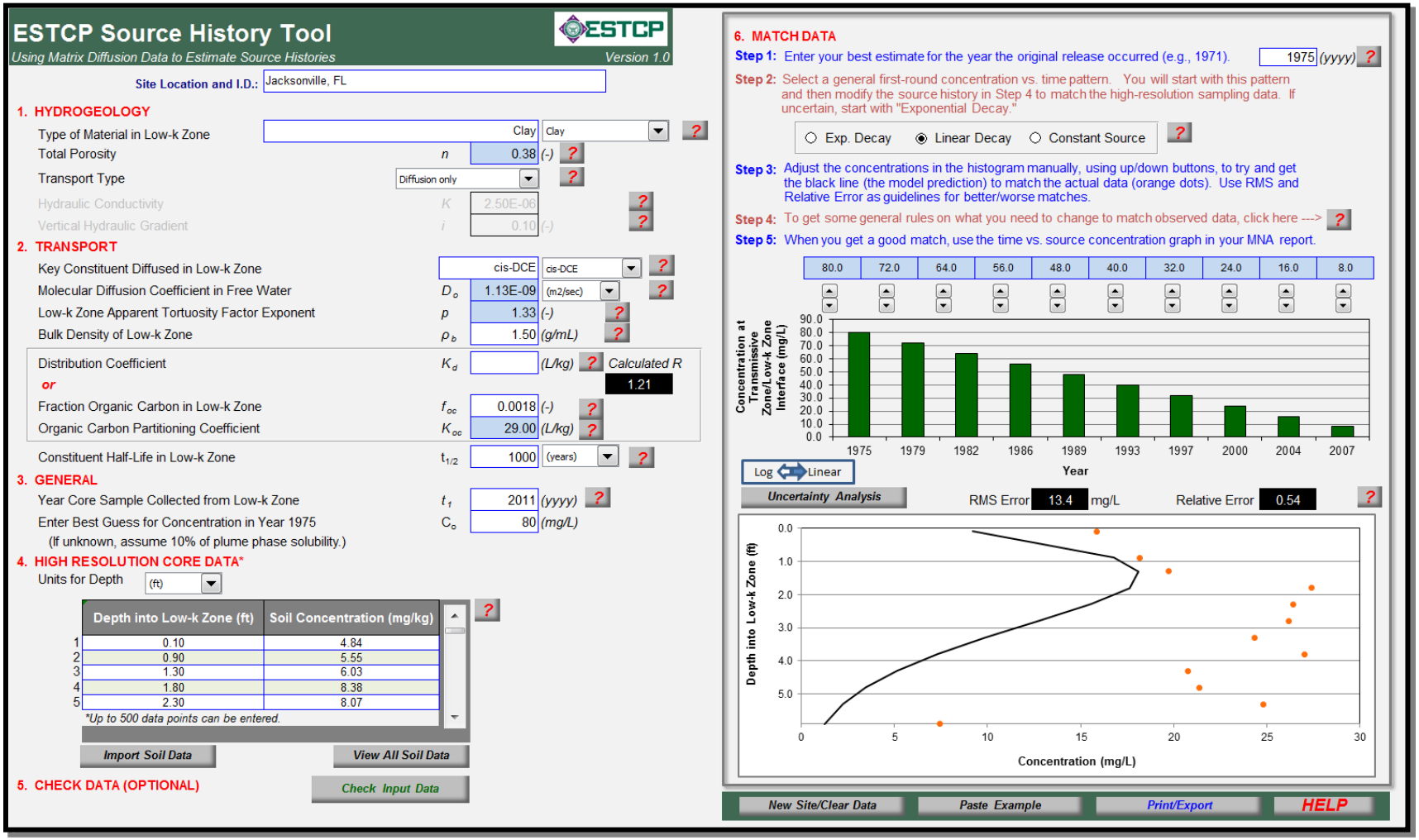


Figure 2.2. Initial Model for Case Study 2.

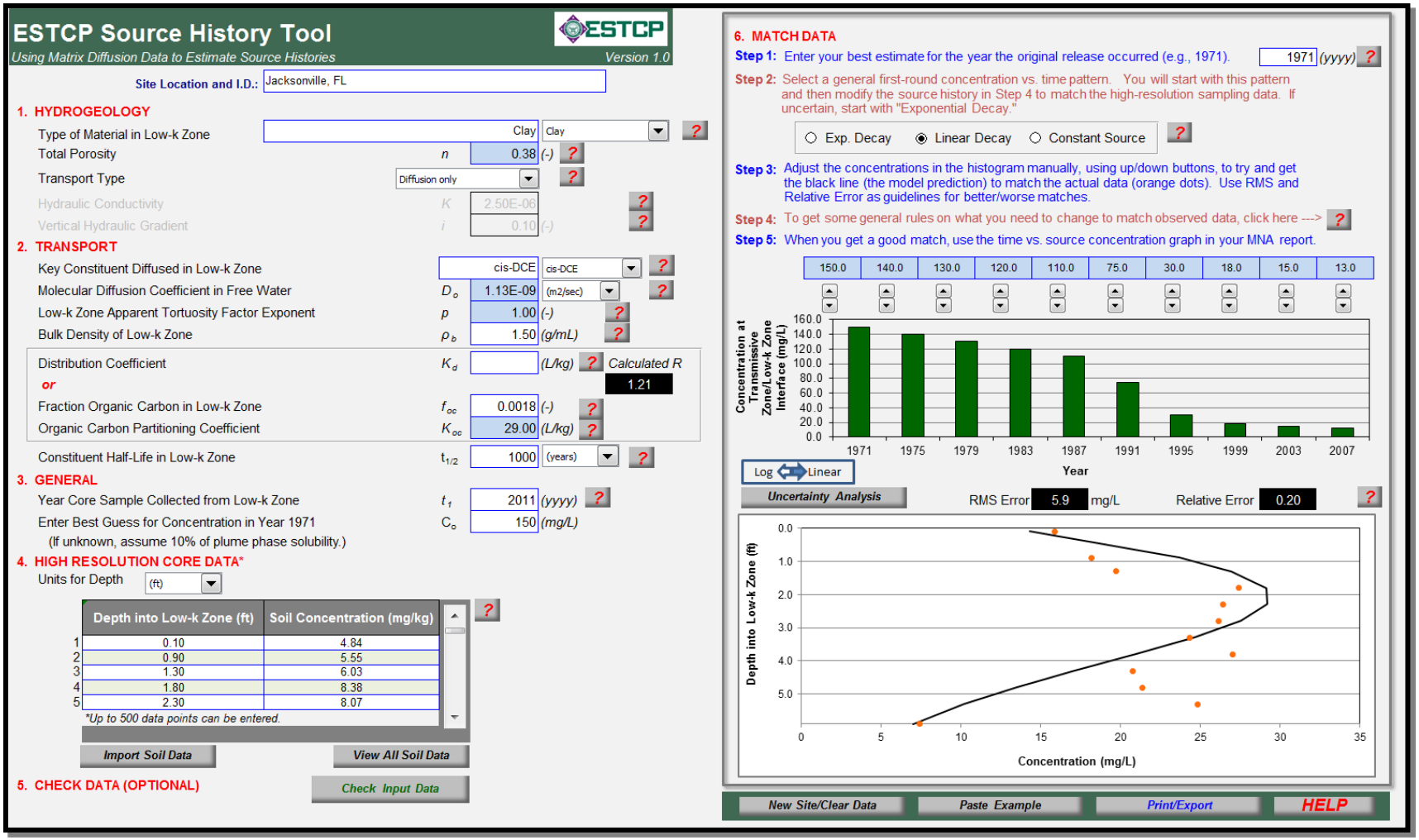


Figure 2.3. Calibrated Model for Case Study 2.

APPENDIX Q

Summary of Modeling Results – Project Locations

Table Q.1 Results of Source History Modeling: Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Table Q.2 Results of Source History Modeling: Predicted Groundwater Concentrations Based on Source History Modeling

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TABLE Q.1
RESULTS OF SOURCE HISTORY MODELING
Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All soil concentrations are converted to equivalent porewater concentration (mg/L)

OU3-3					OU3-3					OU3-4					OU3-4				
Depth (ft below interface)	Actual Soil Data PCE only mg/L	Model Data PCE only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Equivalent mg/L	Model Data PCE Equivalent mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Only mg/L	Model Data PCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Equivalent mg/L	Model Data PCE Equivalent mg/L	RPD	ABS (RPD)
0.5	54.4	56.0	-3%	3%	0.5	61.1	61.6	-1%	1%	0.3	20.5	37.0	-57%	57%	0.3	27.6	43.0	-44%	44%
1	47.1	42.2	11%	11%	1	51.4	46.4	10%	10%	0.7	19.7	29.2	-39%	39%	0.7	25.8	34.0	-27%	27%
1.5	34.0	30.2	12%	12%	1.5	36.4	33.2	9%	9%	1	21.4	23.9	-11%	11%	1	27.0	27.8	-3%	3%
1.7	34.7	26.0	29%	29%	1.7	36.6	28.6	25%	25%	1.3	40.2	19.1	71%	71%	1.3	46.6	22.2	71%	71%
2	20.2	20.5	-2%	2%	2	21.3	22.5	-6%	6%	1.6	16.0	14.9	7%	7%	1.6	20.4	17.4	16%	16%
2.4	12.9	14.4	-11%	11%	2.4	13.3	15.8	-17%	17%	1.9	8.0	11.4	-35%	35%	1.9	10.0	13.2	-28%	28%
2.7	8.9	10.8	-19%	19%	2.7	9.2	11.9	-26%	26%	2.2	6.6	8.5	-25%	25%	2.2	8.0	9.8	-20%	20%
3	6.0	7.9	-28%	28%	3	6.2	8.7	-33%	33%	2.5	2.3	6.1	-92%	92%	2.5	2.8	7.1	-88%	88%
4.33	1.9	1.6	17%	17%	4.33	2.0	1.7	16%	16%	3.7	0.9	1.3	-32%	32%	3.7	1.2	1.5	-20%	20%
4.67	1.1	1.0	12%	12%	4.67	1.2	1.1	13%	13%	4	0.6	0.8	-35%	35%	4	0.8	1.0	-22%	22%
5	0.7	0.6	12%	12%	5	0.8	0.6	21%	21%	4.5	0.4	0.4	12%	12%	4.5	0.6	0.4	34%	34%
5.33	0.3	0.3	-6%	6%	5.33	0.5	0.4	29%	29%	5	0.3	0.1	74%	74%	5	0.5	0.2	99%	99%
5.67	0.2	0.2	-10%	10%	5.67	0.4	0.2	63%	63%	5.5	0.1	0.1	89%	89%	5.5	0.3	0.1	130%	130%
6	0.1	0.1	-41%	41%	6	0.3	0.1	79%	79%	6	0.1	0.0	125%	125%	6	0.3	0.0	169%	169%
6.33	0.1	0.1	14%	14%	6.33	0.4	0.1	144%	144%	6.5	0.0	0.0	109%	109%	6.5	0.2	0.0	189%	189%
		MEDIAN	**-2%**	**12%**			**MEDIAN**	**13%**	**21%**			**MEDIAN**	**-11%**	**39%**			**MEDIAN**	**-3%**	**34%**
		RMS		**2.9**			**RMS**		**2.87**			**RMS**		**7.49**			**RMS**		**7.9**
		RMS/Max Actual Ratio		**5.3%**			**RMS/Max Actual Ratio**		**4.7%**			**RMS/Max Actual Ratio**		**19%**			**RMS/Max Actual Ratio**		**17%**

Notes:

1. RMS= Relative mean square error.
2. RMS/Max Actual Ratio is the relative mean square error divided by the maximum actual soil concentration measured over the entire depth interval being modeled.
3. RPD = Relative percent difference.
4. ABS (RPD) = Absolute value of RPD (i.e., non-directional RPD).

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TABLE Q.1
RESULTS OF SOURCE HISTORY MODELING
Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All soil concentrations are converted to equivalent porewater concentration (mg/L)

OU3-5					OU3-5					OU3-5-DUP					OU3-5-DUP				
Depth (ft below interface)	Actual Soil Data PCE Only mg/L	Model Data PCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Equivalent mg/L	Model Data PCE Equivalent mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Only mg/L	Model Data PCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Equivalent mg/L	Model Data PCE Equivalent mg/L	RPD	ABS (RPD)
0	20.34	23.00	-12%	12%	0	28.07	32.00	-13%	13%	0	18.23	18.00	1%	1%	0	29.62	30.00	-1%	1%
0.4	22.71	18.42	21%	21%	0.4	30.83	25.63	18%	18%	0.5	1.09	13.55	-170%	170%	0.5	19.30	22.59	-16%	16%
0.8	14.38	14.14	2%	2%	0.8	20.04	19.68	2%	2%	1	1.94	9.54	-132%	132%	1	11.34	15.89	-33%	33%
1.2	9.01	10.38	-14%	14%	1.2	13.46	14.44	-7%	7%	1.5	1.81	6.24	-110%	110%	1.5	7.25	10.40	-36%	36%
1.6	6.10	7.26	-17%	17%	1.6	9.87	10.10	-2%	2%	2	0.59	3.78	-146%	146%	2	3.84	6.30	-49%	49%
2	6.08	4.83	23%	23%	2	10.14	6.72	41%	41%	2.5	0.08	2.11	-186%	186%	2.5	1.42	3.52	-85%	85%
2.4	3.65	3.05	18%	18%	2.4	6.39	4.25	40%	40%	3	0.03	1.09	-189%	189%	3	0.53	1.81	-109%	109%
2.8	1.06	1.83	-54%	54%	2.8	2.30	2.55	-10%	10%	5	0.00	0.03	-155%	155%	5	0.22	0.05	123%	123%
3.2	0.81	1.04	-25%	25%	3.2	1.86	1.45	25%	25%	5.5	0.00	0.01	-92%	92%	5.5	0.27	0.02	176%	176%
3.6	0.22	0.56	-85%	85%	3.6	0.73	0.78	-6%	6%	6	0.01	0.00	58%	58%	6	0.36	0.01	194%	194%
4	0.06	0.28	-130%	130%	4	0.35	0.39	-13%	13%	6.5	0.01	0.00	178%	178%	6.5	0.44	0.00	199%	199%
4.3	0.01	0.16	-171%	171%	4.3	0.18	0.23	-24%	24%	7	0.08	0.00	199%	199%	7	0.35	0.00	200%	200%
5.5	0.00	0.01	-128%	128%	5.5	0.22	0.02	169%	169%	7.5	0.18	0.00	200%	200%	7.5	0.87	0.00	200%	200%
6	0.01	0.00	23%	23%	6	0.24	0.01	191%	191%	8	0.25	0.00	200%	200%	8	1.05	0.00	200%	200%
6.5	0.00	0.00	124%	124%	6.5	0.29	0.00	198%	198%	8.5	0.16	0.00	200%	200%	8.5	0.70	0.00	200%	200%
7	0.00	0.00	178%	178%	7	0.31	0.00	200%	200%			**MEDIAN**	**-92%**	**170%**			**MEDIAN**	**123%**	**123%**
7.5	0.01	0.00	198%	198%	7.5	0.39	0.00	200%	200%			**RMS**		**3.21**			**RMS**		**1.94**
8	0.02	0.00	200%	200%	8	0.43	0.00	200%	200%			**RMS/Max Actual Ratio**		**18%**			**RMS/Max Actual Ratio**		**6.5%**
8.5	0.04	0.00	200%	200%	8.5	0.52	0.00	200%	200%										
9	0.07	0.00	200%	200%	9	0.61	0.00	200%	200%										
9.5	0.19	0.00	200%	200%	9.5	0.92	0.00	200%	200%										
9.9	0.21	0.00	200%	200%	9.9	0.96	0.00	200%	200%										
		MEDIAN	**19%**	**104%**			**MEDIAN**	**40%**	**40%**										
		RMS		**1.2**			**RMS**		**1.69**										
		RMS/Max Actual Ratio		**5.3%**			**RMS/Max Actual Ratio**		**5.5%**										

Notes:

1. RMS= Relative mean square error.
2. RMS/Max Actual Ratio is the relative mean square error divided by the maximum actual soil concentration measured over the entire depth interval being modeled.
3. RPD = Relative percent difference.
4. ABS (RPD) = Absolute value of RPD (i.e., non-directional RPD).

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TABLE Q.1
RESULTS OF SOURCE HISTORY MODELING
Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All soil concentrations are converted to equivalent porewater concentration (mg/L)

OU3-6					OU3-6					OU3-9					OU3-9				
Depth (ft below interface)	Actual Soil Data PCE Only mg/L	Model Data PCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data PCE Equivalent mg/L	Model Data PCE Equivalent mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data TCE Only mg/L	Model Data TCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data TCE Equivalent mg/L	Model Data TCE Equivalent mg/L	RPD	ABS (RPD)
0	3.13	3.10	1%	1%	0	13.41	13.00	3%	3%	0.10	1.01	1.24	-20%	20%	0.1	15.85363916	16.02098734	-1%	1%
0.5	0.06	2.08	-189%	189%	0.5	7.24	8.72	-18%	18%	0.90	1.86	2.98	-46%	46%	0.9	18.17926764	23.4735722	-25%	25%
1	0.04	1.23	-186%	186%	1	3.99	5.14	-25%	25%	1.30	2.33	3.59	-43%	43%	1.3	19.73999936	26.17199438	-28%	28%
1.5	0.07	0.63	-162%	162%	1.5	1.66	2.63	-45%	45%	1.80	3.83	4.02	-5%	5%	1.8	27.41894152	28.13278897	-3%	3%
2	0.01	0.28	-189%	189%	2	0.78	1.16	-39%	39%	2.30	3.96	4.05	-2%	2%	2.3	26.39688382	28.4125118	-7%	7%
2.5	0.01	0.10	-179%	179%	2.5	0.48	0.44	10%	10%	2.80	3.87	3.75	3%	3%	2.8	26.1528704	27.14431791	-4%	4%
3	0.00	0.03	-172%	172%	3	0.26	0.14	58%	58%	3.30	3.79	3.24	16%	16%	3.3	24.33387558	24.65706517	-1%	1%
5	0.00	0.00	191%	191%	5	0.22	0.00	199%	199%	3.80	4.17	2.63	45%	45%	3.8	27.02930222	21.3818746	23%	23%
5.5	0.00	0.00	199%	199%	5.5	0.23	0.00	200%	200%	4.30	3.23	2.01	47%	47%	4.3	20.76774491	17.75978329	16%	16%
6	0.00	0.00	200%	200%	6	0.26	0.00	200%	200%	4.80	3.34	1.46	-2%	20%	4.8	21.34795031	14.1695612	-3%	7%
6.5	0.01	0.00	200%	200%	6.5	0.34	0.00	200%	200%	5.30	3.94	1.01	-2%	20%	5.3	24.81445852	10.88648599	-3%	7%
7	0.01	0.00	200%	200%	7	0.44	0.00	200%	200%	5.90	1.32	0.61	-2%	20%	5.9	7.415727634	7.572470771	-3%	7%
7.5	0.02	0.00	200%	200%	7.5	0.50	0.00	200%	200%			**MEDIAN**	**-2%**	**20%**			**MEDIAN**	**-3%**	**7%**
8	0.06	0.00	200%	200%	8	0.78	0.00	200%	200%			**RMS**		**1.27**			**RMS**		**5.49**
8.5	0.17	0.00	200%	200%	8.5	1.11	0.00	200%	200%			**RMS/Max Actual Ratio**		**30%**			**RMS/Max Actual Ratio**		**20%**
8.7	0.14	0.00	200%	200%	8.7	0.83	0.00	200%	200%										
8.8	0.06	0.00	200%	200%	8.8	0.46	0.00	200%	200%										
9	0.07	0.00	200%	200%	9	0.45	0.00	200%	200%										
9.4	0.07	0.00	200%	200%	9.4	0.48	0.00	200%	200%										
		MEDIAN	**200%**	**200%**			**MEDIAN**	**200%**	**200%**										
		RMS		**0.45**			**RMS**		**0.68**										
		RMS/Max Actual Ratio		**14%**			**RMS/Max Actual Ratio**		**5.1%**										

Notes:

1. RMS= Relative mean square error.
2. RMS/Max Actual Ratio is the relative mean square error divided by the maximum actual soil concentration measured over the entire depth interval being modeled.
3. RPD = Relative percent difference.
4. ABS (RPD) = Absolute value of RPD (i.e., non-directional RPD).

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TABLE Q.1
RESULTS OF SOURCE HISTORY MODELING
Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All soil concentrations are converted to equivalent porewater concentration (mg/L)

OU3-9					OU3-9					OU3-10					OU3-10				
Depth (ft below interface)	Actual Soil Data 1,1,1-TCA Equivalent mg/L	Model Data 1,1,1-TCA Equivalent mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data 1,2-DCA Only mg/L	Model Data 1,2-DCA Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data TCE Only mg/L	Model Data TCE Only mg/L	RPD	ABS (RPD)	Depth (ft below interface)	Actual Soil Data TCE Equivalent mg/L	Model Data TCE Equivalent mg/L	RPD	ABS (RPD)
0.1	0.90	0.86	4%	4%	0.1	0.98	1.14	-15%	15%	0.5	6.26	6.46	-3%	3%	0.5	12.4152021	12.92167995	-4%	4%
0.9	0.49	0.59	-20%	20%	0.9	1.94	2.86	-39%	39%	1.0	7.19	9.64	-29%	29%	1	11.29614698	12.48813735	-10%	10%
1.3	0.32	0.47	-39%	39%	1.3	2.43	3.47	-35%	35%	1.5	6.97	10.92	-44%	44%	1.5	8.923147833	11.497054	-25%	25%
1.8	0.24	0.34	-33%	33%	1.8	3.69	3.91	-6%	6%	2.0	10.77	10.48	3%	3%	2	12.02982585	9.980940633	19%	19%
2.3	0.11	0.23	-69%	69%	2.3	3.58	4.02	-12%	12%	2.5	9.09	8.93	2%	2%	2.5	9.623681669	8.145899851	17%	17%
2.8	0.10	0.15	-40%	40%	2.8	3.76	3.86	-3%	3%	3.0	8.02	6.94	14%	14%	3	8.319934857	6.254852867	28%	28%
3.3	0.10	0.10	-1%	1%	3.3	3.63	3.50	4%	4%	3.5	6.86	5.00	31%	31%	3.5	7.090711962	4.52920532	44%	44%
3.8	0.05	0.06	-20%	20%	3.8	4.23	3.02	33%	33%	4.0	4.30	3.39	24%	24%	4	4.478087728	3.101395763	36%	36%
4.3	0.05	0.03	37%	37%	4.3	3.18	2.50	24%	24%	5.5	4.44	0.77	141%	141%	5.5	4.668204634	0.729702611	146%	146%
4.8	0.05	0.02	-20%	33%	4.8	3.32	1.99	-6%	15%	6.0	5.22	0.43	170%	170%	6	5.512238896	0.40854514	172%	172%
5.3	0.05	0.01	-20%	33%	5.3	3.96	1.52	-6%	15%	6.5	4.38	0.23	180%	180%	6.5	4.646456225	0.218230337	182%	182%
5.9	0.05	0.00	-20%	33%	5.9	1.26	1.05	-6%	15%	7.0	4.32	0.12	190%	190%	7	4.596856643	0.111282527	191%	191%
		MEDIAN	**-20%**	**33%**			**MEDIAN**	**-6%**	**15%**	7.5	4.73	0.06	195%	195%	7.5	5.025251678	0.054192418	196%	196%
		RMS		**0.075**			**RMS**		**0.99**	8.0	4.98	0.03	198%	198%	8	5.294784244	0.025208735	198%	198%
		RMS/Max Actual Ratio		**8.3%**			**RMS/Max Actual Ratio**		**23%**	8.5	4.66	0.01	199%	199%	8.5	4.972863455	0.011202789	199%	199%
										9.0	2.76	0.00	199%	199%	9	3.025686474	0.004756641	199%	199%
												MEDIAN	**86%**	**86%**			**MEDIAN**	**95%**	**95%**
												RMS		**3.25**			**RMS**		**3.49**
												RMS/Max Actual Ratio		**30%**			**RMS/Max Actual Ratio**		**28%**

Notes:

1. RMS= Relative mean square error.
2. RMS/Max Actual Ratio is the relative mean square error divided by the maximum actual soil concentration measured over the entire depth interval being modeled.
3. RPD = Relative percent difference.
4. ABS (RPD) = Absolute value of RPD (i.e., non-directional RPD).

TABLEQ.1
RESULTS OF SOURCE HISTORY MODELING
Actual Measured Soil Concentration Data vs. Modeled Soil Concentration Data

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All soil concentrations are converted to equivalent porewater concentration (mg/L)

OU3-11				
Depth (ft below interface)	Actual Soil Data TCE Equivalent mg/L	Model Data TCE Equivalent mg/L	RPD	ABS (RPD)
0	0.198	0.124	46%	46%
0.5	0.126	0.154	-20%	20%
0.8	0.135	0.169	-22%	22%
1.5	0.225	0.186	19%	19%
2	0.176	0.182	-4%	4%
2.5	0.137	0.169	-21%	21%
3	0.120	0.149	-22%	22%
3.5	0.118	0.126	-6%	6%
4	0.082	0.102	-22%	22%
4.5	0.094	0.080	16%	16%
5	0.124	0.060	69%	69%
5.5	0.033	0.044	-30%	30%
		MEDIAN	**-13%**	**21%**
		RMS		**0.036**
		RMS/Max Actual Ratio		**16%**

Notes:

1. RMS= Relative mean square error.
2. RMS/Max Actual Ratio is the relative mean square error divided by the maximum actual soil concentration measured over the entire depth interval being modeled.
3. RPD = Relative percent difference.
4. ABS (RPD) = Absolute value of RPD (i.e., non-directional RPD).

GSI ENVIRONMENTAL

TABLE Q.2
RESULTS OF SOURCE HISTORY MODELING
Predicted Groundwater Concentrations Based on Source History Modeling

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All groundwater concentrations based on modeled fit to actual soil concentrations shown in Table Q.1

OU3-3			OU3-3			OU3-4			OU3-4		
Based on PCE Only			Based on PCE Equivalents			Based on PCE Only			Based on PCE Equivalents		
Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)
1962	49	71	1962	49	78	1971	40	43	1971	40	50
1967	44	71	1967	44	78	1975	36	43	1975	36	50
1972	39	71	1972	39	78	1979	32	43	1979	32	50
1977	34	71	1977	34	78	1983	28	43	1983	28	50
1982	29	71	1982	29	78	1987	24	43	1987	24	50
1987	24	71	1987	24	78	1991	20	43	1991	20	50
1991	20	71	1991	20	78	1995	16	43	1995	16	50
1996	15	71	1996	15	78	1999	12	43	1999	12	50
2001	10	71	2001	10	78	2003	8	43	2003	8	50
2006	5	71	2006	5	78	2007	4	43	2007	4	50

TABLE Q.2
RESULTS OF SOURCE HISTORY MODELING
Predicted Groundwater Concentrations Based on Source History Modeling

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All groundwater concentrations based on modeled fit to actual soil concentrations shown in Table Q.1

OU3-5 Based on PCE Only			OU3-5 Based on PCE Equivalents			OU3-5-DUP Based on PCE Only			OU3-5-DUP Based on PCE Equivalents		
Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)
1976	35	23	1976	35	32	1976	34	18	1976	34	30
1980	31	23	1980	31	32	1980	30.6	18	1980	30.6	30
1983	28	23	1983	28	32	1983	27.2	18	1983	27.2	30
1987	24	23	1987	24	32	1987	23.8	18	1987	23.8	30
1990	21	23	1990	21	32	1990	20.4	18	1990	20.4	30
1993	18	23	1993	18	32	1993	17	18	1993	17	30
1997	14	23	1997	14	32	1997	13.6	18	1997	13.6	30
2001	10	23	2001	10	32	2001	10.2	18	2001	10.2	30
2004	7	23	2004	7	32	2004	6.8	18	2004	6.8	30
2008	3	23	2008	3	32	2008	3.4	18	2008	3.4	30

GSI ENVIRONMENTAL

TABLE Q.2
RESULTS OF SOURCE HISTORY MODELING
Predicted Groundwater Concentrations Based on Source History Modeling

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All groundwater concentrations based on modeled fit to actual soil concentrations shown in Table Q.1

OU3-6			OU3-6			OU3-9			OU3-9		
Based on PCE Only			Based on PCE Equivalents			Based on TCE Only			Based on TCE Equivalents		
Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)
1992	19	3	1990	21	13	1971	40	30	1971	40	160
1994	17.1	3	1992	18.9	13	1975	36	28	1975	36	156
1996	15.2	3	1994	16.8	13	1979	32	26	1979	32	152
1998	13.3	3	1996	14.7	13	1983	28	24	1983	28	148
2000	11.4	3	1998	12.6	13	1987	24	12	1987	24	115
2002	9.5	3	2001	10.5	13	1991	20	3	1991	20	29
2003	7.6	3	2003	8.4	13	1995	16	1	1995	16	16.5
2005	5.7	3	2005	6.3	13	1999	12	1	1999	12	16
2007	3.8	3	2007	4.2	13	2003	8	1	2003	8	15.5
2009	1.9	3	2009	2.1	13	2007	4	1	2007	4	15

TABLE Q.2
RESULTS OF SOURCE HISTORY MODELING
Predicted Groundwater Concentrations Based on Source History Modeling

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All groundwater concentrations based on modeled fit to actual soil concentrations shown in Table Q.1

OU3-9 Based on 1,1,1-TCA Equivalents			OU3-9 Based on 1,2-DCA Only			OU3-10 Based on TCE Only			OU3-10 Based on TCE Equivalents		
Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)	Release/ Starting Date (t_0)	Years Prior to Core Collection	Interfacial GW Conc. (mg/L)
1988	23	0.9	1971	40	34	1973	38	50	1973	38	50
1990	20.7	0.9	1975	36	27	1977	34.2	47	1977	34.2	45
1993	18.4	0.9	1979	32	21	1981	30.4	43	1981	30.4	40
1995	16.1	0.9	1983	28	16	1984	26.6	39	1984	26.6	35
1997	13.8	0.9	1987	24	11	1988	22.8	35	1988	22.8	30
2000	11.5	0.9	1991	20	4.5	1992	19	32	1992	19	25
2002	9.2	0.9	1995	16	3.5	1996	15.2	29	1996	15.2	15
2004	6.9	0.9	1999	12	2.5	2000	11.4	4	2000	11.4	14
2006	4.6	0.9	2003	8	1.5	2003	7.6	3	2003	7.6	13
2009	2.3	0.9	2007	4	0.9	2007	3.8	2	2007	3.8	13

TABLE Q.2
RESULTS OF SOURCE HISTORY MODELING
Predicted Groundwater Concentrations Based on Source History Modeling

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

Note: All groundwater concentrations based on modeled fit to actual soil concentrations shown in Table Q.1

OU3-11		
Based on TCE Equivalents		
Release/ Starting Date (t_0)	**Years Prior to Core Collection**	**Interfacial GW Conc. (mg/L)**
1976	35	1.40
1980	31.5	0.86
1983	28	0.70
1987	24.5	0.53
1990	21	0.42
1994	17.5	0.33
1997	14	0.26
2001	10.5	0.20
2004	7	0.16
2008	3.5	0.10

APPENDIX R

Summary of Modeling Results – Other Locations (presented as screenshots from ESTCP Source Attenuation Tool)

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Source Area, WCP-14

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	8.10E-08	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.90	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.20
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1962 (If unknown, assume 10% of plume phase solubility.)	C_o	1200	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	830.00
2	0.16	250.00
3	0.33	270.00
4	0.49	260.00
5	0.66	210.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1962 (yyyy)

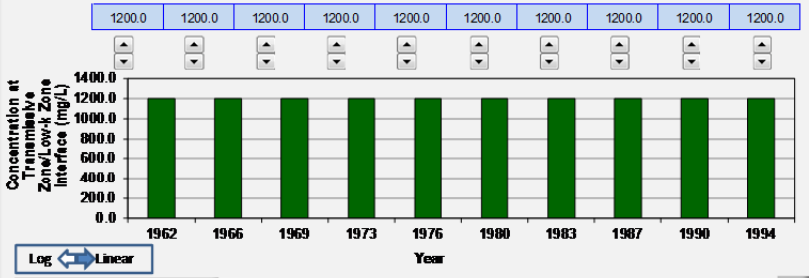
Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

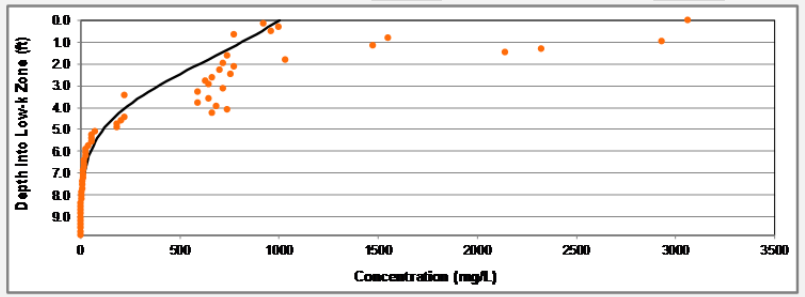
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.



Log ⇔ Linear

Uncertainty Analysis — RMS Error 509.138 mg/L — Relative Error 0.47



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Source Area, WCP-15

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	5.00E-08	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.90	(g/mL)
Distribution Coefficient	K_d		(L/kg) — Calculated R: 1.20
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1962 (If unknown, assume 10% of plume phase solubility.)	C_o	1200	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	150.00
2	0.16	185.00
3	0.33	147.00
4	0.49	220.00
5	0.66	240.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1962 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

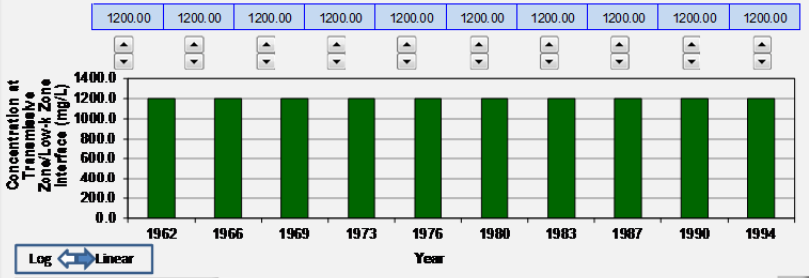
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

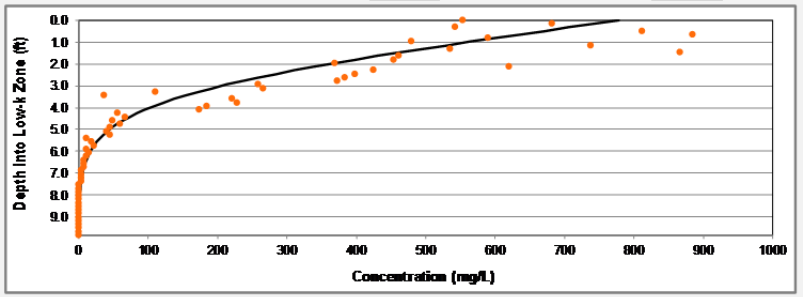
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1962	1966	1969	1973	1976	1980	1983	1987	1990	1994
1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00



Uncertainty Analysis — RMS Error 97.445 mg/L — Relative Error 0.35



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Connecticut Site, Source Area, WCP-70

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	7.80E-08	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.90	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

Calculated R: 1.20

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1952 (If unknown, assume 10% of plume phase solubility.)	C_o	1200	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	300.00
2	0.16	300.00
3	0.33	230.00
4	0.49	340.00
5	0.66	240.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1952 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

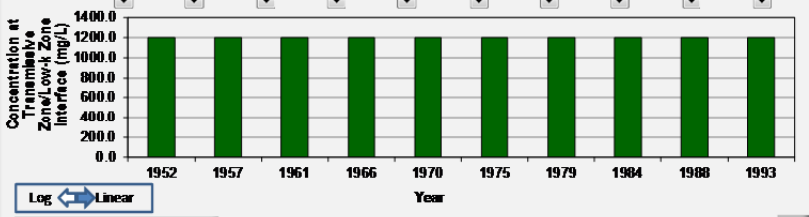
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

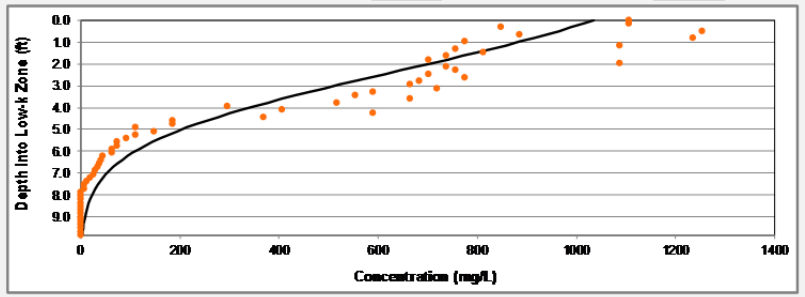
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1952	1957	1961	1966	1970	1975	1979	1984	1988	1993
1200.0	1200.0	1200.0	1200.0	1200.0	1200.0	1200.0	1200.0	1200.0	1200.0



Uncertainty Analysis — RMS Error 119.266 mg/L — Relative Error 0.58



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Source Area, WCP-71

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	6.50E-08	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.90	(g/mL)
Distribution Coefficient	K_d		(L/kg) — Calculated R: 1.20
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1952 (If unknown, assume 10% of plume phase solubility.)	C_o	1200	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	260.00
2	0.16	263.00
3	0.33	270.00
4	0.49	207.00
5	0.66	230.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1952 (yyyy)

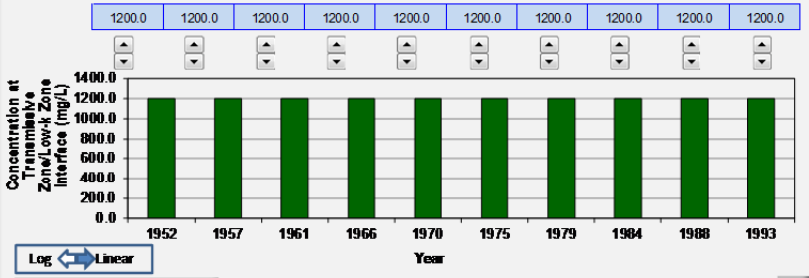
Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

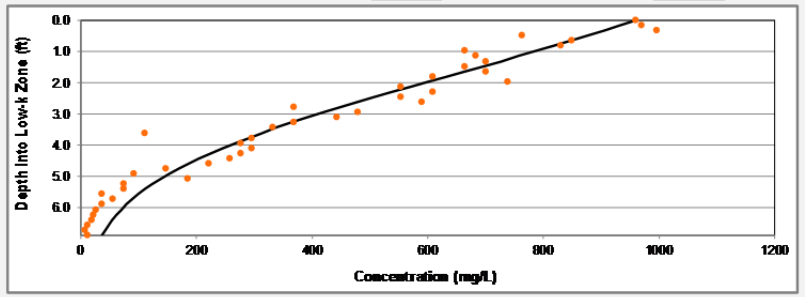
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.



Log ⇔ Linear

Uncertainty Analysis — RMS Error 63.653 mg/L — Relative Error 0.60



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Source Area, WCP-87

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	7.00E-08	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.90	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.20
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1952 (If unknown, assume 10% of plume phase solubility.)	C_o	1200	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	65.00
2	0.16	75.00
3	0.33	80.00
4	0.49	77.00
5	0.66	35.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1952 (yyyy)

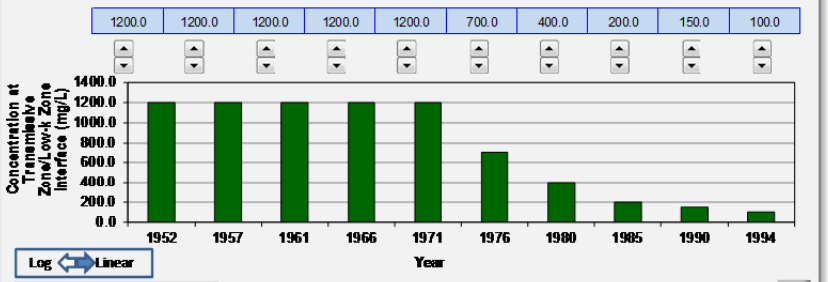
Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

(•) Exp. Decay ( ) Linear Decay ( ) Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

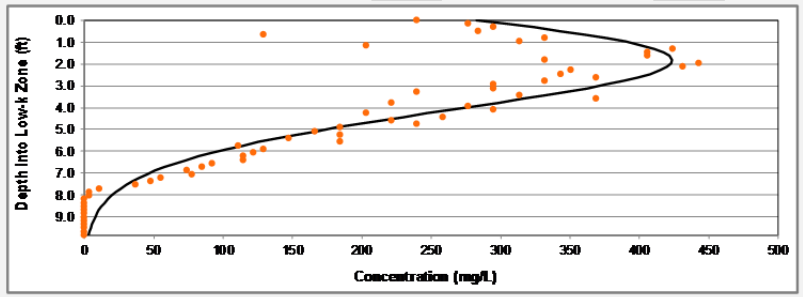
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.



Log ⇔ Linear

Uncertainty Analysis — RMS Error 54.443 mg/L — Relative Error 0.43



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Connecticut Site, Downgradient Area, ML-4

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	1.60E-07	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.95	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.20
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1954 (If unknown, assume 10% of plume phase solubility.)	C_o	140	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	0.90
2	0.16	0.95
3	0.33	1.05
4	0.49	1.20
5	0.66	1.15

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1954 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

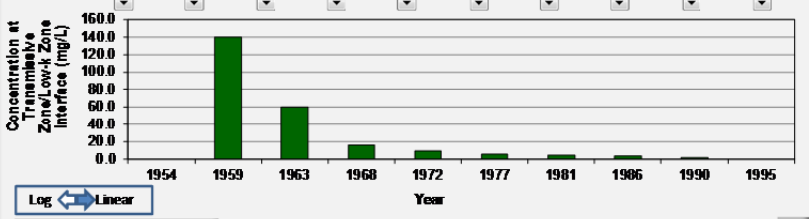
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

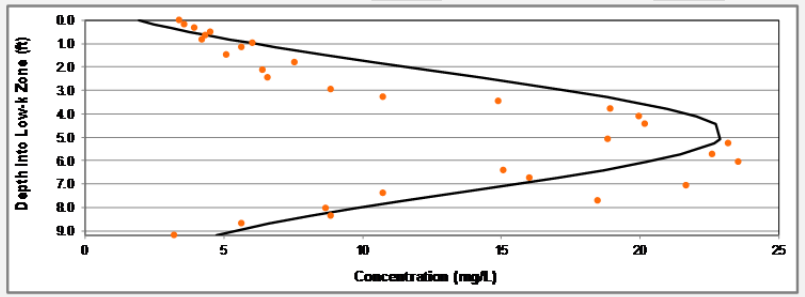
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.00	140.00	60.00	16.00	9.00	6.00	4.50	3.50	2.00	0.00



Log ⇔ Linear

Uncertainty Analysis — RMS Error 3.757 mg/L — Relative Error 0.31



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Downgradient Area, ML-10

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	1.00E-07	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.95	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R = 1.20
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1954 (If unknown, assume 10% of plume phase solubility.)	C_o	250	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.16	1.30
2	0.49	1.50
3	0.66	1.90
4	0.82	2.30
5	0.98	5.80

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1954 (yyyy)

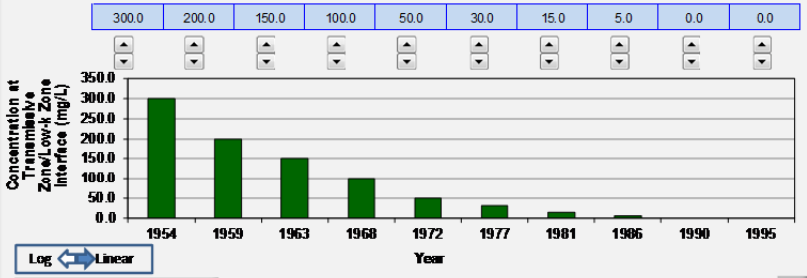
Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

(•) Exp. Decay ( ) Linear Decay ( ) Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

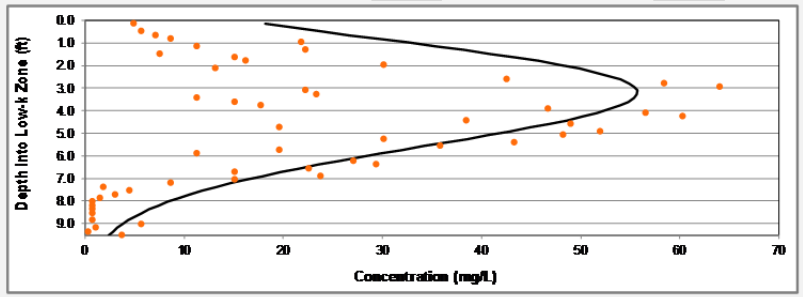
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.



Log ⇔ Linear

Uncertainty Analysis — RMS Error 17.492 mg/L — Relative Error 2.01



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Connecticut Site, Downgradient Area, ML-11

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.43	(-)
Transport Type		Advection and Diffusion	
Hydraulic Conductivity	K	2.00E-07	(cm/sec)
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.10	(-)
Bulk Density of Low-k Zone	ρ_b	1.95	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R = 1.20
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0005	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1952 (If unknown, assume 10% of plume phase solubility.)	C_o	50	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	1.10
2	0.49	0.80
3	0.98	1.05
4	1.48	1.10
5	1.64	1.30

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1952 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

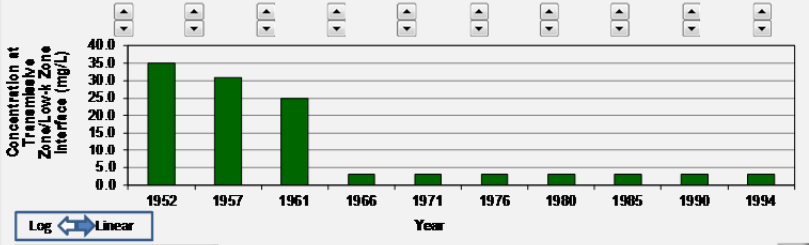
(•) Exp. Decay ( ) Linear Decay ( ) Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

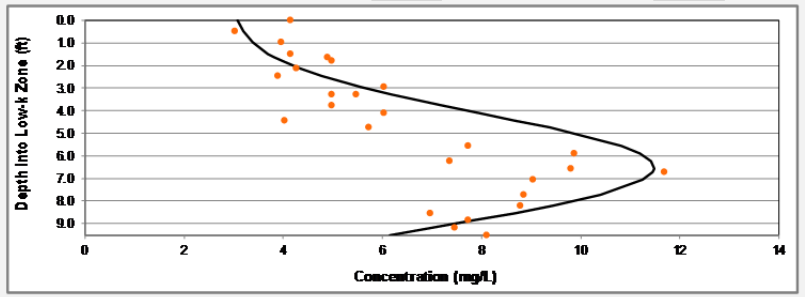
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1952	1957	1961	1966	1971	1976	1980	1985	1990	1994
35.0	31.0	25.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0



Log ⇔ Linear

Uncertainty Analysis — RMS Error 1.880 mg/L — Relative Error 0.24



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Ontario Site, AC-6

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.35	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	2.00E-07	
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.33	(-)
Bulk Density of Low-k Zone	ρ_b	2.05	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.49
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0009	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1975 (If unknown, assume 10% of plume phase solubility.)	C_o	1100	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	385.00
2	0.11	380.00
3	0.23	350.00
4	0.34	300.00
5	0.46	290.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1975 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

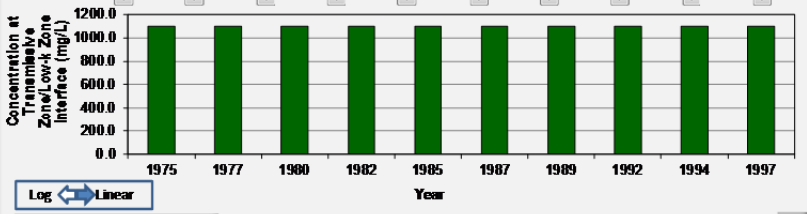
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

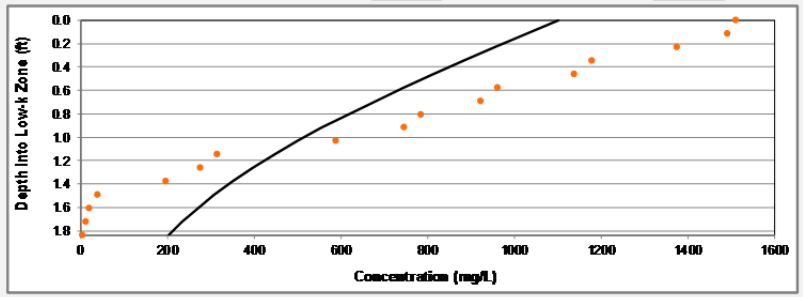
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0



Log ⇔ Linear

Uncertainty Analysis — RMS Error 267.242 mg/L — Relative Error 5.47



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Florida Site, PM-18

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.35	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	2.00E-07	
Vertical Hydraulic Gradient	i	0.40	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	7.10E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	1.33	(-)
Bulk Density of Low-k Zone	ρ_b	2.05	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 4.39
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0062	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1999	(yyyy)
Enter Best Guess for Concentration in Year 1964 (If unknown, assume 10% of plume phase solubility.)	C_o	500	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	330.00
2	0.33	250.00
3	0.66	255.00
4	0.98	170.00
5	1.31	110.00

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1964 (yyyy)

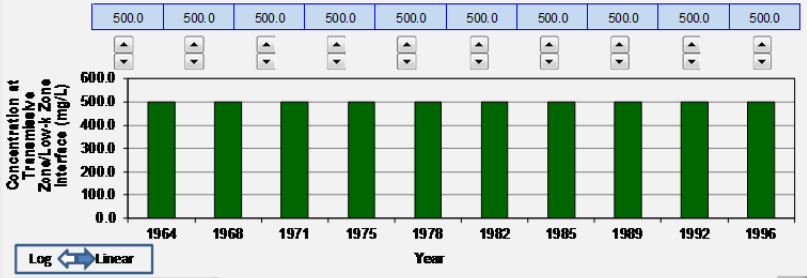
Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

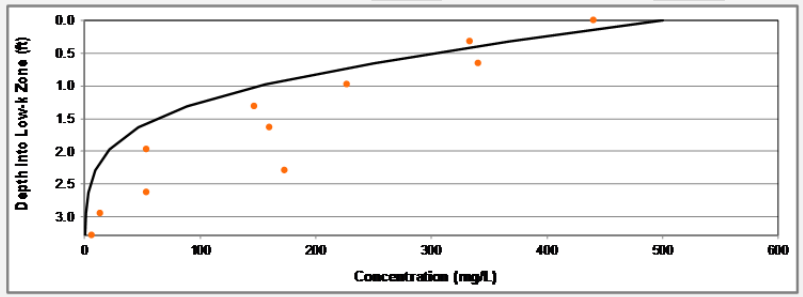
Step 4: To get some general rules on what you need to change to match observed data, click here —>

Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.



Log ⇔ Linear

Uncertainty Analysis — RMS Error 76.775 mg/L — Relative Error 0.57



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Dover AFB Site, PPC-11

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		PCE	PCE
Molecular Diffusion Coefficient in Free Water	D_o	5.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0028	( )
Organic Carbon Partitioning Coefficient	K_{oc}	155.00	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

Calculated R: 2.00

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1994	(yyyy)
Enter Best Guess for Concentration in Year 1974 (If unknown, assume 10% of plume phase solubility.)	C_o	0	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.20	0.05
2	0.30	0.05
3	0.39	0.04
4	0.49	0.02
5	0.59	0.02

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1974 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

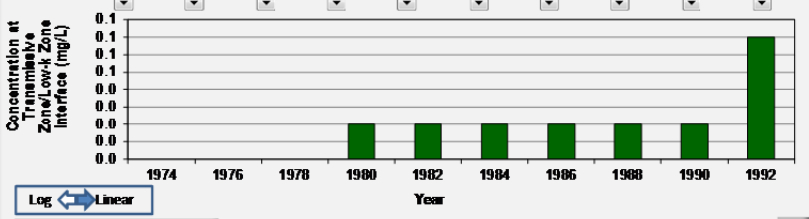
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

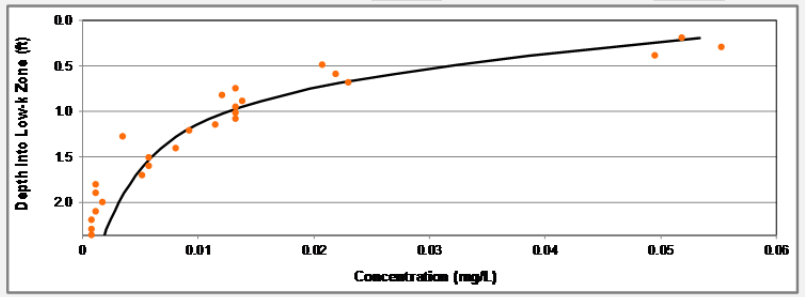
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1974	1976	1978	1980	1982	1984	1986	1988	1990	1992
0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.07



Log ⇔ Linear

Uncertainty Analysis | RMS Error 0.004 mg/L | Relative Error 0.62



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Dover AFB Site, PPC-11

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	6.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.40
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0019	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1994	(yyyy)
Enter Best Guess for Concentration in Year 1974 (If unknown, assume 10% of plume phase solubility.)	C_o	0	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.20	1.08
2	0.30	1.40
3	0.39	1.55
4	0.49	1.02
5	0.59	0.98

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1974 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

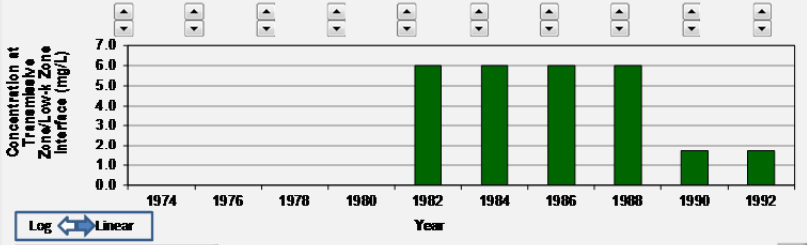
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

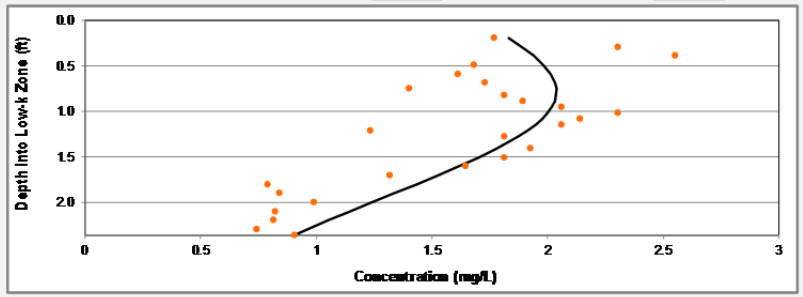
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.00	0.00	0.00	0.00	6.00	6.00	6.00	6.00	1.70	1.70



Log ⇔ Linear

Uncertainty Analysis — RMS Error 0.338 mg/L — Relative Error 0.21



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Dover AFB Site, PPC-13

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		PCE	PCE
Molecular Diffusion Coefficient in Free Water	D_o	5.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 2.00
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0028	( )
Organic Carbon Partitioning Coefficient	K_{oc}	155.00	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1996	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.07	0.01
2	0.23	0.02
3	0.39	0.02
4	0.56	0.04
5	0.72	0.03

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

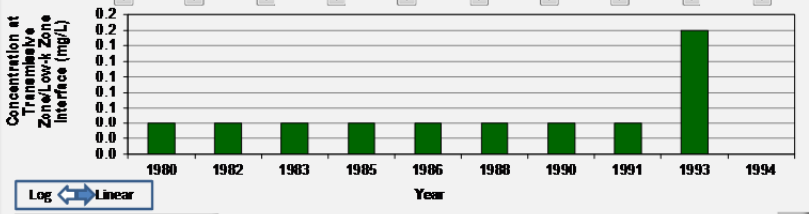
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

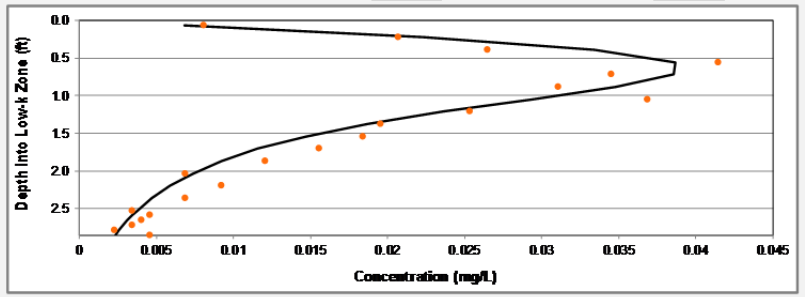
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1980	1982	1983	1985	1986	1988	1990	1991	1993	1994
0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.16	0.00



Log ⇔ Linear

Uncertainty Analysis | RMS Error 0.003 mg/L | Relative Error 0.19



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Dover AFB Site, PPC-13

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	6.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.40
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0019	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.07	0.20
2	0.23	0.45
3	0.39	0.60
4	0.56	1.00
5	0.72	0.90

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

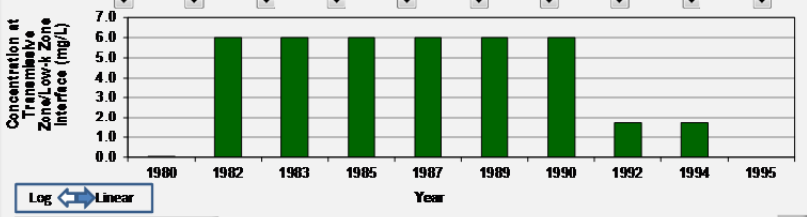
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

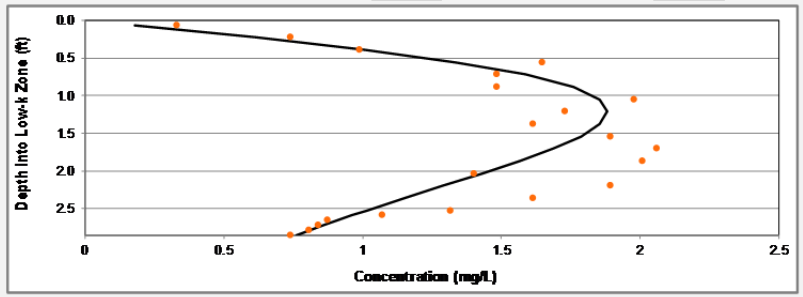
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.02	6.00	6.00	6.00	6.00	6.00	6.00	1.70	1.70	0.00



Log ⇔ Linear

Uncertainty Analysis | RMS Error 0.254 mg/L | Relative Error 0.14



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Dover AFB Site, PPC-16

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		PCE	PCE
Molecular Diffusion Coefficient in Free Water	D_o	5.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0028	( )
Organic Carbon Partitioning Coefficient	K_{oc}	155.00	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

Calculated R: 2.00

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.17	0.01
2	0.35	0.02
3	0.52	0.02
4	0.70	0.02
5	0.88	0.02

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

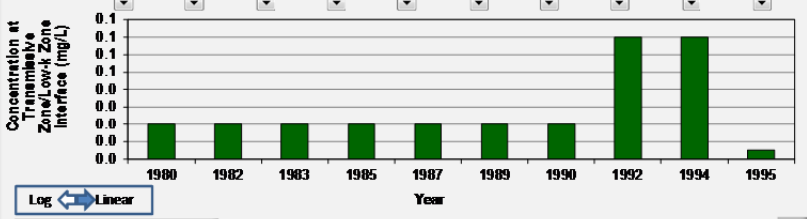
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

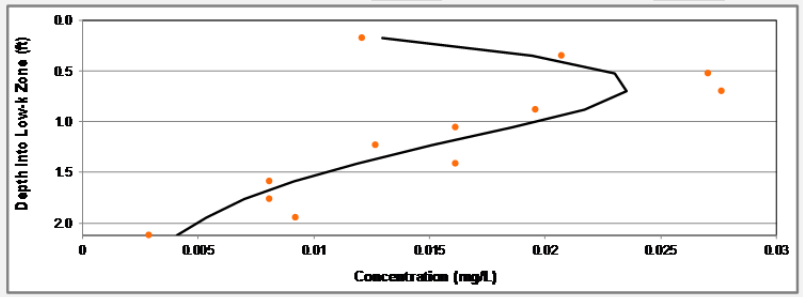
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.07	0.07	0.01



Log ⇔ Linear

Uncertainty Analysis | RMS Error 0.003 mg/L | Relative Error 0.19



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Dover AFB Site, PPC-16

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	6.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.40
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0019	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.00	0.10
2	0.17	0.20
3	0.35	0.30
4	0.52	0.31
5	0.70	0.50

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

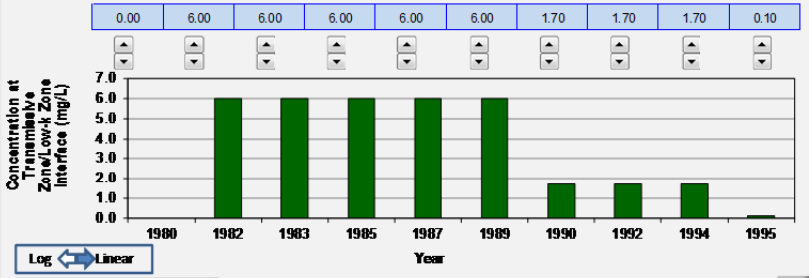
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

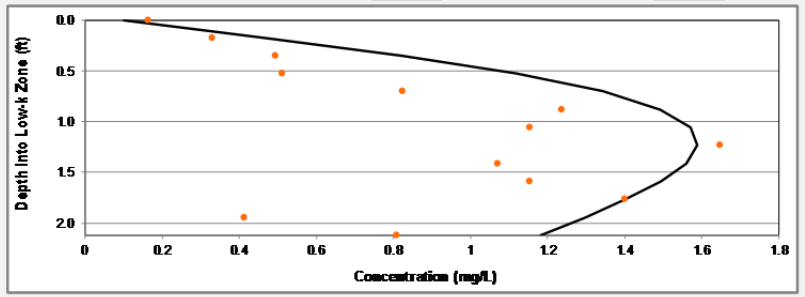
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.00	6.00	6.00	6.00	6.00	6.00	1.70	1.70	1.70	0.10



Log ⇔ Linear

Uncertainty Analysis — RMS Error 0.420 mg/L — Relative Error 0.56



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — Version 1.0

Site Location and I.D.: Dover AFB Site, PPC-19

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		PCE	PCE
Molecular Diffusion Coefficient in Free Water	D_o	5.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0028	( )
Organic Carbon Partitioning Coefficient	K_{oc}	155.00	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

Calculated R: 2.00

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.17	0.02
2	0.35	0.02
3	0.52	0.03
4	0.70	0.03
5	0.88	0.02

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

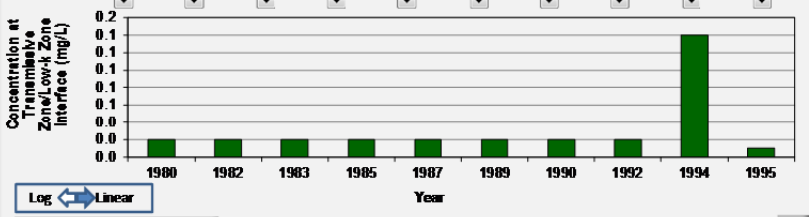
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

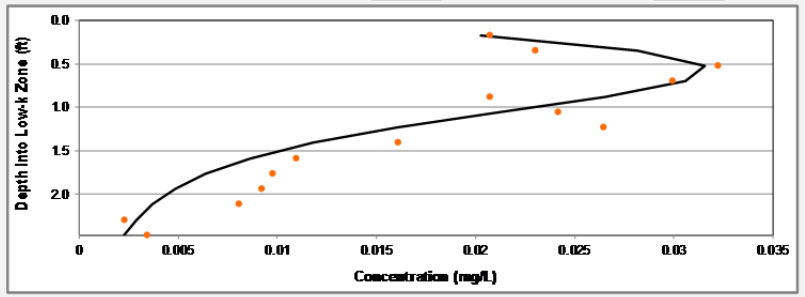
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

1980	1982	1983	1985	1987	1989	1990	1992	1994	1995
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.14	0.01



Log ⇔ Linear

Uncertainty Analysis | RMS Error 0.004 mg/L | Relative Error 0.25



New Site/Clear Data | Paste Example | Print/Export | HELP

ESTCP Source Attenuation Tool

Using Matrix Diffusion Data to Estimate Source Histories — *Version 1.0*

Site Location and I.D.: Dover AFB Site, PPC-19

1. HYDROGEOLOGY

Type of Material in Low-k Zone		Clay	Clay
Total Porosity	n	0.53	(-)
Transport Type		Diffusion only	
Hydraulic Conductivity	K	5.00E-08	
Vertical Hydraulic Gradient	i	0.90	(-)

2. TRANSPORT

Key Constituent Diffused in Low-k Zone		TCE	TCE
Molecular Diffusion Coefficient in Free Water	D_o	6.89E-10	(m2/sec)
Low-k Zone Apparent Tortuosity Factor Exponent	p	0.54	(-)
Bulk Density of Low-k Zone	ρ_b	1.22	(g/mL)
Distribution Coefficient	K_d		(L/kg)
or			Calculated R: 1.40
Fraction Organic Carbon in Low-k Zone	f_{oc}	0.0019	( )
Organic Carbon Partitioning Coefficient	K_{oc}	93.33	(L/kg)
Constituent Half-Life in Low-k Zone	$t_{1/2}$	1000	(years)

3. GENERAL

Year Core Sample Collected from Low-k Zone	t_1	1997	(yyyy)
Enter Best Guess for Concentration in Year 1980 (If unknown, assume 10% of plume phase solubility.)	C_o	1	(mg/L)

4. HIGH RESOLUTION CORE DATA*

Units for Depth: (ft)

	Depth into Low-k Zone (ft)	Soil Concentration (mg/kg)
1	0.17	0.20
2	0.35	0.30
3	0.52	0.40
4	0.70	0.45
5	0.88	0.80

*Up to 500 data points can be entered.

Import Soil Data | View All Soil Data

5. CHECK DATA (OPTIONAL)

Check Input Data

6. MATCH DATA

Step 1: Enter your best estimate for the year the original release occurred (e.g., 1971). 1980 (yyyy)

Step 2: Select a general first-round concentration vs. time pattern. You will start with this pattern and then modify the source history in Step 4 to match the high-resolution sampling data. If uncertain, start with "Exponential Decay."

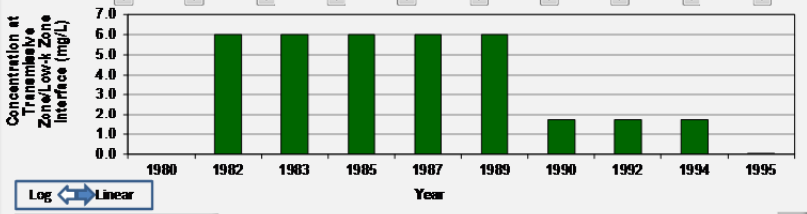
○ Exp. Decay ○ Linear Decay ◉ Constant Source

Step 3: Adjust the concentrations in the histogram manually, using up/down buttons, to try and get the black line (the model prediction) to match the actual data (orange dots). Use RMS and Relative Error as guidelines for better/worse matches.

Step 4: To get some general rules on what you need to change to match observed data, click here —>

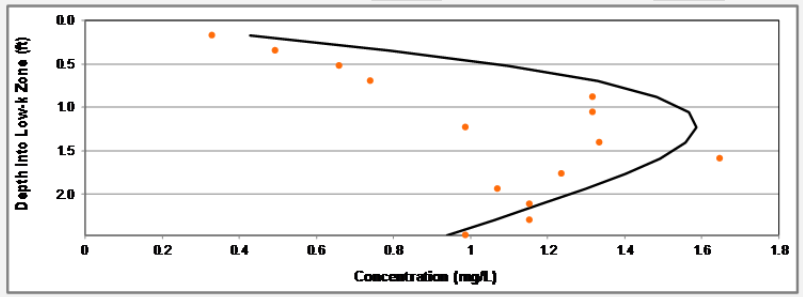
Step 5: When you get a good match, use the time vs. source concentration graph in your MNA report.

0.00	6.00	6.00	6.00	6.00	6.00	1.70	1.70	1.70	0.05



Log ⇔ Linear

Uncertainty Analysis — RMS Error 0.299 mg/L — Relative Error 0.29



New Site/Clear Data | Paste Example | Print/Export | HELP

APPENDIX S

Cost Table

GSI ENVIRONMENTAL

TABLE S.1
RESULTS OF COST MODELING

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

		SCENARIO 1	SCENARIO 2		SCENARIO 3	
COST ELEMENT	DATA TRACKED OR ESTIMATED	Source History Characterization Only (Duration = 3 months)	Source History Characterization Followed by MNA (Duration = 30 years)	In Situ Source Treatment Followed by MNA (Duration = 15 years)	Characterization Followed by MNA (Duration = 30 years)	Pump-and-Treat as Sole Remedy (Duration = 30 years)
TASK 1. Review of Available Data and Location Selection						
Project management	Labor (Sr EGSH), 10 hr	$950	$950		$950	
Data Review, Reporting, and Prep for Field Work	Labor					
ESGH III	40 hr	$5,200	$5,200		$5,200	
ESGH I	20 hr	$2,000	$2,000		$2,000	
Miscellaneous costs	-	$500	$500		$500	
Task 1 Total		**$8,650**	**$8,650**	**$0**	**$8,650**	**$0**
TASK 2. Screening-Level Characterization						
Project management	Labor (Sr ESGH), 10 hr	$1,900	$1,900		$1,900	
Travel to site	Airfare, per diem, etc.	$1,000	$1,000		$1,000	
Field Labor						
ESGH III	40 hr (travel plus 3 day field program)	$5,200	$5,200		$5,200	
Profiling Services	Subcontracted; MIP or WaterlooAPS; day rate for 3 days ($2000); out-of-state mobilization ($8000 fee)	$14,000	$14,000		$14,000	
Drilling Services	Subcontracted; day rate for 3 days ($2000/day); local (minimal mob fee)	$7,000	$7,000		$7,000	
Analytical	Subcontracted; not applicable if MIP is used	$0	$0		$0	
VOCs	Assumes 60 samples at $80/sample	$4,800	$4,800		$4,800	
Shipping		$200	$200		$200	
Miscellaneous costs		$1,000	$1,000		$1,000	
TASK 2 Total		**$35,100**	**$35,100**	**$0**	**$35,100**	**$0**
TASK 3. High-Resolution Soil Coring and Sampling						
Project management	Labor (Sr ESGH), 10 hr	$1,900	$1,900		$1,900	
Travel to site	Airfare, per diem, etc.	$2,000	$2,000		$2,000	
Prep	Labor (ESGH I), 10 hr	$1,000	$1,000		$1,000	
Field Labor						
ESGH III	50 hr (travel plus 5-day field program)	$6,500	$6,500		$6,500	
ESGH I	50 hr (travel plus 5-day field program)	$5,000	$5,000		$5,000	
Drilling Services	Subcontracted; day rate for 5 days ($2000/day); local (minimal mob fee)	$11,000	$11,000		$11,000	
Analytical	Subcontracted					
VOCs	Assumes 220 samples at $80/sample	$17,600	$17,600		$17,600	
foc	Assumes 20 samples at $90/sample	$1,800	$1,800		$1,800	
Other	Optional: biomarkers, isotopes, physical properties	OPTIONAL	OPTIONAL		OPTIONAL	
Shipping		$500	$500		$500	
Miscellaneous costs	Materials (methanol, samplers, etc.)	$2,000	$2,000		$2,000	
TASK 3 Total		**$49,300**	**$49,300**	**$0**	**$49,300**	**$0**
TASK 4. Modeling						
Project management	Labor (Sr EGSH), 10 hours	$1,900	$1,900		$1,900	
Data Review and Reporting						
Sr ESGH	Validation (20 hr)	$3,800	$3,800		$3,800	
ESGH III	Initial Model Testing (40 hr)	$5,200	$5,200		$5,200	
Reporting	Sr ESGH, 50 hr; Included as part of final report for Scenario 1	NA	$9,500		$9,500	
Task 4 Total		**$10,900**	**$20,400**	**$0**	**$20,400**	**$0**
TASK 5. Other Characterization/Reporting in Support of Remedy Selection/Design						
Not included						
Task 5 Total		**$0**	**$0**	**$0**	**$0**	**$0**
TASK 6. Well Installation (monitoring wells, injection wells, extraction wells)						
Project management	Labor (Sr ESGH), 10 hr		$1,900	$1,900	$1,900	$1,900
Reporting (work plan)	Labor (ESGH II), 20 hr		$2,300	$2,300	$2,300	$2,300
Travel to site	Airfare, per diem		$2,000	$2,000	$2,000	$2,400
Field Labor	Install 8 permanent monitoring wells for all options; install 2 extraction wells for pump and treat option					
ESGH II	50 to 70 hr		$6,500	$6,500	$6,500	$9,100
Tech	50 to 70 hr		$3,750	$3,750	$3,750	$5,250
Drilling Services	Subcontracted; day rate for 5 to 7 days ($2000/day); local (minimal mob fee)		$11,000	$11,000	$11,000	$11,000
Miscellaneous costs	Well materials		$2,000	$2,000	$2,000	$2,000
TASK 6 Total		**$0**	**$29,450**	**$29,450**	**$29,450**	**$33,950**

GSI ENVIRONMENTAL

TABLE S.1
RESULTS OF COST MODELING

Determining Source Attenuation History to Support Closure by Natural Attenuation
ESTCP ER-201032

COST ELEMENT	DATA TRACKED OR ESTIMATED	SCENARIO 1 Source History Characterization Only (Duration = 3 months)	SCENARIO 2 Source History Characterization Followed by MNA (Duration = 30 years)	SCENARIO 2 In Situ Source Treatment Followed by MNA (Duration = 15 years)	SCENARIO 3 Source History Characterization Followed (Duration = 30 years)	SCENARIO 3 Pump-and-Treat as Sole Remedy (Duration = 30 years)
TASK 7. Treatment System Design and Installation						
Project management	Labor (Sr ESGH), 20 hr			$3,800		$3,800
System Design and Work Plan						
ESGH III	50 to 100 hr depending on option			$6,500		$13,000
ESGH I	50 to 100 hr depending on option			$5,000		$10,000
System Fabrication	Subcontracted			$0		$50,000
Travel to Site	Airfare, per diem			$14,000		$4,000
Field Labor	Includes oversight of system installation and sytem testing					
ESGH III	150 hr (pump and-treat option); 450 hr (bio option)			$58,500		$19,500
ESGH I	150 hr (pump and-treat option); 1100 hr (bio option)			$110,000		$15,000
System Installation	Subcontracted; Installing and injecting through 150 temporary wells for in situ bio option (2 rigs at 20 days per rig; 2 events)); installing ex situ treatment system for pump-and-treat option			$160,000		$100,000
Materials	Piping, substrate, etc			$40,000		$10,000
Shipping	Shipping of teratment system components to site			$15,000		$10,000
Miscellaneous costs				$10,000		$10,000
TASK 7 Total		**$0**	**$0**	**$422,800**	**$0**	**$245,300**
TASK 8. Treatment System Operations and Maintenance						
Project management	Labor (Sr ESGH), 80 hr annual for 30 years					$285,000
O&M Labor						
ESGH I	Subcontracted; Daily checks, 250 hr annual for 30 years					$750,000
O&M Consumables, Electricity, Waste Disposal	Consumables (GAC), Electricity, waste disposal, replacement parts					$200,000
TASK 8 Total		**$0**	**$0**	**$0**	**$0**	**$1,235,000**
TASK 9. Long-Term Monitoring						
Project management	Labor (Sr ESGH), 30 hr annually for 20 to 30 yr		$171,000	$114,000	$171,000	$228,000
Field Labor						
ESGH I	Subcontracted; 15 hr per bi-annual event for 20 to 30 yr		$90,000	$60,000	$90,000	$180,000
Analytical	Subcontracted					$0
VOCs	Assumes 10 sample per event at $80/sample		$48,000	$24,000	$48,000	$96,000
Consumables	$100 per event		$6,000	$4,000	$6,000	$12,000
Data review and reporting						
ESGH II	10 hr per bi-annual event for 20 to 30 yr		$69,000	$46,000	$69,000	$138,000
Miscellaneous costs			$3,000	$2,000	$3,000	$3,000
TASK 9 Total		**$0**	**$387,000**	**$250,000**	**$387,000**	**$657,000**
TASK 10. Closeout and Decomissioning						
Decomissioning	lump sum estimate					$20,000
Waste disposal	Subcontracted					$10,000
TASK 10 Total		**$0**	**$0**	**$0**	**$0**	**$30,000**
TASK 11. Final Reporting						
Project management	Labor (Sr ESGH), 20 hr	$3,800	$3,800	$3,800	$3,800	$3,800
Prepare and submit draft Final Report						
ESGH III	100 hr	$13,000	$13,000	$13,000	$13,000	$13,000
ESGH I	100 hr	$10,000	$10,000	$10,000	$10,000	$10,000
Revise draft and submit Final Report						
ESGH III	50 hr	$6,500	$6,500	$6,500	$6,500	$6,500
ESGH I	25 hr	$2,500	$2,500	$2,500	$2,500	$2,500
TASK 11 Total		**$35,800**	**$35,800**	**$35,800**	**$35,800**	**$35,800**
CONTINGENCY (15%)		$20,963	$80,438	$106,290	$80,438	$330,465
TOTAL COST		**$160,713**	**$616,688**	**$814,890**	**$616,688**	**$2,533,565**
COST PER LOCATION (4)	Includes only those intervals that were cored	**$40,178**	NA	NA	NA	NA
COST PER FT	Includes only those intervals that were cored	**$1,148**	NA	NA	NA	NA
LIFE-CYCLE COST PER CUBIC YD TREATED	Treatment volume = 11,100 cubic yard	NA	**$56**	**$73**	**$56**	**$228**