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5.7 Manage, Interpret, and Present Data

Once collected, data must be interpreted, synthesized, managed, and used to develop remediation alternatives. The tools used and the data generated for fractured rock can differ from those used and generated in unconsolidated porous materials.

5.7.1 Data Management

When investigating bedrock sites, unique geophysical data sets related to fractures should be generated early to help direct the collection of borehole data (such as drill cutting or core characterization, or to identify packer testing intervals). Although many geophysical tools are used in unconsolidated settings, the data related to fracture orientation, aperture, frequency by orientation and depth, lithology, infilling, alteration, and hydraulic activity are unique and should be managed in the following five phases:

1. Geophysical logging data from instruments. ▼*Read more*

Data files are generated by individual logging tools such as a mechanical caliper, acoustic televiewer, natural gamma log, or transmissivity profiling techniques. These data files are in different formats, depending on the nature of the data and the manufacturer's practices. The critical step is to capture these raw data files as part of site reporting. These files, along with the report describing what each file contains, should be archived in a secure file storage system and protected for future use.

2. Integrated borehole logs. ▼*Read more*

Data management and visualization software tools are commercially available. These tools include a database component to organize and store the information used to create boring logs, cross-sections, and three-dimensional visualizations. Some of these tools have the comprehensive capabilities to store and manage data, and to prepare boring logs, well construction diagrams, and cross-sections. Other tools are better suited for data presentation and visualization as opposed to data storage and management. In practice, because the preparation of lithologic and well construction data can be a dynamic process as data are reviewed and finalized, it is good practice to upload data to the database management software after logs are finalized. Some of the available tools are more appropriate for integrating and analyzing data from a single borehole and, in the case of fractured rock boreholes, may also be the best tool to create the boring log and well construction diagram. Other tools are better suited to compile and present key data from individual boreholes into cross-sections (and are also very good for generating boring logs and well construction diagrams).

3. Data visualization software. ▼*Read more*

Data visualization software can be used effectively in developing the CSM and evaluating remedial alternatives. These tools are best used with 2-D visualization tools, which are typically better able to show data, such as water levels and water sample results, at discrete points (well screens) in cross-section. At their core, 3-D data visualization tools have a data modeling component. Data collected at discrete points or intervals, such as lithologic data, water level, and water quality data are modeled to create surfaces and 3-D solids. The input and output from these models must be managed by an experienced hydrogeologist to ensure that the results conform to basic hydrogeologic principles and site conditions. This expertise is especially important when creating 3-D solids to represent contamination in groundwater, because these models typically represent the bedrock matrix as an oversimplified, homogeneous, isotropic space—and it is not. The hydrogeologist should ensure that the model represents the plume accurately based on an understanding of the site hydrogeology, groundwater flow direction, and changes in transmissivity, which are all parameters that are unlikely to be embedded in the model.

4. Date Management Software. ▼*Read more*

Commercially available database software can process data generated at fractured bedrock sites. These tools consist of a set of tables related by common fields in each table. Typically, one table, such as a location table, defines the locations stored in the data base and serves as the root table in the database. A location is a unique point in space with a unique name (for example, there can only be one monitoring well MW-1 in the project database). In general, database management software used on environmental projects focuses on the significant task of importing, storing, managing, and reporting environmental sample data collected from a location, point, or interval, at a specific time. Examples of the kinds of tables in these databases include: location, sample, sample results, well construction, and water level data.

5. Archive data storage systems. ▼*Read more*

It is a good practice to store output from specific logging tools in database management software. The data can then be combined with other information such as x, y, z values and used in data visualization applications. Borehole geophysical data, which is collected at a point in the borehole, such as natural gamma data, can be stored in the data management software. However, the data must be prepared in and then exported as an electronic data deliverable (EDD) for uploading to the database.

An archive data storage system is an important part of the project data management system because it provides a central, secure repository to store data from instruments as well as data files compiled using data analysis and presentation applications.

5.7.2 Data Analysis

Various tools can be used for data analysis at fractured rock sites. This guidance does not provide a comprehensive "how-to" guide for interpreting all types of responses for these tools, but rather offers examples of what can be learned from these tools. Typical outputs and presentations from these tools are provided.

5.7.2.1 Borehole Geophysics

Many down-hole geophysical tools are available to aid in the characterization of fractured rock sites. Because they can rapidly collect large amounts of high-resolution data, certain combinations of tools are commonly used.

Borehole Mechanical Caliper. ▼*Read more*

Borehole diameter enlargements measured with a caliper logging tool can indicate presence of individual fractures or fracture zones. The response amplitude is directly proportional to the borehole diameter, which can be influenced by general fracture size and local rock structural integrity. An important consideration when analyzing mechanical caliper data is how the individual caliper arms respond to a single fracture. For example, when the fracture is horizontal, all arms respond simultaneously. For a steep, vertical fracture, however, the arms intersect the fracture at different depths. The differing depths create separate anomalies that should not to be mistaken for separate fractures. These anomalies can be checked with other tools such as the optical and acoustic televiewer.

Optical and Acoustic Televiewers. ▼*Read more*

The continuous view of the borehole wall presented in the televiewer log can be used to identify fracture patterns, their relative sizes, and their planar orientations. The varying size of fractures can make it difficult to determine if they are open, partially open, or filled (mineralized). A filled or mineralized fracture exhibits little or no transmissivity.

The results from the acoustic televiewer are particularly useful when combined with the results from the optical televiewer because together they can differentiate between weathered and competent surfaces. For example, a healed fracture generates a significantly smaller acoustic echo as opposed to an open fracture.

The results from the optical and acoustic televiewers are generally analyzed with computer software to automate the procedure for identifying the orientation of the fracture plane (strike and dip orientation). These results should be evaluated to ensure the computer outputs are representative and comprehensive. The results from the structural orientation analysis are commonly shown on projection, tadpole, and stereo plots. The structural projection displays the trace of planar features and can be overlaid directly on the televiewer image. The tadpole plot displays the strike and dip angles of the individual fractures where they occur on the log, with the tail of the tadpole pointing in the direction of dip. The stereonet displays the strike and dip of the fractures and provides a consolidated view of the distribution of the depicted fractures set. The tadpole plot provides increased detail about the individual fractures, while the stereo plot allows for the rapid identification of general patterns in fracture orientation.

Fluid Resistivity (induction resistivity) and temperature profiling. ▼*Read more*

Changes or inflections in fluid resistivity may indicate a fracture contributing water to the borehole with a different dissolved solids concentration from the fluid in the borehole. Changes or inflections in borehole fluid temperatures may indicate groundwater inflow or outflow from the borehole. Indications of vertical flow in the borehole can be inferred based on temperature gradients changes and differences from normal regional gradient values. When analyzing the fluid resistivity and temperature logs, pay attention to the amount of time allowed for equilibration between drilling completion and the geophysical measurements. For instance, a single high-yield fracture could fill the entire borehole during drilling. If not allowed sufficient time for equilibration, the fluid resistivity and temperature changes at smaller features would remain masked by the water from the high-yield fracture.

As noted in the Tool Selection Worksheet, resistivity (conductivity is the inverse measurement of resistivity) is a versatile parameter that offers multiple possibilities for applying various methods for collecting the data.

Heat-pulse flow meter (HPFM). ▼*Read more*

The heat-pulse flow meter measures the direction and rate of vertical flow within the borehole. Measurements are collected at selected depths (or “stations”), which may be regularly spaced or chosen based on fractures identified by other means (e.g., core samples, caliper or televiewer). Changes in vertical flow direction, flow rates, or both between measurement stations indicate transmissive fractures between the measurement stations. These changes may include differences in vertical flow direction (such as upflow or downflow, or changes in the rate of vertical flow). When analyzing heat-pulse flow meter data, it is important to understand if the data was collected under ambient or stressed conditions and the sensitivity of the specific heat-pulse flow meter tool. Equipping an HPFM with a baffle maximizes the flow through the instrument. Stations should be selected at depths where the borehole wall is relatively smooth so that the baffle seats properly and seals the station, thereby diverting flow through the instrument.

Unlike other geophysical logs, which are typically run continuously up and down the borehole, the HPFM log is positioned one station at a time during data collection. The data are collected, the instrument is moved and stopped at the next station, and data are collected again. If information is available about specific features of interest (typically fractures), the objective is to collect flow measurements above and below such features to detect changes in fluid flow associated with the features. Other borehole logs that provide information regarding these specific features can be analyzed in the field so that HPFM logging can follow immediately. The HPFM log is best run under ambient conditions and then repeated at the same stations under stressed (pumped) conditions. Pumping is done at a low flow rate, typically on the order of 1 gpm, to change the head in the borehole while maintaining a constant water level. Changing the head by pumping can induce changes in flow to or flow from otherwise nontransmissive fractures. In some cases, fractures that were nontransmissive under ambient conditions produce flow during stressed conditions. The changes in vertical flow rates and directions (comparing the ambient and stressed measurements), in combination with the steady-state pumping rate and drawdown, can be used to estimate the transmissivity (T) and hydraulic conductivity (K) of each interval between measurement stations.

Natural gamma. ▼*Read more*

Generally, clay and clay-filled fractures are more likely to have higher relative gamma signatures. This technique can be useful in fractured sedimentary rock formations to differentiate sand units from shale units (or sands from clays in unconsolidated formations). Natural gamma readings can aid significantly in correlating features between boreholes across a site or for regional stratigraphic correlations. In fractured metamorphic and igneous terranes, these signatures can indicate clay filled fractures and may help to differentiate between transmissive and nontransmissive features.

5.7.2.2 Hydraulic Testing Analysis

As demonstrated in the Tools Selection Worksheet, many technologies are available for characterizing the hydraulic properties of a bedrock aquifer. This section summarizes the data analysis aspect for commonplace technologies and emerging options for efficient collection of high-resolution hydraulic data sets.

Borehole packer. ▼*Read more*

One of the more common methods for determining hydraulic properties is using borehole packers to isolate and subsequently test specific features of interest. Depending on which tests were conducted in the packed off borehole interval, the results are often used for determining transmissivity from slug tests or from pumping from the isolated intervals. It is vital to the interpretation of borehole packer results that there is no leakage (hydraulic cross connection) between the packed off interval and the remainder of the borehole. The integrity of the packer seal is verified by pressure transducer data inside and outside the packed off interval.

HPFM. ▼*Read more*

An HPFM dataset can also be used to produce a profile of K within a borehole based on changes in vertical flow rates and directions. The degree of detail depends on the number of HPFM measurement stations. If desired, data can be collected for individual fractures. The calculation process is based on fundamental well hydraulics principles assuming radial flow. Data can be processed using a spreadsheet. Alternatively, the USGS has developed a free, downloadable software package known as FLASH (Flow-Log Analysis of Single Holes) to facilitate the calculations.

Transmissivity Profile. ▼*Read more*

One emerging approach is to develop a transmissivity profile by measuring the rate of eversion of a flexible liner into a well under a fixed head. As it is lowered into the well, the liner displaces groundwater relative to the driving head on the liner. The rate that the formation accepts the displaced water depends on its transmissivity. Thus, the profile can provide borehole transmissivity at vertically discrete intervals (for example, depth-discrete one-foot intervals) and for individual wells, thus identifying key fractures and fracture zones. The resolution limit of this method is a function of the total transmissivity below a given feature. For example, if a large transmissive feature is identified approximately half-way down a borehole, the resolution limit would become lower below this fracture, after the fracture was sealed by the liner. Although the transmissivity profile provides quantitative results, these results do not represent ambient flow in these fractures, but instead the hydraulic head applied to advance the liner.

Reverse-Head Profile. ▼*Read more*

In contrast to the flexible liner eversion method, the reverse-head profile measures vertical hydraulic head below the flexible liner as it is being removed from the borehole. These data can be used to identify separate hydrogeologic units and can be verified over time by measuring the heads within depth to water in a well screen placed across corresponding isolated intervals. The data represents a snapshot of the hydraulic heads below the respective depth of the liner. Data analysis should also include a review of the equilibration curves for each interval to assess the accuracy of the measurements.

5.7.2.3 Fracture Connectivity Analysis

Monitoring the water level in surrounding fractured rock while drilling wells provides a method for determining how wells are interconnected. By correlating groundwater elevation anomalies in the surrounding wells with the corresponding depth of the drill bit, it is possible to deduce which intervals are connected to fractures in existing wells. Different drilling methodologies create different signatures; thus in order to use this approach the type of drilling performed must be known.

Pumping tests can also be effective in determining interconnectivity. Although the primary purposes for a pumping tests is to assess storativity, hydraulic conductivity (K), and yield, short term pumping tests can be used to propagate a pressure signature that can be observed in interconnected wells monitored by pressure transducers. In addition to analyzing which locations respond to the pumping test, time series drawdown and recovery charts can also be plotted together on a single graph to group the various response patterns. Depending on the spatial and vertical distribution of existing monitoring wells, technique can help to differentiate between multiple hydrogeologic units and to deduce the direction of predominant anisotropy (if present).

Hydraulic tomography (HT) is a method for estimating the deterministic (not interpolated or statistically estimated) 3-D distribution of K in an investigated volume that using two approaches:

- many successive pumping tests, each from an individual packer-isolated zone, while recording drawdown with time in many packer-isolated observation zones in all the wells in the investigated volume for each test
- inversion of data from all tests and responses together to find the 3-D distribution of K that best fits the data

In current proof-of-concept HT field applications using EPM forward models, the resulting 3-D distribution of higher K locates restricted volumes (that contain fractures) surrounded by lower K volumes of rock matrix. Fracture connectivity is estimated by the 3-D structure of intersecting higher K restricted volumes.

5.7.2.4 Matrix Contamination Assessment

Qualitative analytical results provide continuous screening data from water (pore water and groundwater) in both primary and secondary porosity. While the data offer lower certainty than the quantitative rock samples, this approach yields a continuous log of relative concentrations measured directly from the saturated primary and secondary porosity. The log is helpful for quickly assessing the general distribution of contaminants (Figure 5-3) and this data is used for selecting monitoring well intervals.

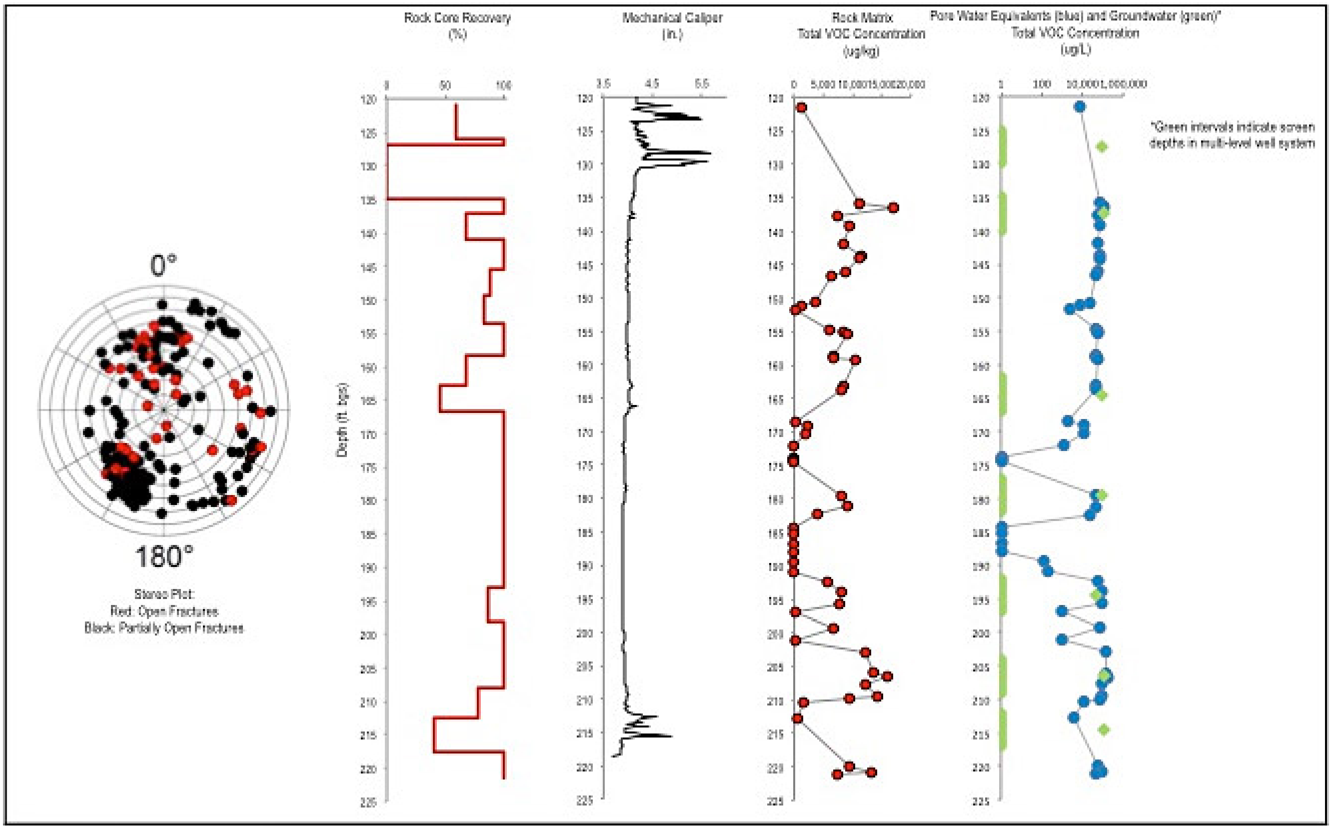


Figure 5-3. Example of a rock matrix analysis, with percent core recovery, mechanical caliper, total VOC, in a multilevel screened well system.

Quantitative analytical results from the rock matrix provide valuable insight into how primary porosity affects contaminant fate and transport at a site. This level of analytical detail may be useful when more detail is required to assess the potential for mass flux and to estimate plume longevity.

Subsequent installation and sampling of groundwater monitoring screens can provide additional information about the mass balance between primary and secondary porosity. For example, suppose groundwater contaminant concentrations from a fracture are notably higher than the calculated pore water concentrations from the adjacent primary porosity. The mass balance ratio provides a line of evidence that contaminants are diffusing into the primary porosity of the rock matrix and presumptive equilibrium has not occurred. These observations indicate a high primary porosity or a contaminant release that occurred in the relatively recent past. In the opposite scenario, the reversed mass balance would indicate that the source has been removed or depleted and concentrations in the secondary porosity are the result of back-diffusion from the primary porosity. When analyzing rock matrix results, note that the pore water concentrations are calculated results based on samples presumed to be representative of the physical properties and carbon content of the rock matrix.

Regardless of the methods used, analyzing the results identifies individual compounds and their concentrations. Speciation along a borehole profile, and laterally across a site, may provide critical information about fate and transport of known and potentially new uncharacterized releases, including from potential off-site sources.

5.7.3 Data Presentation

Compiling the interpreted data into a concise CSM presents challenges unique to each site and the target audience. A well-designed CSM includes a concise summary of interpreted results from the various data collected during the site characterization process. While borehole logs themselves are not considered a complete presentation of a CSM, they provide an essential component of data interpretation that becomes the CSM. These interpretations are typically presented in plan view and as cross-sections. The following examples illustrate these three CSM components (borehole logs, plan view, and cross-sections). Three-dimensional components may also play a useful role and are discussed in more detail in Section 5.7.1 (Data Management) and Chapter 8 (Modeling).

5.7.3.1 Integrated Borehole Logs

Integrated borehole logs combine the multiple logs from the borehole to allow analysis and interpretation of the borehole characteristics, including groundwater and contaminant movement. Interpretation of the data from individual boreholes starts during field logging and is accomplished through the integration and interpretation of the data from the borehole. As discussed in Section 5.7.1, various tools are available to store, assemble, manage, and present data from the various logging tools and to accept user input of other data such as lithologic logs and sample results. These tools can help to arrange logs and other data adjacent to one another and to rescale these data vertically and horizontally, as needed, to display relevant features.

An example of an integrated borehole log is presented in Figure 5-4. This borehole was an open bedrock borehole below the bottom of the steel casing. The bedrock coring information, FLUTe flexible liner transmissivity data, sampling data, and final FLUTe liner construction were plotted at the time of the geophysical logging. This example includes optical and acoustic televiewer logs, lithologic descriptions, various geophysical parameters, HPFM results, and contaminant sampling data.

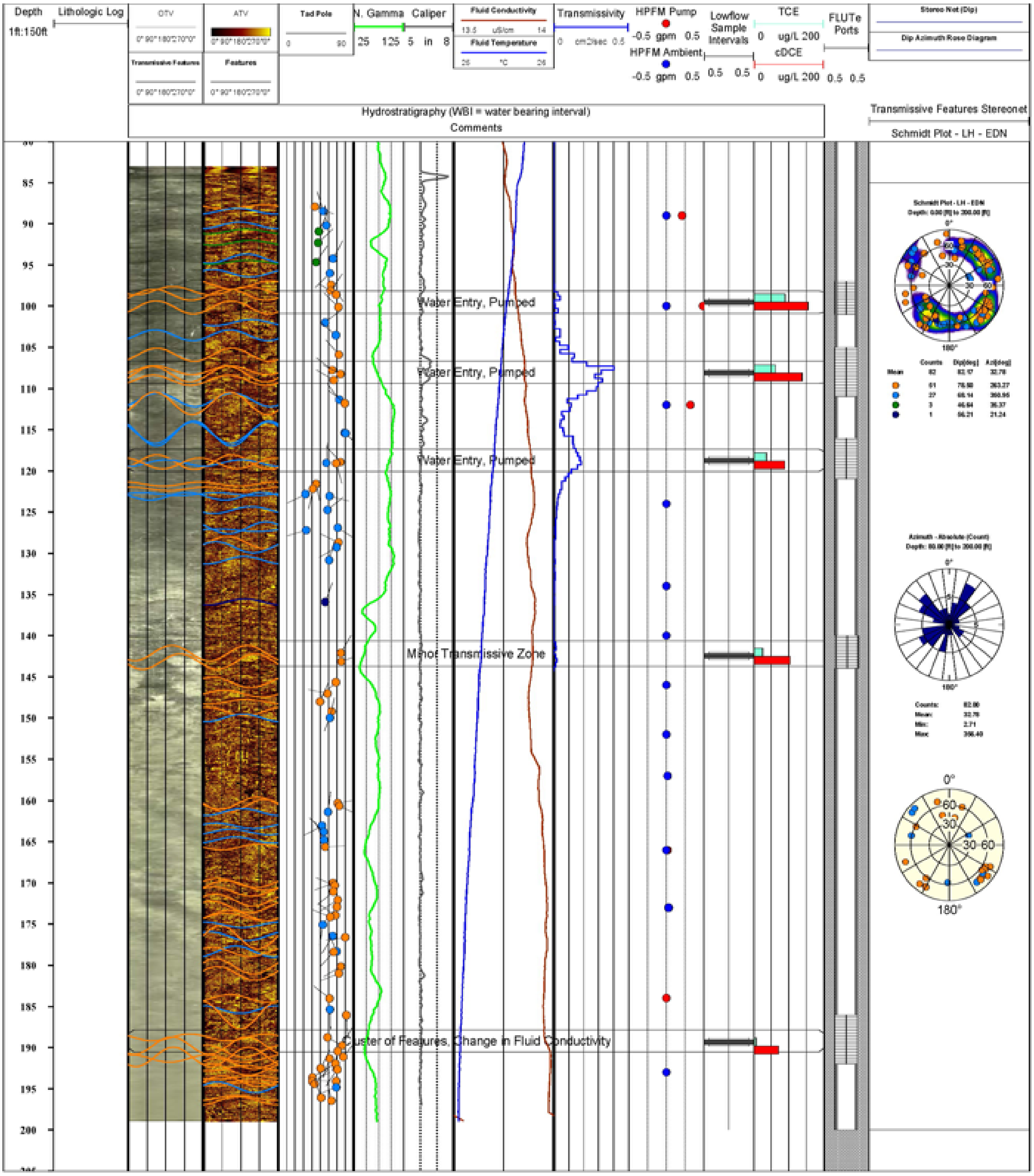


Figure 5-4. An example of an integrated borehole log.

The raw data for this example were imported into a commercially available software tool and arranged next to one another, from the left to right, on a common vertical scale and datum (for example, top of casing). Typically, rock core and the caliper log are arranged on the left. The televiewer logs are placed next to one another to make it easier to evaluate the same section of borehole in both logs. Likewise, the fluid temperature and fluid conductivity logs are arranged next to, or stacked on, one another so that inflections in both properties can be identified. One advantage of software is that it allows the user to stack logs, such as fluid temperature and conductivity, on top of each other to facilitate data interpretation and to fit more data into the available space. Another critical capability of the software is the log analysis tools built into the software. For example, advanced technology video (ATV) and overlay transport visualization (OTV) data can be used to determine borehole deviation. This feature also allows overlay of a feature log on the ATV and OTV logs and to fit a curve to features, such as fracture, bedding planes, and joints, to determine their dip angle, dip azimuth, and aperture. The feature orientation data can be represented as sinusoidal curves or as tadpole plots. (tadpole plots display the dip angle and azimuth.) The feature log can also be used to create a stereonet diagram and the data can be exported so that all orientation data from all boreholes at the site can be compiled in one stereonet.

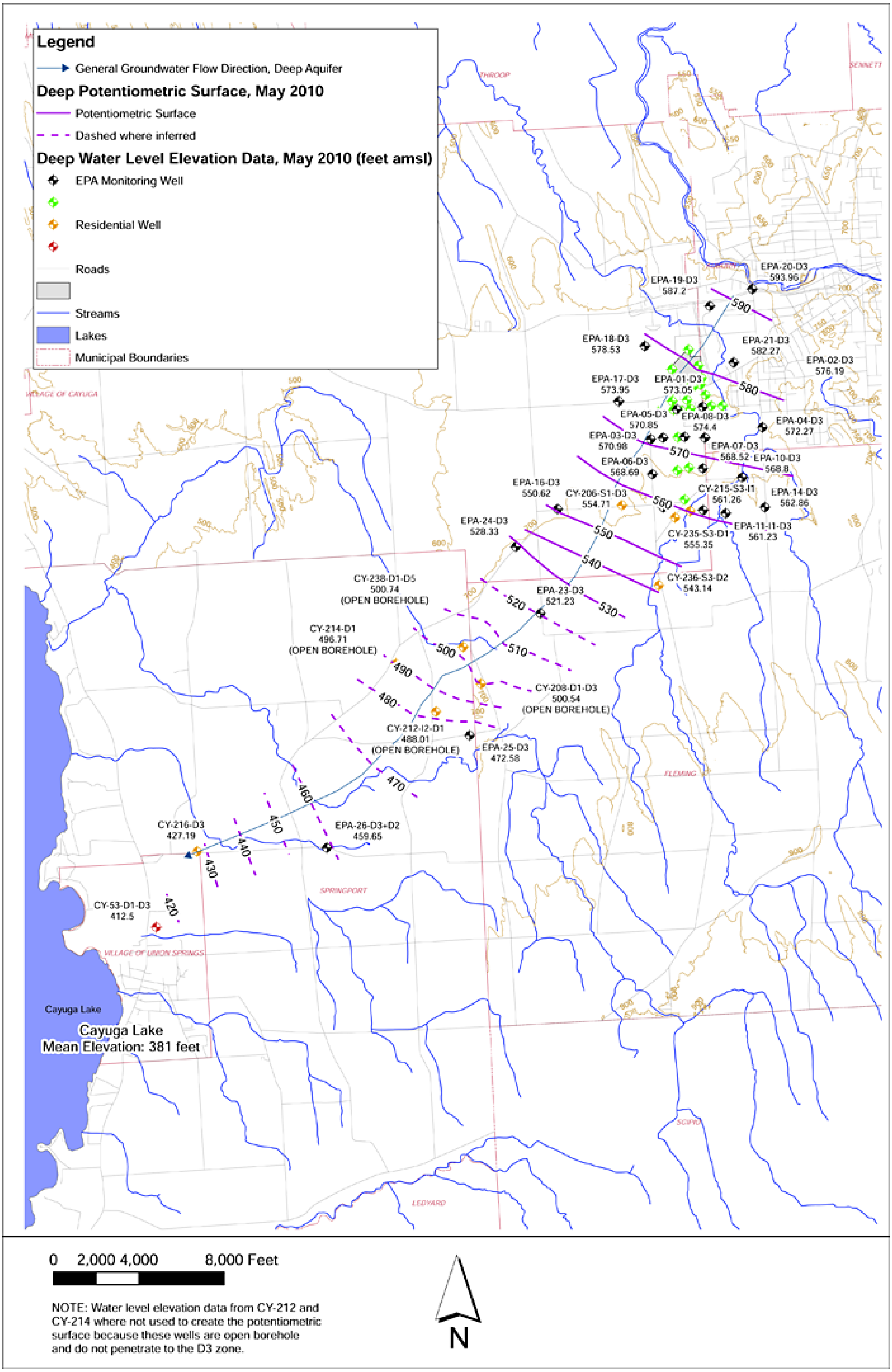
The HPFM data were added to the log and used to advance the interpretation of borehole hydraulics, fluid movement, and head distribution. Typically, the pumped and ambient logs are overlaid on one another using a common horizontal scale with zero flow in the middle, negative flow (down flow) to the left, and positive flow (up flow) to the right. This arrangement makes it easier to identify changes in vertical fluid movement between the ambient and pumped logs. The data sets shown on Figure 5-4 were not necessarily all collected at once. Initial logging/profiling activities (such as geophysical logs and televiewer) can be used to define further data collection activities based on the project objectives. As these data are collected, the results can also be incorporated into the software to facilitate data analysis and interpretation of the design of a single screen or multilevel well interval. In this way, each borehole is interpreted individually and then integrated into an overall picture of bedrock hydrogeology of the CSM.

5.7.3.2 Plan View Maps

The purpose of the plan view maps is to depict the lateral component of a 3-D CSM. Multiple maps can be prepared as necessary to encompass regional features but also to offer sufficient detail on the site level. A regional map could be prepared to include lineaments, water shed areas and surface water bodies and high-capacity wells or well fields to orient the reader about general groundwater flow. Increased detail on the site level can include smaller scale plan view maps with focus on contaminant distribution and transport. Illustrating contaminant speciation can help to delineate plumes and their sources, including potential off-site sources upgradient of the site. It is also useful to illustrate groundwater flow direction in the various hydrogeologic units, if available. Because utility trenches are most often dug in overburden and weathered bedrock (saprolite), these trenches are a potentially significant consideration to include in the fractured rock CSM. A utility trench can act as a preferential pathway for source migration or, in the case of leaking utilities, constitute the contaminant source itself. While not comprehensive, Table 5-3 lists various features that should be considered for the various plan view CSM maps. An example of a plan view map as a component of a CSM is shown in Figure 5-5.

Table 5-3. Features that should be included considered for a plan view representing a CSM

Physical Features	**Geology**	**Hydrogeology/Hydrology**	**Contamination**
Monitoring Locations	Topography (surface)	Water sheds	Source Locations
Utility Trenches	Lineaments	Piezometric Contours and Flow Direction	Plume Boundaries and Contaminant Contours
Property Boundaries	Top of Weathered Bedrock Elevation Contours	Extraction Wells in Each Aquifer	Plume Speciation
Human and Ecological Receptors	Faults	Surface Discharge or Recharge Bodies	NAPL Presence
	Top of Competent Bedrock Elevation Contours	Subcropping and Fracture Planes	



NOTE: Water level elevation data from CY-212 and CY-214 where not used to create the potentiometric surface because these wells are open borehole and do not penetrate to the D3 zone.

Figure 5-5. Example of a plan view map.

5.7.3.3 Cross-Sections

Geological cross-sections should be positioned and aligned to take maximum advantage of available information and to best present the geology (folds and faults), contaminant transport (groundwater flow direction), and the relationship between them. Relevant well data, however, are commonly situated off the cross-section line and it is useful to project this information onto the section line rather than ignore it. The spatial variability in the geology, groundwater flow, and contaminant distribution warrants increased scrutiny with distance from the cross-section line when projecting data onto a cross-section line. It may not be appropriate to project information such as well data on to a cross-section if there is significant geology or groundwater variation, especially in the direction of the projection (perpendicular to the cross-section line). Use care and professional judgment if these conditions are present.

Intersecting cross-sections, when possible, can help reduce the uncertainty associated with projecting significant amounts of data onto an individual cross-section by constraining the geologic and contaminant transport interpretations in three dimensions and by demonstrating the validity of the CSM. Alternately, cross-sections can be aligned from point to point, with bends in the section. This approach presents other challenges, such as varying apparent dips, and may result in cross-sections that complicate interpretation and visualization of the subsurface.

While not comprehensive, Table 5-4 lists various features that should be considered in the cross-section CSM figures. An example of a cross-section as a component of a CSM is provided in Figure 5-6.

Table 5-4. Features that should be considered for inclusion on a cross section representing a CSM

Physical Features	**Geology**	**Hydrogeology/Hydrology**	**Contamination**
Monitoring Locations	Bedrock Geology	Flow Direction	Source Locations
Utility Trenches	Fracture Orientation	Extraction Wells	Matrix Concentrations
Grade Elevation	Fracture Type	Water Table	Plume Boundaries
Scale and Vertical Exaggeration	Bedding Units (if applicable)	Piezometric Water Levels (if different than water table)	Plume Speciation and Concentration Contours
	Top of competent Bedrock Surface	Hydrogeologic Units and Lower Boundaries	NAPL
	Faults	Surface Discharge and Recharge bodies	
	Top of weathered bedrock	Receptors	
		Preferential Migration Pathways	
		Interconnectivity	

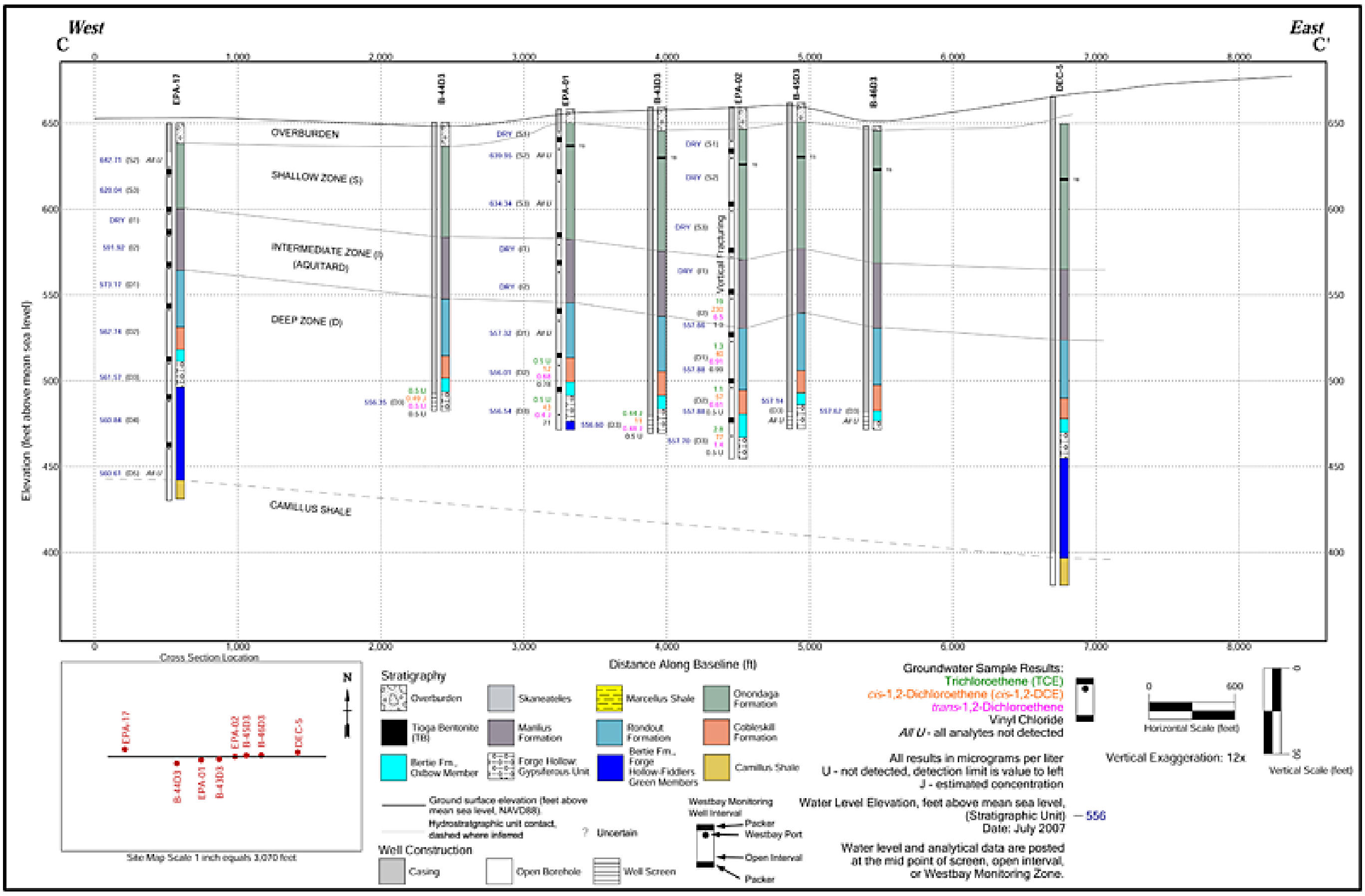


Figure 5-6. Example of a cross section used within a CSM